16th Conference on

Computer and IT Applications in the Maritime Industries

COMPIT'17

Cardiff, 15-17 May 2017

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TUHH
Technische Universität Hamburg-Harburg
Institut für Entwerfen von Schiffen und Schiffssicherheit
Schwarzenbergstraße 95 Gebäude C D-21073 Hamburg

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Maritime Training in the 21st Century

Volker Bertram, Tracy Plowman, DNV GL, Hamburg/Germany,
{volker.bertram,tracy.plowman}@dnvgl.com

Abstract

The paper discusses expected or desirable changes in teaching engineering, in particular post-graduate and professional training in maritime technologies. Several factors drive the developments: changes in students, changes in technology, changes in expectations from industry and governments. These factors determine what we need to teach and how we need to teach. A different teaching infrastructure with possibly different providers is expected to evolve. The paper discusses both market and technological aspects, highlighting challenges and pitfalls of new technologies commonly referred to as "e-learning". The paper argues in favor of pedagogy-driven education rather than technology-driven education.

1. Introduction

A new method to the 3d flow around a ship on shallow water and in oblique waves is a safe topic for an engineering conference. An estimated three colleagues may be interested to start with. A suitable mixture of complex equations, daunting diagrams and colorful displays will evoke admiration, little interest and no aggression. In comparison, education in engineering is a dangerous topic. All engineers have been exposed to the topic (as students). It is a bit like soccer:

- It used to be better in the past.
- The players (students) today just do not want to work anymore. Shame on them!
- The coaches (professors) are incompetent. We could do a better job.
- It is still great fun to talk about…

Teaching environments and techniques have changed over time, Fig.1. In Germany in the early 1980s, all professors used blackboard and chalk. Today, a mixture of PowerPoint and blackboard (or whiteboard) prevails. Discussions about future teaching employ terms like "web-based teaching", "e-learning" or "m-learning" (e-learning describes learning (or teaching) through the use of assorted technologies, mainly Internet or computer-based. Students rarely, if ever, are face-to-face with each other or teachers. m-learning describes learning through the use of mobile devices, particularly mobile telephones.) This comes typically with reorganization of departments and curricula, introduction of further quality management procedures and reduction of budgets. One must be a politician or university president to understand how this will result in better engineers for our industries.

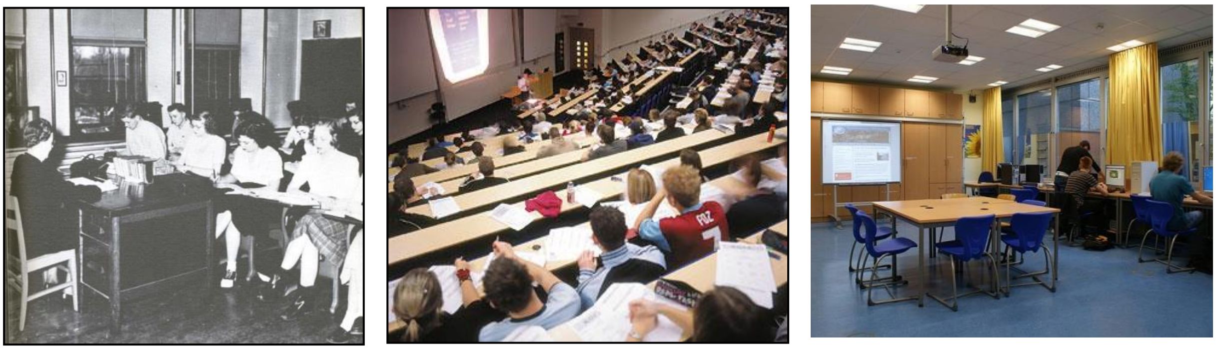


Fig.1: Teaching over time (around 1940, 1975 and 2008)

A lot of the new teaching technology has been driven by mass markets like language teaching. Here the financial incentives are higher due to much higher numbers of students. In addition, there is a traditionally much higher focus on pedagogy and openness to multi-media teaching. Much of what is now discussed for maritime teaching has been tested in other fields like language teaching, law, and medicine. Highly specialized engineering (like graduate and post-graduate training in maritime technologies) is different from these fields in required skills, available market size, and other aspects. Some approaches that work for example in English language teaching do not work for teaching naval architecture.

Despite changes in students and technologies, there are some constants in our fundamental guidelines to teaching:

- You learn by doing and face-to-face time with teachers is expensive. So we need to encourage students to work outside class time.
- Students should use tools that they are familiar with. For our generation, that meant books. For the new generation of students, this may increasingly mean computers and even smart phones.
- Communication with peers should be encouraged. This happened too little in classical engineering training, where frontal teaching has ruled supreme. Internet technology allows virtual meeting spaces for students. While popular for "net-working" (gossiping), we are not aware of any real academic benefits in the maritime field. However, traditional teamwork continues to work well and team communication is then automatically based on internet and mobile phones.
- Modern teaching approaches advocate: Make teaching competitive, make it fun! We are supposed to move from education to edutainment, where students are entertained while learning quasi without noticing it. This is easier in language education than in engineering. Material science was no fun 30 years ago, still is no fun, and is unlikely to ever be fun. No pain, no gain.

2. Changing conditions

The introduction has already mentioned several of the driving factors shaping our teaching: budgets, technology, and politics. The demographic and political changes are fairly universal. They will be discussed in the following subsections.

2.1. Different students

"Students these days are not what they used to be." We heard this sentence when we were students from our professors. We hear it today, and it is the same the world over:

- They do not want to study as much as we did.
- They cannot write properly even in their mother tongue.
- They only want to play with computers; they are not interested in "real" science (i.e. the mathematics involved in fluid or structural analyses).

These are not senile professors ranting, with a selective memory of their past. There are real changes, due to changes in the way of life and upbringing of children. Today's children are exposed to computers before they go to school. *Prensky (2001,2011)* calls them "digital natives": "Today's average college grads [in the USA] have spent less than 5,000 hours of their lives reading, but over 10,000 playing video games […] It is very likely that our students' brains have physically changed […] ." These digital natives are our raw material and they are different from us, with strengths and weaknesses:

- They are used to getting information fast. They google rather than open 20 books in a library.
- They prefer graphics to texts.
- They prefer random access to information (like hypertext links).
- They function best when networked.
- They thrive on instant gratification.
- They prefer games to serious work.

Does any of this sound familiar? Our generation of teachers is called “digital immigrants” by *Prensky (2001).* We are always one generation behind in the latest technology tools. Digital Immigrants have to teach Digital Natives. We cannot change the students or course participants we get. Instead, we should work on understanding them better and try to adapt our teaching to them, without sacrificing our goal to teach them what we know (or believe) to be important in their professional careers.

2.2. Changing political frameworks

Several political trends influence the evolution of teaching in general:

- There is an increasing demand for life-long training, with upgrades on new developments in legislation and technology. Industry engineers looking for continuous professional development are willing to spend more money, but less time and will favor on-site training rather than on-campus training. The demand for distance learning will increase.
- The transition towards a unified bachelor-master-PhD system in Europe (following the Bologna treaty) has reduced thresholds between the various states in making university degree compatible. This means that students will have more choice in where they can study. The winners of the resulting competition between universities are likely to be large Anglophone universities.
- Funding for education is reduced in most countries. There is a trend to “privatize” state universities, cutting their budgets and encouraging them to generate more own income.

2.3. New media

“New” media invariably involve computer technology. Technology develops and new terms come and go. After initial hype and large investments, universities and other higher learning institutes frequently experience a sobering disillusion.

An example may illustrate the problems encountered: “Self-access centers” (SACs) are educational facilities designed for student learning that are at least partially, if not fully self-directed. Several websites promote SACs as follows: “Self-access learning gives you the opportunity to develop initiative, responsibility, self-awareness, confidence and independence in learning. It is about making choices and having flexibility in learning.” This sounds great in theory, but SACs often do not live up to these expectations, for a variety of reasons:

- It is expensive to set up a good SAC. Learning institutes like to boast having an SAC, but do not want to pay much. Token efforts are a waste of money when it comes to SACs.
- SACs are frequently poorly staffed. Some existing teacher or technician gets tasked with running the new multi-media lab. There is no budget for hiring a dedicated expert or even for training the person responsible.
- Material gets stolen or vandalized.
- SACs are set up as a once-off prestige object, often with external once-off funding. There is no budget for maintenance and upgrades. As a result, half the computers do not work after a short period or have outdated and incompatible software.
- Students have no time or no motivation to use SACs, at least not for studying.

3. Challenges and Trends

The requirements for future engineering teaching involve some changes in infrastructure and teacher profiles:

- More teaching will have to be based on e-learning and short courses. We have observed course times moving from 1 week, to one day with demand increasing for 5 to 45 minutes e-learning solutions to respond to industry demand for continuous professional development.

So units of learning become ever shorter. Similarly, expectations for development times become ever shorter: “Can we have training on latest XYZ developments next week?”

- Teachers will continue with some traditional tasks (selection or creation of appropriate teaching material, checking that learning goals have been achieved (tests), monitoring of results, evaluation of learners), even if based on different media.
- “Edutainment” will require more frequent changes of media (more video) and topics than traditional teaching.

New media may or may not offer better ways of teaching, but pedagogy comes first. First we must decide what to teach, and then we can decide how best to teach it. Poor pedagogy results in poor training, regardless what media is employed. No doubt we have all seen more than enough useless e-learning courses.

The appendix lists some goals compiled during a workshop on training future ship designers, *Rusling et al. (2005)*. The elementary learning techniques to teach these goals are (largely) media independent and migrate naturally into web-based teaching:

	Traditional	e-learning
watching	Blackboard	PowerPoint embedded videos
reading	Books Lecture notes	Books Online texts
doing	Exercises Assigned homework/projects Laboratory work	Exercises (web-based) Assigned homework/projects Virtual lab visits
testing/evaluating	In class	On-line Homework submission

Here the pedagogy remains largely the same. The change is gradual and there is better acceptance among the traditional trainers/teachers. In principle, all traditional elements in our curricula could migrate to digital form, except for laboratories and visits to industry sites. The vast majority of the “digital immigrants” defend traditional laboratory time, but personal experience is that they are expensive and ineffective in teaching. If you really want to learn experimental techniques, make an internship or project in a professional testing facility. If you just want some hands-on feeling on some physical behavior then a virtual (numerical) lab could serve a similar purpose. So, in principle, migration to e-learning should be feasible in most cases. Then, why don’t we see widespread e-learning activities in the maritime world and why do many efforts fall well short of their targets?

There are many factors contributing to the slow transition in our field:

- Often, there is no or insufficient budget for the conversion to electronic teaching.
- Our best teachers are often not 100% computer savvy and the computer gurus lack competence in the subject matter and in pedagogy.
- E-learning is frequently not desirable:
  - You have no feedback from the learners (do they understand the material?)
  - E-learning requires self-discipline and maturity, frequently not found in our average high-school graduate;
  - E-learning requires more technological skills from teachers and students.

Some web-based means to support teaching are found in most universities today. At ENSTA Bretagne a decade ago, we employed Moodle (http://en.wikipedia.org/wiki/Moodle) as a platform for the teaching of naval architects and offshore engineers. Students accessed teaching schedules, lecture notes, assignments, and even grades via this platform. The project was moderately successful. The “download" center was readily accepted. Moodle also made it easier to integrate special students who were part time in industry (in other cities) and followed part-time courses at ENSTA Bretagne.

In Germany, four universities offering naval architecture and ocean engineering at graduate level and the research group "instructional design and interactive media" joined forces within the multi-million project mar-ing to develop e-learning infrastructure and material, *Bronsart and Müsebeck (2007).* Some years later, the video conference facilities were used for occasional lectures by visiting lecturers from industry or academia. Each university continued to use the developed material, but no mention of core lectures being offered in distance learning could be found.

We should not be surprised. The same mechanisms have prevented a text book culture in our field:

- The considerable effort to develop and update material for specialized topics cannot be recuperated.
- Teachers like to use their own material, because some topics are not covered in a book, or not explained in a way the teacher likes.

We will therefore not see a rapid e-learning development as e.g. in English language teaching. Still, the demand (and pressure) is there to develop web-based courses, which may come in the form of e-learning or webinars or evolving other forms. As universities do not reward effective teaching, much of this development towards web-based training will be driven mainly by industry providers.

4. Our own experience

Until fairly recently, DNV GL's Academy and our own training experience was based on classroom courses, where frontal teaching is interspersed with various tasks to actively involve and engage the learners who are usually limited to 15- 20 people to allow small-group interaction. Over the past few years, our Academy has responded to the increasing demand for "e-learning", which is a frequently used term by our customers expressing "something on the computer where my employees don't have to travel and sit in your classroom". Often the real training need and most suitable form of training require further elucidation through discussion of available options and constraints. We discuss our experience with various options in the following subchapters.

4.1. Classical e-learning courses

Some years ago we developed our first e-learning course on energy efficiency in ship operation. The course was rolled out via USB sticks branded with the customer's logo. The focus was on having a training solution that could be used anytime and anywhere, targeted at ship crews who would not have (easy and cheap) access to the internet. The course was subdivided into modules of typically a few minutes' duration with small tasks or quizzes to keep the participants' attention and to provide feedback on achieved learning goals. Since then technology platforms have progressed with web-based solutions and more user-friendly software to create small cartoon-type videos, Fig.2.

Fig.2: Typical stills from e-learning videos merging cartoon characters with tailored image elements

We have seen an exponential growth in demand for e-learning solutions both for internal and external training, the goal always being to save costs. But e-learning is neither cheap nor fast to produce. It requires a team of domain experts, pedagogical experts and programming experts. Once produced, the solution is more rigid than classroom training. In this respect, producing e-learning resembles writing a textbook. For example, local trainers can easily conduct classroom training in the native language of participants using PowerPoint material in English. Translating e-learning to multiple languages is usually prohibitively expensive in the limited maritime market.

A key lesson learnt over a variety of projects is that costs and time for e-learning are easily underestimated:

- Scope creep is frequently an issue in e-learning projects, especially if there is no designated single point of contact on the customer side. Change requests should be budgeted in and made explicitly clear in terms of time and cost to the customer. It is a good idea to have a script similar to a movie with sketched stills before producing any video. Only after such a script (or storyboard) has been mutually agreed upon should the rather expensive video production commence.
- Customers mostly have no idea about video production effort. Costs depend on many factors, but as a rule of thumb 1 minute of video costs 1000-3000 € to produce. It should thus be considered in each case whether a video is “nice to have”, “important” or “essential” in the context of the learning goals.
- Costs for e-learning production vary globally and depend on the sophistication of original classroom material and desired e-learning material, but in a 2017 market survey transposing a 40 slide presentation into e-learning gave costs of 7500 to 15000 €.

We would propose that E-learning is suitable for the following cases:

- There is a clearly defined topic where the state of the art does not change rapidly. E.g. non-destructive testing of welds is suitable as it has used the same technologies for decades and the fundamental physics do not change.
- There is a large and distributed pool of learners, with economies of scale justifying the relatively high initial production costs.
- The reason for training is compliance. A typical example is the instruction by airlines on safety procedures. “In the unlikely event of a sudden drop in cabin pressure…” Do all passengers really know what to do in an emergency? Of course not, but the airlines need to have proof that passengers were “instructed”. Training employees across a corporate empire on compliance issues (company mission, anti-corruption policies. etc.) is often based on e-learning. Record keeping of “successful instruction” can be automated, making it a popular option with human resource and compliance departments.

E-learning generally has less impact than classroom training where individual feedback is possible and where learners generally have a higher attention rate. It is an unlikely candidate for once-off trainings, as the initial development investment can rarely be recovered. It is not suitable when a fast response to a new training need is called for.

4.2. Virtual Reality based training

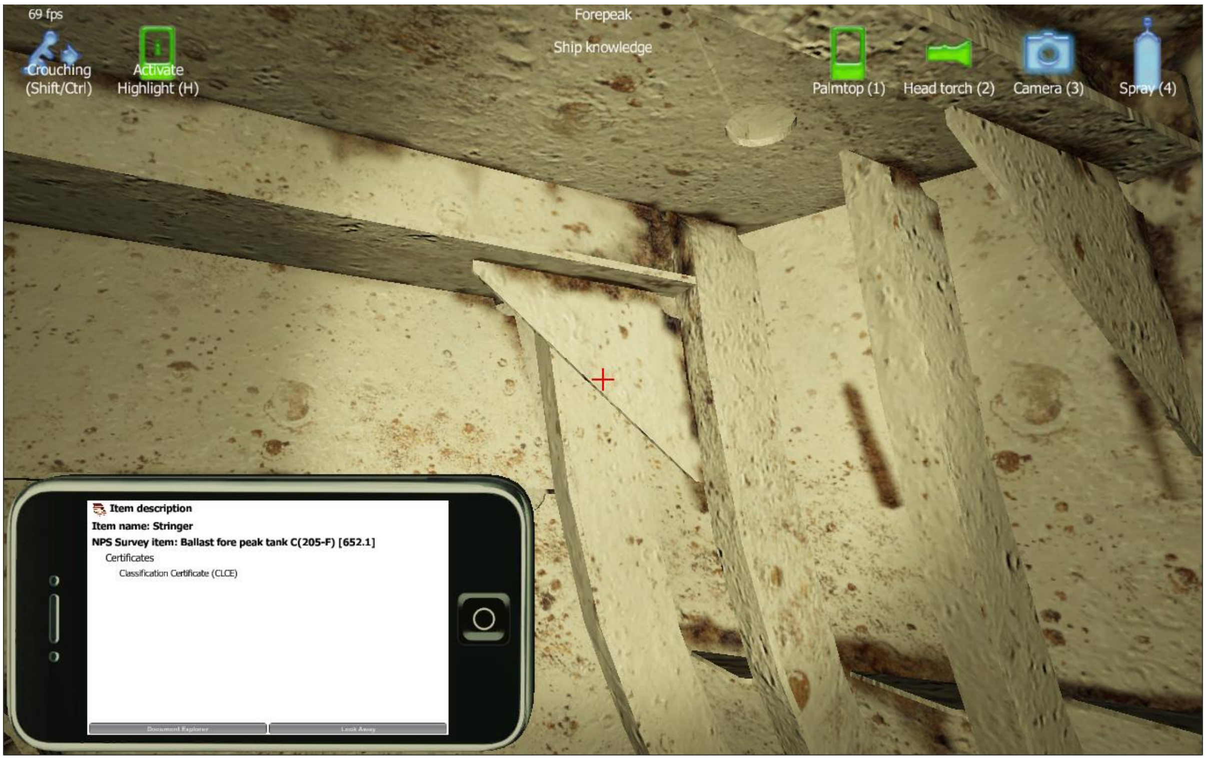
Gamification of teaching using video game technology has attracted a lot of attention. Virtual Reality is seen as a key technology for (maritime) training, and this has been reflected in various COMPIT papers, *Doig and Kaeding (2007), Katzky (2014), Venter and Juricic (2014), MacKinnon et al. (2016).* Virtual Reality is not only fascinating and fun; it is indeed also a powerful tool for training, especially when it comes to visual assessment and human interaction, e.g. judging when to initiate action in maneuvering, crane operation, etc.

However, the price of developing Virtual Reality-based training is high. Creating virtual worlds has become easier, faster and cheaper, but it is still far from being easy, fast and cheap. Models need to have the right level of detail, balancing realism and response time. Import/export from CAD systems or other models (e.g. finite-element models) may save time, but in our experience is never as straightforward as hoped for or promised by vendors. Having a ship modelled over several decks, along with equipment, interactivity, etc. may run into 5 or 6 digits of Euros. Such an investment needs either subsidizing from R&D projects or a suitable mass market willing to pay premium fees for training, such as firefighting. Often solutions have been developed for larger industries and are then adapted to maritime applications, reducing the development effort.

DNV GL has developed a Virtual Reality-based training solution for ship inspections, called SuSi (Survey Simulator), https://www.dnvgl.com/services/survey-simulator-for-ship-surveyor-training-in-virtual-reality-shipmanager-survey-simulator-2173. SuSi provides realistic and cost-efficient 3D training software for survey inspections, using Virtual Reality technology and detailed models of ships and offshore structures, Fig.3. The virtual inspection gets trainees exposed to deficiencies that would take years for a surveyor to experience in real life. An inspection run can be recorded and discussed in a debriefing with an experienced supervisor/trainer, pointing out oversights and errors by the trainee.

Fig.3: Level of detail in SuSi (Virtual Reality based survey simulator)

SuSi offers a variety of interactive elements, such as a virtual camera, virtual smartphone with product data information and access to DNV GL Rules, virtual spray to mark deficiencies, Fig.4, and obviously navigation control to explore the virtual ship or offshore platform.



Item description
Item name: Stringer
NPS Survey item: Ballast fore peak tank C(205-F) [652.1]
Certificates
Classification Certificate (CLCE)

Fig.4: Virtual Reality based training with DNV GL's SuSi (Surveyor Simulator)

Initially, the designers of the software envisioned trainees running the software from individual PCs or laptops and exploring in parallel "their" ship in a rather self-centered learning approach. The user interface was deemed to be so intuitive that - after minimal instruction - each trainee would embark on his survey. But practice revealed that to be too optimistic. The user interface was intuitive for digital natives, but "digital immigrants" struggled with the video gaming controls and navigational concepts and got lost in the virtual world, often leading to frustration and missing the training goals. The solution has been to adopt a pragmatic approach where the trainer guides the class collectively through the ship (with a single PC and a data projector) and trainees shout out when they spot a deficiency which can then be discussed. Such a blended approach of classroom instruction and Virtual Reality tour may be frustrating for the video game programmer, but achieves the training goal for all trainees. It also requires fewer licenses and hardware. This approach has been very well received by participants from industry across a wide range of nationalities (cultures), educational backgrounds, management levels and age groups.

The lesson learnt in this case is that less is sometimes more. Never fall in love with technology, but look first at the pedagogy. Also consider heterogeneity in trainees and possibly hardware and think about possible hurdles.

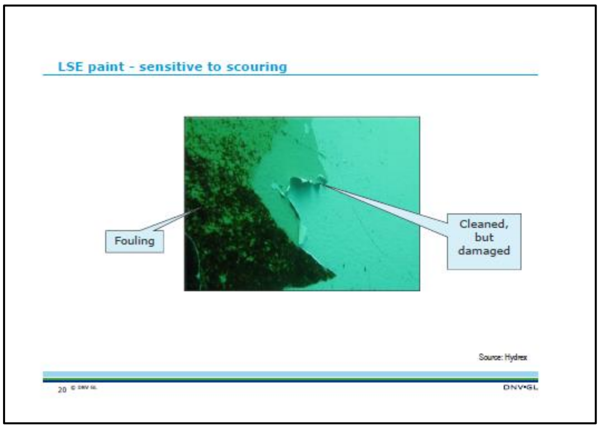
4.3. Webinars

In our line of training, we often have to respond rapidly to new developments, e.g. new regulations coming into force. Domain experts in the specific field of competence are scarce (say 1-2 key experts in the company) and their time is in high demand. Customers need training quickly as e.g. non-compliance may lead to costly detentions. Traditional classroom training and e-learning are not suited to such requirements. We have found that webinars are an attractive addition to our toolbox of training solutions in this respect. DNV GL's line of external webinars is called "smart-ups", https://www.dnvgl.com/maritime/maritime-academy/smart-ups.html.

In 2016, we delivered 10 smart-ups, reaching out to customers around the globe. We also used webinars internally to support the training needs that came with new Rules of DNV GL (merging the rules of the two Class societies) and training colleagues on new developments, such as our cyber-security training or advances in performance monitoring with the ECO Insight solution.

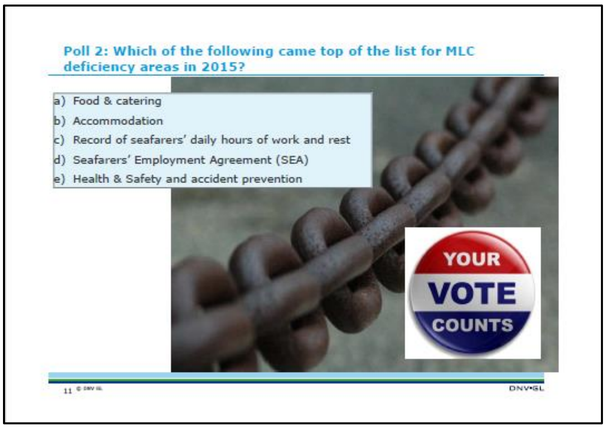
Key lessons learnt were:

- Domain experts are generally neither communication experts nor webinar technology experts. Raw material (PowerPoint) needs more or less extensive reworking for a webinar and delivery is similar to being on the radio: domain experts need technical support and possibly some coaching on how to speak during a webinar.
- Domain experts are much more willing to take the time for a webinar than for the development and wide-scale delivery of classroom training. Once made aware that the option exists, we encountered general enthusiasm for this training solution.
- Webinars should be designed for maximum 20-30 minutes presentation time. Beyond that audience attention cannot be maintained and the message is lost.
- Powerpoint slides used for webinars should have even less text than the classroom version and rely much more on visual language to convey the message, Fig.5.
- After a maximum of 10 minutes speaking time, an interactive element ("poll" in the jargon of webinar designers, Fig.6) should stimulate the audience to refocus on the topic. Otherwise the temptation to multi-task (i.e. read incoming emails, etc.) becomes overwhelming for most people.
- While recordings of webinars were offered after the event, the live versions were clearly more attractive. Consequently webinars for a global audience need to be offered several times "live" to cover different time zones. Extra resources then need to be allocated for the repeats.



LSE paint - sensitive to scouring

Fig.5: Typical webinar slide



Poll 2: Which of the following came top of the list for MLC deficiency areas in 2015?

a) Food & catering
b) Accommodation
c) Record of seafarers' daily hours of work and rest
d) Seafarers' Employment Agreement (SEA)
e) Health & Safety and accident prevention

Fig.6: "Polls" stimulate audience to think

5. Conclusions

Content is more important than transmission. Flashy e-learning portals do not substitute qualified teachers. E-learning is particularly interesting for commodity subjects (English, business administration, mathematics, etc.). Webinars are often overlooked as a training solution, but offer more flexible and cost-efficient options for global maritime training needs.

The private training market is expected to gain in importance with life-long learning in incremental steps on latest industry developments. DNV GL's Academy will continue to play an important role in this regard.

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Appendix: Requirements for Naval Architects

The following is based on an ONR workshop on Future Warship Designers, *Rusling (2005)*. In discussion between (mostly US American) representatives of industry and academia, the following items were listed as guidelines for future curricula for naval architecture:

- Good base in naval architecture / engineering principles
    - strength analyses, structural design and production
    - hydrostatics / stability and ship design (rules, layout, estimation methods)
    - hydrodynamics
    - marine engineering
- Computer literate
    - CAD proficiency seen as main gap
    - Level of competence (hours spent with specific software) should be recorded
    - Naval architecture is increasingly applied computer science and less mechanical engineering
- Hands-on experience
    - as worker and as engineer
    - at sea / at shipyard
- more specialized knowledge 7 more mathematics at post-grad level
- soft skills
    - ability to study independently
    - creative with feel for viability of solutions
    - enthusiastic
    - team capability
- management skills
    - project management
    - communication
    - basic legal frameworks for contract / work laws
    - motivation
- engineering English
    - vocabulary (incl. mathematical expressions)
    - technical / scientific communication in English

Future of Shipbuilding and Shipping - A Technology Vision

Volker Bertram (DNV GL), Hamburg/Germany, volker.bertram@dnvgl.com

Abstract

The paper discusses key trends in ship design, ship building and ship operation and attempts to extrapolate those trends into the future. While navy vessels, high-speed and unconventional designs will play a minor role in this overall shipping scenario, they will remain to be key technology drivers. With growing emphasis on fuel efficiency and low-emission solutions, we should see more wind assisted technologies, propulsion improving devices, and friction-reducing technology. This trend will be enabled and supported by simulation-based design. Cleaner fuels, notably LNG, and condition-based maintenance will lead to low-maintenance and low-crew ships. Meanwhile, a proliferation of sensors and increased satellite bandwidth will fundamentally change logistics. Virtual reality and Augmented Reality will become key technologies for design, production and operation. The future is smart and connected, not only for the technologies but also for the people driving the technology.

1. Introduction

In the 1970s book "Ships and Shipping of Tomorrow" by *Schönknecht et al. (1973)*, wonderful artistic visions predicted a future of nuclear powered submarines transporting crude oil, giant hydrofoils bringing people around the world and streamlined catamarans carrying containers at speeds of up to 35 knots across the Atlantic. There have been assorted other bold and fascinating visions for future ships in the course of time, Fig.1. And while some predictions have proven to be correct, at least in some aspects, many more have been completely wrong.

Fig.1: Ships of the future over time: conveyor belt loading and unloading ro-ro ship, 1950s (top left), transatlantic giant hydrofoils, 1960s (top right), Luigi Colani design for fast container ships, 1970s (bottom left), 2010 NYK's Super ECO-ship 2030 (bottom right).

When I was asked to speculate on ships and shipping of the future in 2016 for the Maritime Future Summit, my first port of call (to borrow a maritime phrase) was to browse through my bookshelf and to search on the Internet. When you google for “ships of the future” you could be misled into believing that the world’s future fleet will be evenly divided between cruise vessels and warships.

The truth is likely to be more down to earth, but might fascinate just as much. In the following pages, I will draw on my own research and that of DNV GL work, industry best practice (as documented in assorted COMPIT papers) and the views of key experts to hopefully sketch a more realistic scenario of maritime future. DNV GL’s report “The future of shipping”, *Longva et al. (2014)*, has been a key resource in this endeavor.

2. Hardware - Ships of Tomorrow

Broadly speaking, ships of the future will evolve naturally in line with economic trends and advancing technologies becoming widely available.

2.1. Ship types and hull shape

“Air transporters” (navy ships, megayachts, ferries, cruise vessels) often influence public opinion about the appearance of future ships. Exotic hull forms and hydrodynamic concepts, Fig.2 and Fig.3, will remain the exemption and not the rule. However, such high-performance and unconventional craft have an above-proportion impact on technology; in short, think of aerospace technology meeting creative design. The world’s fleet is and will continue to be much more mundane and pragmatic. Shipping of the future will still mean mainly dry bulk, liquid bulk and general cargo. The long-term economic and ecological pressure for energy efficiency will inevitably lead to lower ship speeds. At the same time, smarter design processes will look at power requirements in realistic operational scenarios, i.e. variations of operational conditions (speed, load) and ambient conditions (sea state) to minimize yearly fuel consumption, as envisioned by *Hochkirch and Bertram (2012)*. As a result, bulbous bows are likely to decline on many ships and some may even feature straight stems as seen in DNV GL’s concept studies, Green Dolphin (bulk carrier), Fig.4, and ReVolt (container feeder), Fig.5.


Fig.2: Futuristic SWATH design, Source: Sean McCartan


Fig.3: Futuristic hydrofoil ferry Design, Source: EMIT

Fig.4: “Green Dolphin” bulk carrier design

Fig.5: ReVolt container feeder concept

2.2. Materials

Most likely, ship hulls will continue to be made of steel, simply because steel is cheap, strong and easy to recycle. Better coatings and inspection programs will compensate for steel's main shortcoming, namely, corrosion. More ductile steel alloys will lead to more collision-resistant structures. Intelligent condition monitoring schemes will provide the appropriate technologies to extend the average life-span of steel structures while reducing (if not avoiding completely) the risk of structural failure:

- Big Data: embedded monitoring systems and conventional surveying schemes will generate huge volumes of data across fleets of ships in service and offshore platforms. Cross-referencing this data will support future intelligent condition monitoring systems.
- Image Processing: image processing techniques are likely to be used to automatically detect and quantify paint defects, extent of corrosion and cracks, for example, *Mavi et al. (2012)*. The progression of such defects will likely be mapped and quantified through the use of images from different time periods. The availability of cheap miniature cameras (as embedded in mobile phones) is also likely to lead to wide-spread installation and automatic surveying schemes.
- Corrosion Prediction Schemes: using Artificial Intelligence techniques, classical corrosion prediction schemes will be improved, providing a more accurate prediction of location, extent and type of corrosion. *De Masi et al. (2016)* provide an example of pipelines.
- Simulation technology: using 3D ship product models and fast finite-element modelling techniques, the as-is condition of a ship will be capable of being simulated at any time, as envisioned in *Wilken et al. (2011).*

In summary, the life-span of ships will be extended with 30 to 35 years likely to become the new norm. Composites will be increasingly used for high-speed craft (HSC), super-structures for stability-sensitive ships (like passenger ships or naval vessels) and selected equipment and outfitting. However, due to strength and production considerations, the use of composites in the main hull will continue to be limited to vessels up to approximately 100 m length only.

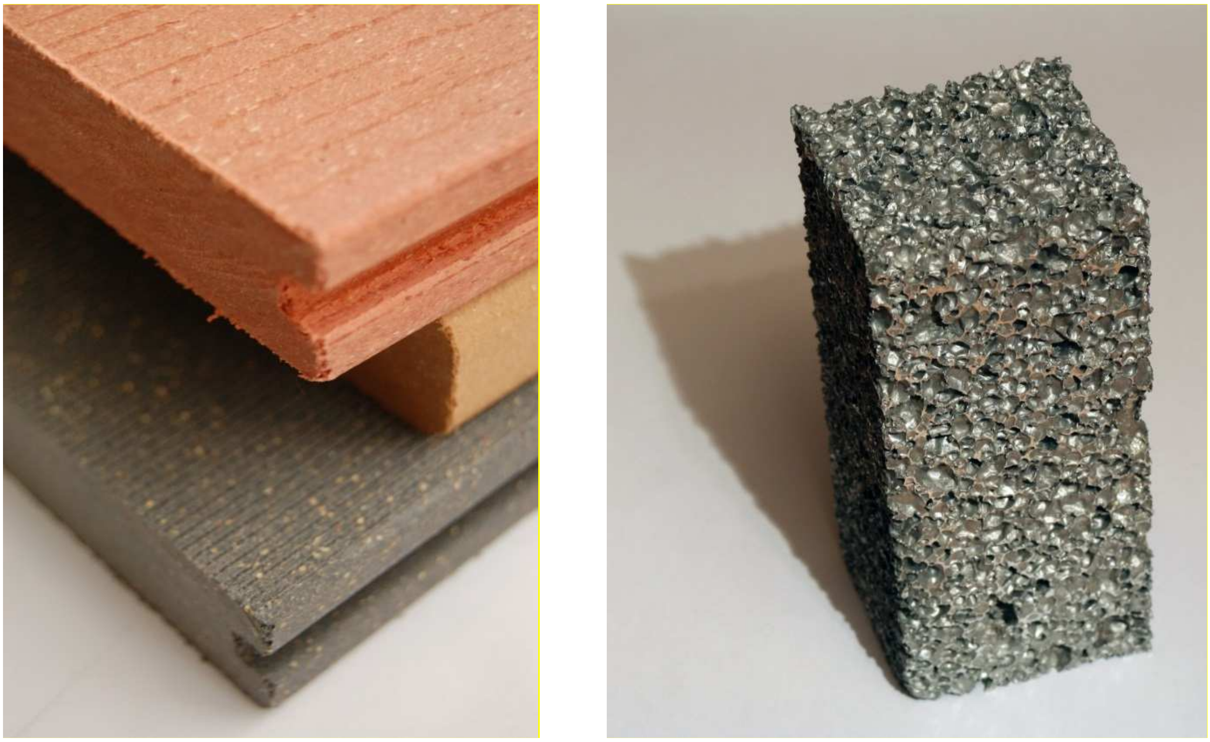


Fig.6: Composites based on renewables (left) and metal foam (right), Source: wikipedia

Metal foams (both aluminum and steel), Fig.6, offer interesting possibilities for ships, improving weight-to-strength ratios, noise and vibration characteristics as well as thermal insulation. In the future, steel may well be combined with metal foams to give higher bending stiffness and lower weight than solid steel constructions. A sandwich panel with steel faces of 1 mm with a 14 mm metal foam core has similar bending stiffness as a 10 mm solid steel plate, but with only 35% of the weight, *Longva et al. (2014).*

Recycling of composites is an issue that also applies to automotive and aerospace applications, *Gramann et al. (2008*). Most likely, the marine industry will follow general trends and increasingly deploy composites based on natural organic materials, Fig.6, as alternatives to classical glass or carbon fiber composites. Similar to the inventory of hazardous materials (IHM), the assorted materials in a ship will be tracked from design to scrapping (cradle-to-grave) in product data management systems, *Gramann et al. (2007).*

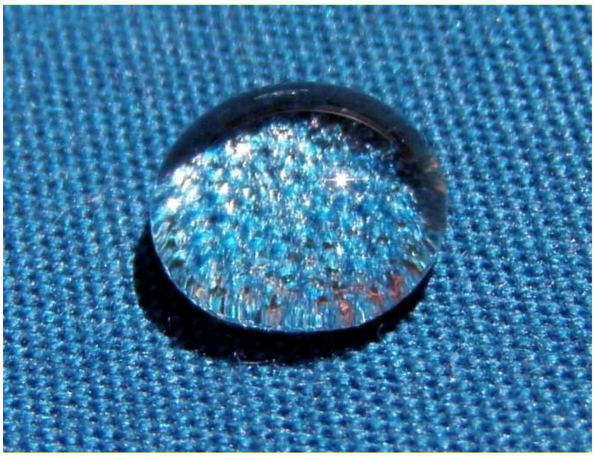


Fig.7: Nano-coating

Fig.8: Underwater hull cleaning robot

Antifouling strategies (for energy efficiency reasons but also to prevent the spread of invasive species) have been based almost exclusively on antifouling (biocide) coatings. The strategy is likely to shift towards more sustainable technologies, *Yebra (2016),* including:

- Mechanically repellent surfaces – for example, nano-coatings with microscopic surface structures, Fig.7, making adhesion difficult, similar to anti-graffiti coatings on houses, *Gose et al. (2016).* While the global properties of nano-coatings have been proven in many commercial applications to ships by now, the fundamental hydrodynamics are still subject to research, using model basins and CFD simulations, *Niebles Atencio and Chernoray (2017).*
- Frequent robot-based grooming – proactive grooming (= mild cleaning) of ship hulls addresses both energy efficiency and the spread of invasive species. Autonomous underwater cleaning robots, http://auvac.org/community-information/community-news/view/672, *Ishii et al. (2014),* resemble lawn-mowing robots, Fig.8. While, these robots have yet to become affordable and widely available, they also need to be equipped with cognitive, cooperative capabilities. Progress in this area may benefit from related work for robotic underwater surveys or robotic marine rescue operations, *Odetti et al. (2016).*
- Ultra-sonic protection schemes – this is a complementary technology for regions that have limited or difficult access (difficult coating and cleaning).

2.3. Fuels and machinery

The broader trend towards cleaner fuels combined with lower design speeds will affect maritime propulsion profoundly. LNG is expected to replace heavy fuel oil (HFO) as a standard fuel, *Chryssakis et al. (2015).* This will affect the whole machinery system. Diesel engines will no longer need separators and filters as the fuel itself is so clean. As for cars, we will see hybrid propulsion, combining combustion engines with electric drives, Fig.9.

With LNG as a fuel, today's four-stroke diesel engine generator sets as the standard option for auxiliary power may be replaced by fuel cells and batteries. Again, we will see a combination of technologies being deployed to maximize individual strengths. Highly efficient fuel cells will supply a constant base load; batteries will supply power for short-term peaks and fast reaction. Overall, cleaner fuel and the more robust set-up of the engine room together with smarter condition-based maintenance schemes will reduce the workload of the engine department.

Fig.9: Zero-emission ferry design with fuel cells and batteries, supplemented by Flettner rotors harnessing wind energy, *Rohde et al. (2013)*

Nuclear power remains the wild card where any prediction remains highly speculative. The pressure to reduce carbon footprint, especially in shipping, is the main argument in favor. Liability issues (possibly also for the flag state), a shortage of marine engineers who are qualified in nuclear reactor operation and the general political climate (at present) towards nuclear energy are the main arguments against.

As previously stated, the quest for transport efficiency (reducing fuel bill and emissions alike) will favor lower ship speeds. Ships are likely to become wider and shorter with propellers having fewer blades. Propulsion improving devices (PIDs, also known as energy saving devices, ESDs) may become standard. There are various technical solutions, some dating back to the 1970s, *Carlton (2012), Bertram (2012),* which may see a widespread renaissance:

- Asymmetric sterns may see wider adoption after patent claims expire.
- Pre-swirl fins (often combined with nozzles such as in the popular Mewis duct for full hulls, or twisted fins for slender hulls, Fig.10) can be attached to gain two to three percent.
- Contra-rotating propellers or vane wheels are likely to play a larger role as better design procedures and lubricants solve traditional issues with these devices.
- Costa bulbs or similar devices (for example, "the Ultimate Rudder" of Nakashima Propellers, *Kajihama et al. (2016)*) may become standard, possibly combined with twisting the rudder.

Air lubrication has enjoyed much attention over the past decade, *Thill (2016),* progressing from fundamental studies to in-service installations, *Silberschmidt et al. (2016). As t*he general trends towards lower speeds and wider ships play in favor of air lubrication technology, we can expect more such installations in the years to come. *Silberschmidt et al. (2016)* report also that air lubrication keeps the hull (bottom) free of fouling.

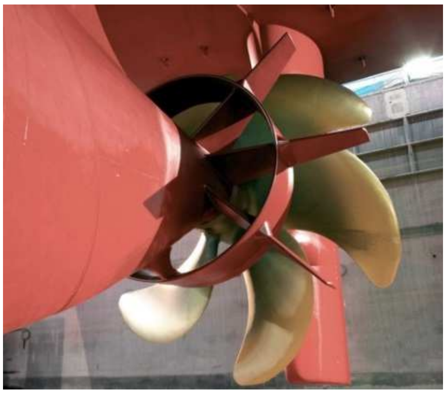


Fig.10: Twisted fin as typical PDI
Source: Becker Marine

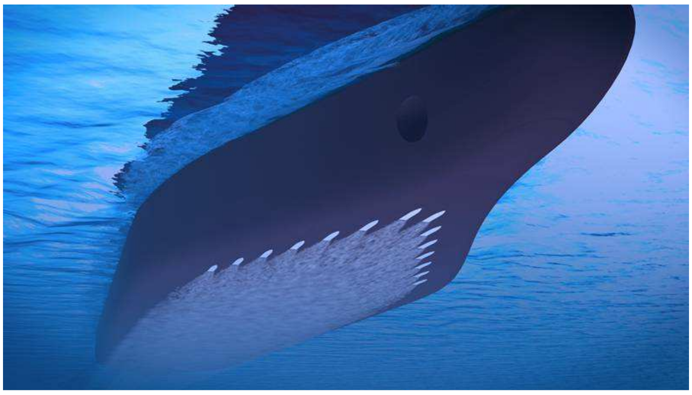


Fig.11: Air lubrication system, source: Silverstream

Low speed also helps the case of wind-assisted propulsion. At present, there are very few (< 10) full-scale installations on cargo ships. However, increasing fuel prices and consolidation in the supply industry may support a proliferation of professional systems for harnessing wind energy for ships. In this context, only robust and highly automated systems make sense, for example, those based on Flettner rotors, Fig.9, *Eggers (2016)*, or employing kites, *Behrel et al. (2016)*. In parallel, we see increasingly sophisticated CFD simulations supporting wind technology for ships, e.g. *Kramer et al. (2016)*.

Falling costs for sensors, computing power and satellite communications make it a safe prediction that ships of the future will be “smart”, i.e. they will be equipped with various embedded data processing. Sensors will become smaller, more robust and cheaper to acquire. As a result, they will be more widely distributed with redundancy built-in coupled with options for intelligent sensor fusion. The vision is having sensors literally “everywhere”, in the hull, main engine, auxiliary machinery and even small equipment items, *Etienne and Romano (2016)*. And they will be smart. “Today’s mobile phones have the processing power of desktop computers 10 years ago. In 2020, mobile phones will have the power of today’s PCs. Cheap and small distributed sensors will have the abilities of today’s mobile phones, and so on,” *Longva et al. (2014)*.

3. Software – Design, Construction and Operation of Tomorrow

3.1. Design

Progress in CAD (computer aided design) systems towards 3D product data models (PDMs) allows us to not only perform a large variety of analyses and simulations, but also deliver photo-realistic virtual reality displays. The traditionally experience-based ship design has already moved considerably towards simulation-based (a.k.a. first-principle) design, Fig.12. The exchange of information between different software and more intelligent pre-processors have dramatically cut down the time and cost associated with running simulations. Cloud-computing with on-demand business schemes gives advanced simulation access to small and medium enterprises, for example, *Hildebrandt and Reyer (2015)*. Simulations are also getting more sophisticated with increased detail represented in captured geometry and more advanced physical models, for example, *Köhlmoos and Bertram (2012), Peric and Bertram (2012)*.

We see the scope of simulations expanding beyond the classical stability, strength and hydrodynamics simulations, for example, aerodynamics, fire, Fig,13, ice-breaking, evacuation, manufacturing, energy generation and consumption in the ship systems, etc. Systematic simulations may be used to derive tailored “numerical series” or knowledge bases. These simulation-based knowledge bases provide highly accurate estimates that are virtually instantaneous, *Harries (2010), Couser et al. (2011)*.

Fig.12: Complex simulations for ship design
Source: Siemens PLM

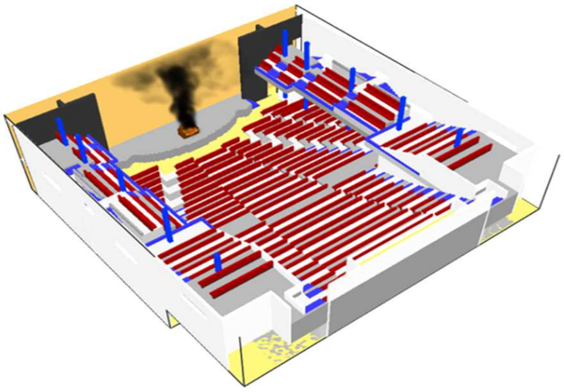
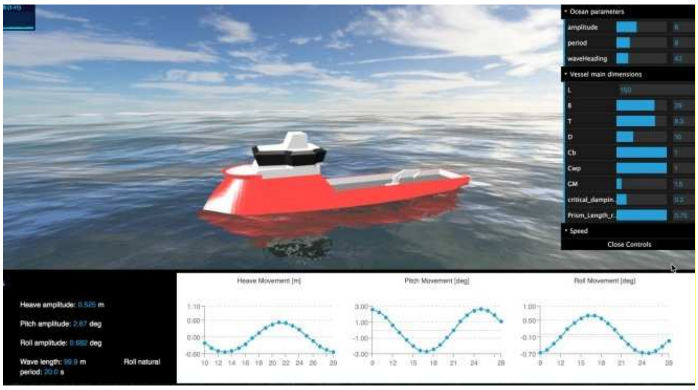


Fig.13: Fire simulation in cruise ship theatre

When human interaction is important, Virtual Reality is a key technology. Virtual Reality uses 3D models of the world with fly-through or walk-through capabilities, and typically some user interaction. VR applications in the maritime industry are proliferating rapidly, e.g. for training, interior design, Fig.14, familiarization in ships, operational aspects (reachability, visibility) and surveying, Fig.15, *Cabos and Wolf (2017)*. Considerable progress has been made by adding real-time physics, thanks to "physics engines", fast emulators of typical kinematics and dynamics of objects. Progress in simulations has been accompanied by similar advances in visualization techniques. In many cases, we can analyze the time-dependent performance of a system in photo-realistic 3D simulations while the visualization allows intuitive assessment, Fig.16, *Chaves and Gaspar (2016)*.

Fig.14: Virtual Reality for interior design of a megayacht, *Lukas et al. (2015)*

Fig.15: Virtual Reality based surveying, *Cabos and Wolf (2017)*



Heave amplitude: 0.525 m
Pitch amplitude: 2.67 deg
Roll amplitude: 0.682 deg
Wave length: 99.9 m
period: 20.0 s

Fig.16: Employing game technology allows rapid and intuitive assessment of design performance, *Chaves and Gaspar (2016)*

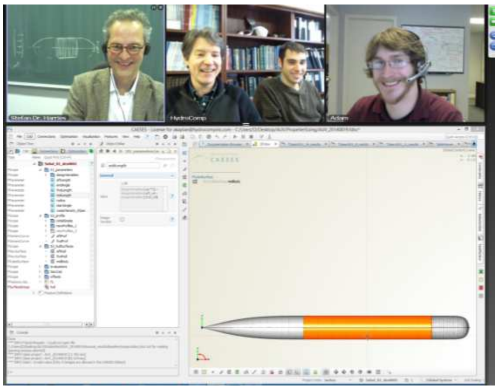


Fig.17: Distributed web-based development, combining best-of-breed software, *Harries et al. (2015)*

Despite numerous attempts, no single monolithic software program has emerged that is optimal for all ship design tasks. Instead, coupling dedicated software packages is a better strategy than trying to develop the “one code to solve all problems”, *Morais et al. (2016b)*. In short: cooperation beats integration. A “plug-and-play” culture is developing where software codes and companies learn to work smoothly together to provide better or new solutions. Best-of-breed solutions are being developed across geographical and company boundaries, using flexible alliances and web-based technology, for example, *Harries et al. (2015)*, Fig.17.

3.2. Construction

“Technologies such as 3D Laser Scanning, Augmented Reality, Enhanced Visual Communication, Automation on the Shop Floor, Internet of Things, Materials Enhancements, Cloud Computing, 3D Printing, and Generative Design are all rapidly improving and more importantly, are set to converge in a synergistic way, enabling an explosion of technology that will affect all industries including shipbuilding,” *Morais et al. (2016a)*. The 3D product data models created in design will be updated as the ship is built and maintained over the ship’s lifecycle. “As-built” PDMs will be passed to owners for asset management, *Thomson and Gordon (2016)*. Along with simulation models to mimic the ship’s behavior (in strength, hydrodynamics, energy characteristics, etc.), “digital twins” in the computer will support operation in normal business and emergency situations, Fig.18, *Ludvigsen et al. (2016)*. Affordable 3D scanning will be widely used, both from the outside (for example, for more accurate performance monitoring models) and the inside (for as-built/as-modified models), Fig.19, *Morais et al. (2011)*, and software is evolving to convert such point clouds into CAD models for efficient further processing, Fig.20, *Bole (2014)*.

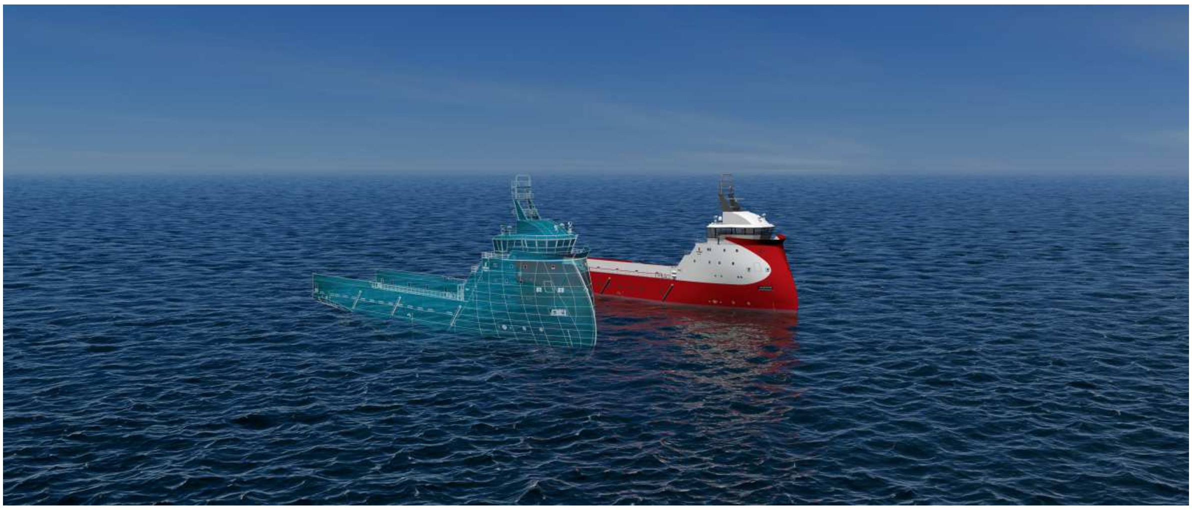


Fig.18: Digital Twins mimicking the behavior characteristics are updated through the life-cycle of the real asset reflecting changes in energy efficiency, strength, etc.

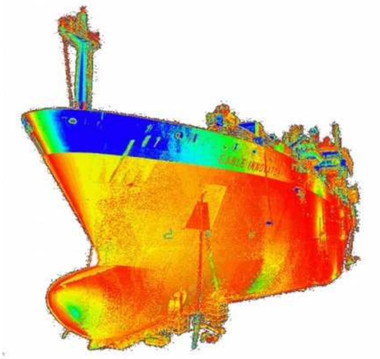


Fig.19: Laser scan of as-built ship, Source: SSI

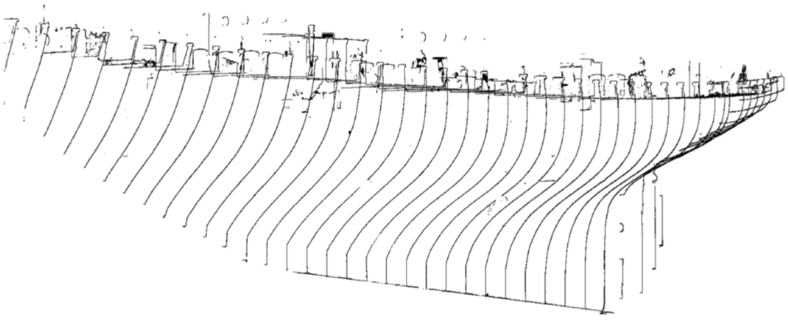


Fig.20: Fitting CAD curves to point cloud, *Bole (2014)*

In Augmented Reality, computers (for example, tablets) overlay a live image with computer generated information. For example, a building block may be shown with a part to be installed, illustrating how both fit together, Fig.21, *Kohei (2016)*. This makes assembly tasks very intuitive, reducing work time and the likelihood of errors. A number of advanced shipbuilding nations are active in Augmented Reality applications for shipbuilding, e.g. *Friedewald et al. (2015), Helle et al. (2014)*. This technology becomes truly powerful when used in combination with vision technologies (for example, marker recognition), PDMs, positioning methods, hands-free operation technology (smart glasses), etc., Fig.22, *Patterson and Webb (2016).*

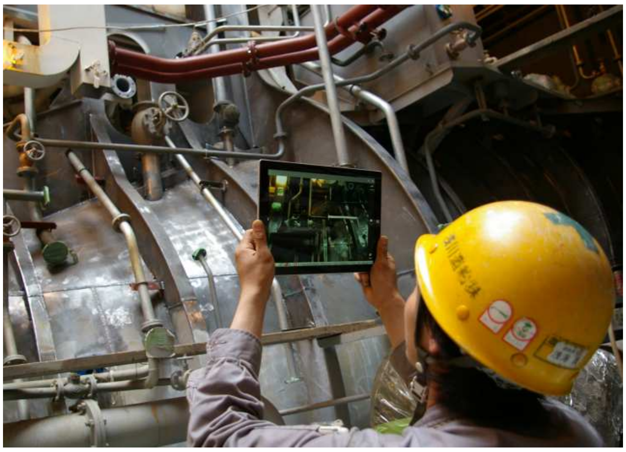


Fig.21: Augmented Reality in ship construction, source: Matsuo Kohei (NMRI)

Fig.22: Smart glasses will allow hands-free operation in assembly and operation, *Patterson and Webb (2016)*

Industry 4.0 will also encompass shipyards and the maritime supply industry. The Internet of Things will change (and accelerate) logistics, especially for time-critical and highly interconnected supply networks, *Borgia (2014), Etienne and Sayers (2016), Morais et al. (2016a)*. Drones may be used to deliver required parts to remote areas, such as ships, as demonstrated in 2016 by Maersk. However, often, delivery will no longer be needed. Instead, 3D printing (a.k.a. additive manufacturing) may generate required parts, mainly in the supply industry and on ships, *Koelman (2013), Bergsma et al. (2016)*. Model basins explore the possibility of using 3D printing for models in towing tanks. Maersk and the US Navy are reported to test 3D printing of spare parts on board their vessels.

3.3. Operation

General developments in ICT (information and communications technologies) will have a profound effect on the shipping industry. Of course, ICT allows us to perform traditional tasks better (faster, cheaper, or more accurately); but perhaps even more importantly, ICT opens the door for us to consider completely new options. Computers and telecommunications as such are not new to shipping. The frequently quoted “revolution” that ICT shall bring to shipping, e.g. *Etienne and Romano (2016),* may also be seen as an accelerated evolution. We will witness “more” of the same trends as in the past decades: an increase in the exchange of data and more collaboration between stakeholders.

Assorted developments, not just in autonomous technology, will make ships easier to operate, *Bertram (2016)*. Condition-based maintenance systems may diagnose eventual problems at an early stage and support the fixing of the problem, e.g. by ordering spare parts, preparing 3D printing or guiding repair by ordinary persons without expert knowledge on the system, using Augmented Reality for intuitive guidance. Along with reduced workload in the engine room due to cleaner fuels, this will allow further reductions in minimum crew sizes.

Many developments mirror trends in the automotive industry: we have smart cars (automatic brake systems if pedestrians are crossing; valet parking; self-monitoring tire pressure; ability to drive autonomously on highways, etc.) and we have driverless cars (most notably the Google driverless car, https://en.wikipedia.org/wiki/Waymo). For ships, we will have low-crew smart ships (with automatic collision avoidance, Fig.23; automatic berthing; self-monitoring for hull, engine and cargo; ability to sail autonomously for limited time in certain conditions, etc.) and unmanned drones for specific applications (for example, short-distance ferries, offshore supply vessels, Fig.24, tugs, Fig.25 and fireboats).

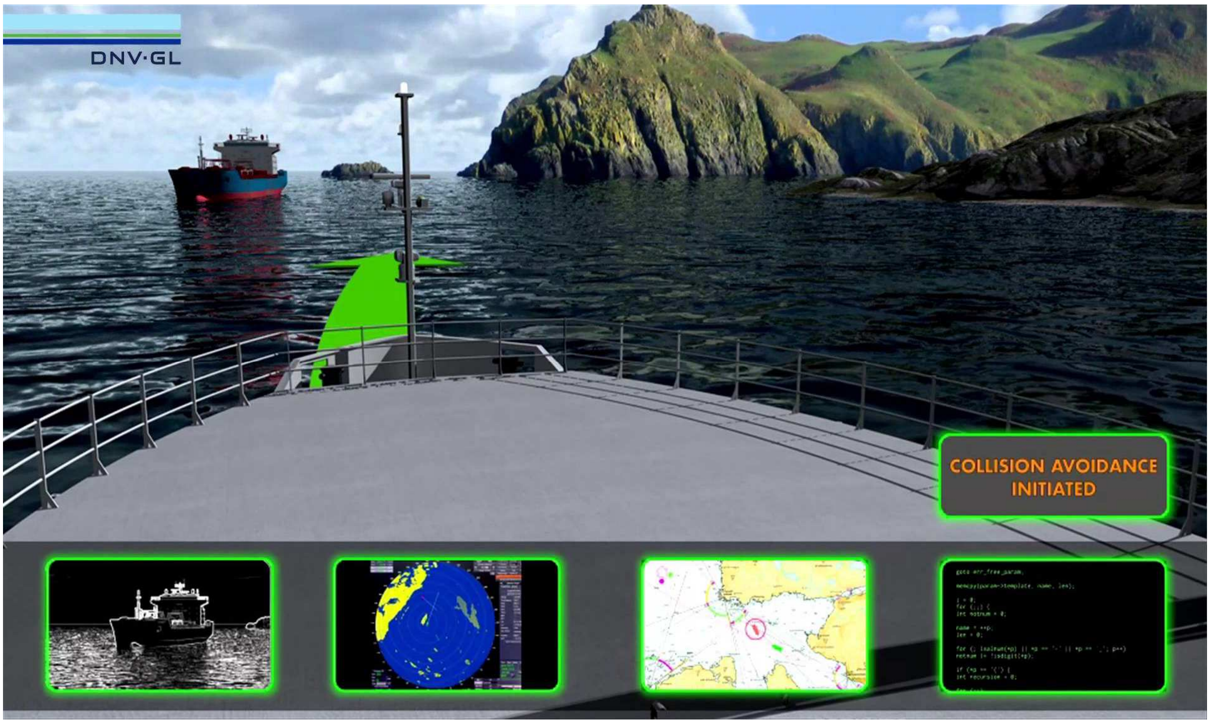


Fig.23: Automatic collision avoidance based on sensor fusion and Artificial Intelligence as envisioned in DNV GL's ReVolt concept study for unmanned shipping

Fig.24:" Hrönn" unmanned offshore supplier, source: Kongsberg

Fig.25: "RAmora" unmanned tug, source: Robert Allan Ltd.

Whether ships are operated locally or by remote control, operational decisions will be data driven, e.g. using AIS (Automatic Identification System, which is a satellite-based data exchange, allowing tracking of virtually all cargo ships) for ship routing, factoring in weather, traffic situation and port capacities. Combining (big) data, simulations and Artificial Intelligence techniques will deliver business and logistics transparency with both economic and ecological benefits. The Internet of Things will play a key role in this development.

However, with ICT becoming an indispensable part of shipping, there are also new issues and concerns. Cybersecurity will become a key concern, both for autonomous and manned shipping, *Patterson and Barton (2017)*. Cybersecurity awareness is already evident in the maritime industry with at least partial solutions on the horizon, e.g. *Rødseth and Lee (2015)* and DNV GL's cybersecurity recommended practice, https://www.dnvgl.com/maritime/dnvgl-rp-0496-recommended-practice-cyber-security-download.html. The technology on ships will largely follow the cybersecurity technology employed for other large assets, such as power plants, traffic control centers, etc.

4. Conclusions

Stand-alone techniques have already reached a high degree of maturity and further progress is best obtained by partnerships and an appropriate combination of technologies and techniques, as illustrated in the individual chapters. We see this trend continuing swiftly: simulation tools with Virtual Reality displays and Artificial Intelligence for user guidance, Big Data using Artificial Intelligence to derive trends for profiles used in formal optimization, etc. In short, it is all about getting smart and connected – as is the COMPIT conference.

Acknowledgments

This paper is the result of countless contributions to the COMPIT conferences and the last HIPER conference, where over the years I have seen the arrival and application of new technologies. The papers, but perhaps even more the discussions, have shaped my view of our industry and the assorted IT developments. For this insight, I am very grateful. If I have overlooked key publications in my already long list of publications, I beg your indulgence.

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Innovative Fast Time Simulation Tools for Briefing/Debriefing in Advanced Ship Handling Simulator Training for Cruise Ship Operation

Knud Benedict, Michael Gluch, Sandro Fischer, Matthias Kirchhoff, Michèle Schaub,
Hochschule Wismar, Warnemünde/Germany knud.benedict@hs-wismar.de
Michael Baldauf, World Maritime University, Malmo/Sweden, mbf@wmu.se
Burkhard Müller, AIDA Cruises, Rostock/Germany. burkhard.mueller@aida.de

Abstract

The innovative system for "Simulation-Augmented Manoeuvring Design, Monitoring & Control" (SAMMON), based on technology of Fast Time Simulation (FTS), has been developed in the Institute for Innovative Ship Simulation and Maritime Systems (ISSIMS) and is fully implemented in the Maritime Simulation Centre Warnemuende MSCW. The system is based on complex ship dynamic models for simulating rudder, thruster or engine manoeuvres under different environmental conditions. The advantage is that the trainee can immediately see the results of the actual rudder, engine or thruster commands and he does not have to wait for the real time response of the vessel. For practical application and testing, the new technology has been interfaced to the Simulators at World Maritime University Malmoe and at the simulation centre of the cruise liner company AIDA Cruise in Rostock. The CSMART Centre of Carnival Corporation at Almere /NL uses this technology as stand-alone version to support more effective lecturing, briefing and debriefing processes in training. Samples from the use of the SAMMON technology will be shown to demonstrate the potential of this technology for advanced manoeuvring education & training and for further application on board ships.

1. Description of the Concept for Using the Fast Time Simulation FTS

1.1. Need for Fast Time Simulation (FTS) and Simulation Support

Manoeuvring of ships is and will be a human centred process despite of expected further technological developments. Most important elements of this process are the human itself and the technical equipment to support its task. However, most of the work is still to be done manually because even today almost no automation support is available neither for routine nor for complex manoeuvres. Up to now there is no electronic tool to demonstrate manoeuvring characteristics efficiently or moreover to design a manoeuvring plan effectively - even in briefing procedures for ship handling training the potential manoeuvres will be "guessed" and drafted on paper or described by sketches and short explanations. Impact of wind or current are taken into account on rather vague estimations based on experiences.

However, due to the new demands there is a need to prepare harbour approaches with complete berth plans specifically in companies with high safety standards like cruise liners. These plans are necessary to agree on a concept within the bridge team and also for the discussion and briefing with the pilot. The plan for the potential manoeuvres must be developed– but still in a contemplative way by thinking ahead – only drafted on paper or described by self-made sketches and short explanations. The plans are made by hand on paper charts or on a printout of electronic chart interface – by now there is no tool available to provide support for manoeuvring planning yet.

Ship Handling Simulation for simulator training has a proven high effect for the qualification. However, it is based on real time simulation, and i.e. 1 s calculation time by the computers represents 1 s manoeuvring time as in real world. This means despite all other advantages of full mission ship handling simulation that collecting/gathering of manoeuvring experiences remains an utmost time consuming process. For instance, a training session for a berthing manoeuvre might take one hour – if the first attempt failed or an alternative strategy should be tried then the next session needs another hour – this is not very effective.

For increasing the effectiveness of training and also the safety and efficiency for manoeuvring real ships the method of Fast Time Simulation will be used in future – Even with standard computers it can be achieved to simulate in 1 second computing time a manoeuvre lasting about to 20 min using innovative simulation methods. These Fast Time Simulation tools were initiated in research activities of the Institute for Innovative Ship Simulation and Maritime System ISSIMS at the Maritime Simulation Centre Warnemuende, which is a part of the Department of Maritime Studies of Hochschule Wismar, University of Applied Sciences - Technology, Business & Design in Germany. They have been further developed by the start-up company Innovative Ship Simulation and Maritime Systems (ISSIMS GmbH, https://www.issims-gmbh.com).

1.2. Overview on the software modules for the Fast Time Simulation (FTS)

A brief overview is given for the modules of the FTS tools and its potential application:

SAMMON is the brand name of the innovative system for “Simulation Augmented Manoeuvring – Design, Monitoring & Conning”, consisting of four software modules for Manoeuvring Design & Planning, Monitoring & Conning with Multiple Dynamic Prediction and for Simulation & Trial:

- Manoeuvring Design & Planning Module: Design of Ships Manoeuvring Concepts as “Manoeuvring Plan” for Harbour Approach and Berthing Manoeuvres (steered by virtual handles on screen by the mariner)
- Manoeuvring Monitoring & Conning Module with Multiple Dynamic Manoeuvring Prediction: Monitoring of Ships Manoeuvres during Simulator Exercises or Manoeuvres on a Real Ship using bridges handles, Display of Manoeuvring Plan and Predicted Manoeuvres in parallel; Calculation of various prediction tracks for full ships dynamic Simulation and Simplified Path prediction as Look Ahead for the future ships motion.
- Manoeuvring Simulation Trial & Training Module: Ship Handling Simulation on Laptop Display to check and train the manoeuvring concept (providing the same functions as Monitoring tool; steered by virtual handles on screen)

These modules are made for application both:

- in maritime education and training to support lecturing for ship handling to demonstrate and explain more easily manoeuvring technology details and to prepare more specifically manoeuvring training in SHS environment, i.e. for developing manoeuvring plans in briefing sessions, to support manoeuvring during the exercise run and to help in debriefing sessions the analysis of replays and discussions of quick demonstration of alternative manoeuvres and
- on-board to assist manoeuvring of real ships e.g. to prepare manoeuvring plans for challenging harbour approaches with complex manoeuvres up to the final berthing / deberthing of ships, to assist the steering by multiple prediction during the manoeuvring process and even to give support for analysing the result and for on board training with the Simulation & Trial module.

SIMOPT is a Simulation Optimiser software module based on FTS for optimising Standard Manoeuvres and modifying ship math model parameters both for simulator ships and FTS Simulation Training Systems and for on board application of the SAMMON System.

SIMDAT is a software module for analysing simulation results both from simulations in SHS or SIMOPT and from real ship trials: the data for manoeuvring characteristics can be automatically retrieved and comfortable graphic tools are available for displaying, comparing and assessing the results.

The SIMOPT and SIMDAT modules were described in *Benedict et al. (2003), Schaub et al. (2015)* for tuning of simulator ship model parameters and also the modules for Multiple Dynamic Prediction & Control, *Benedict et al. (2006)* for the on board use as steering assistance tool. In this paper, the focus will be laid on the potential of the SAMMON software for supporting the lecturing and briefing / debriefing process with elements specifically for simulator training for Advanced Ship Handling in the Maritime Simulation & Training Centre MSTC of the AIDA Cruises Company at Rostock / Germany.

2. Use of FTS for Lecturing and Familiarisation

2.1. Stopping Characteristics: Result diagram and its application for using the speed Vector as Stopping Distance Indicator

One of the elements during the lectures in simulator training courses is the familiarisation with the ship manoeuvring characteristics and its effective application – and Fast Time Simulation is a very smart tool to do this in a short time and with high success. The following sample addresses the ships stopping capability. Specifically for the samples in this paper the cruise ship “AIDAblu” is used; this ship has the following dimensions: length L_{pp} = 244.60 m , beam B = 32.20 m, draft T = 7.00 m. She has two pitch propellers and two rudders, two thrusters each at the bow and at the stern.

To get an overview about the ships stopping distances from several speeds and with various astern power, some test trails could be done either with the Design & Planning tool, Fig.1, or with the SIMOPT and SIMDAT program, Fig.2.

By means of the Planning tool, Fig.1, the ship can be set in the ENC window on an initial position MP0 where the initial speed can be adjusted using the handles in the right window. Then the ships is moved by the slider at the bottom of the ENC window, e.g. to a position after 1 min and there the MP1 is set. Then we use the handles to reverse the engine to EOT = -100% and we see immediately how far ship proceeds maximally and where the stopping position is on the ENC window.

For application of this stopping behaviour during the voyage or in ports, it is helpful to visualise the stopping distances in the ECDIS or RADAR. The SAMMON Monitoring tool allows for high-level prediction of the ships track as result of a change of the EOT or any other handle position already after 1 s, Fig.16. As long as such a sophisticated dynamic prediction tool is not available on the bridge yet, it is helpful to use the speed vector as alternative.

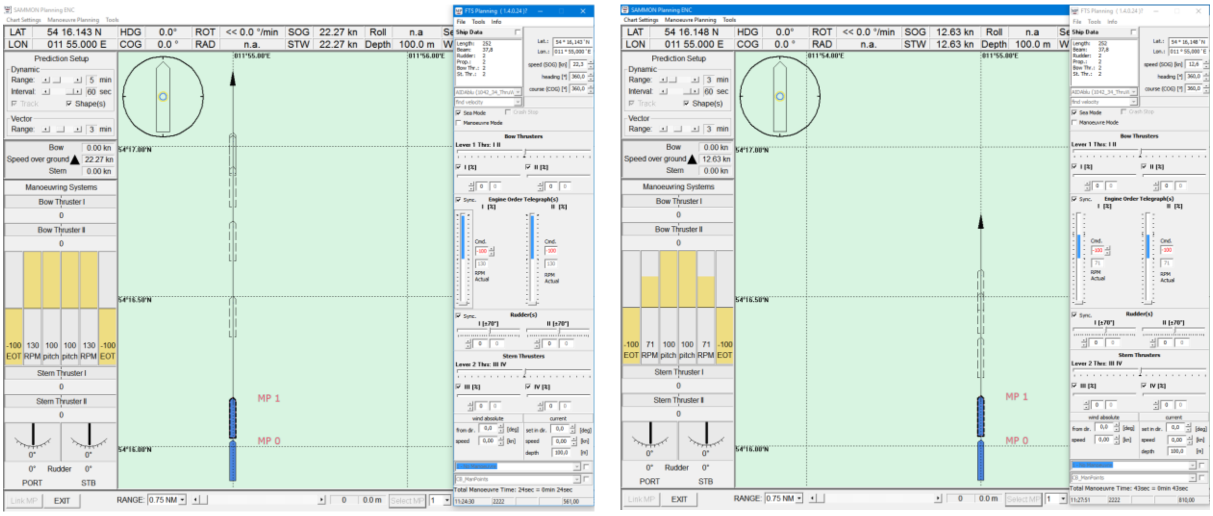
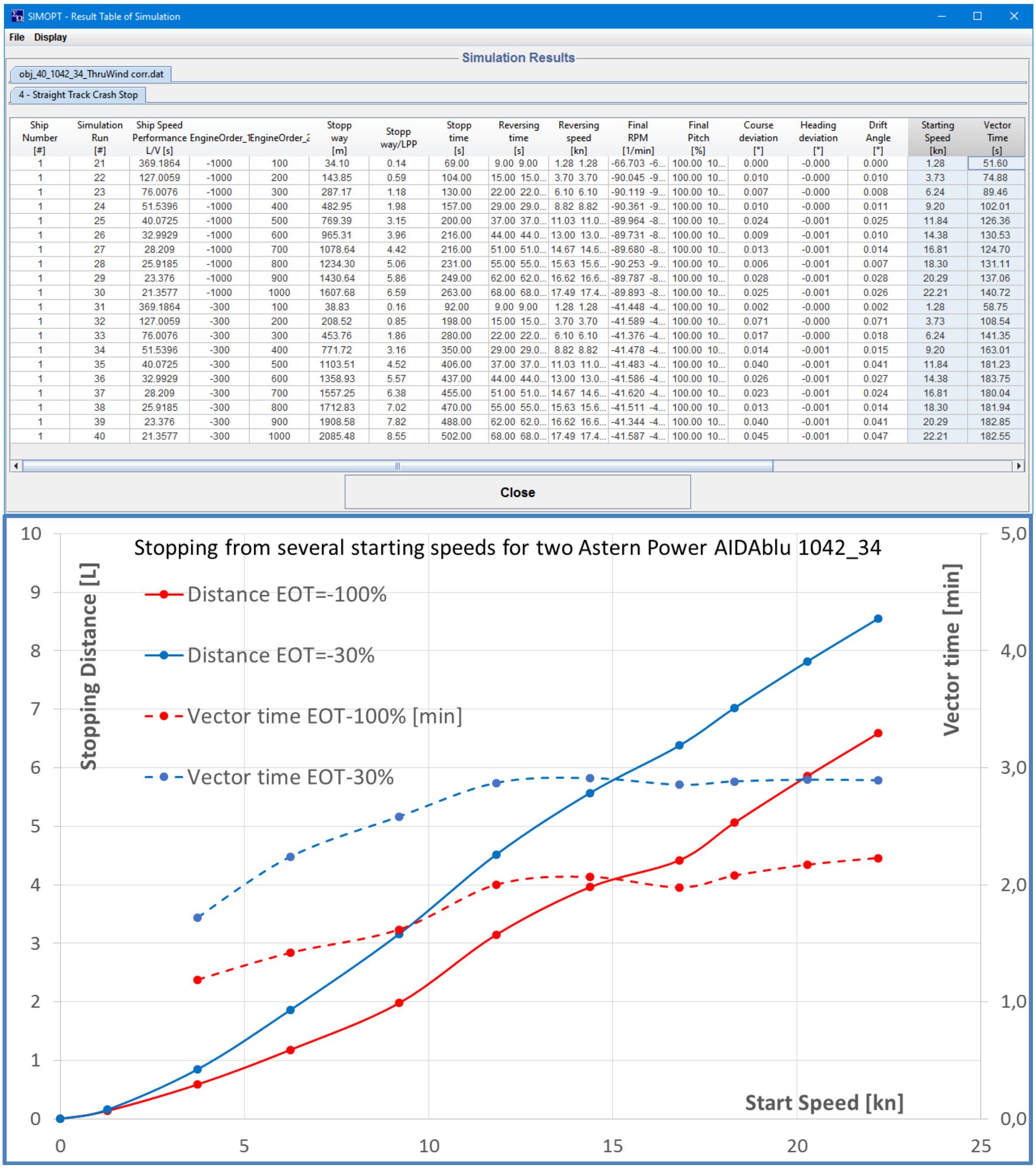


Fig.1: Display of the Manoeuvring Design & Planning Module: Two stopping manoeuvres for AIDA-blu from different speed rates to Full Astern (EOT = -100%): Left: Crash stop from Full Ahead (EOT = +100% for 22.2 kn) at MP1; Right: Stopping manoeuvre from Half Ahead (EOT = +53% for 12.6 kn) at MP1

The basic idea is to adjust the speed vectors’ length to the stopping distance: The required speed vector length can be easily calculated from the well-known relation speed = distance /time, which can be changed to time = distance / speed. From this equation, we can calculate the Vector time t_{vector} as t_{vector}=Stopping distance / Starting speed. E.g. the Crash Stop Stopping Distance 1600 m from starting speed 22.2 kn (11.4 m/s) gives t_{vector}= 1607 m / 12 m/s =140 s = 2:20 min. If we perform these calculations for all stopping distances of the solid lines in Fig.2 we get the dotted graphs. The result is that for all crash stop manoeuvres (blue line) with Full Astern the vector time is 2.5 minutes (blue dotted line); this is to be seen in Fig.1 where the ship stops before to the end of the 3 min speed vector. Therefore the conclusion might be: Setting the speed vector for t_{vector} = 3 min would give some extra safety distance – it would even allow stopping the ship with Astern power of EOT = -30% only!

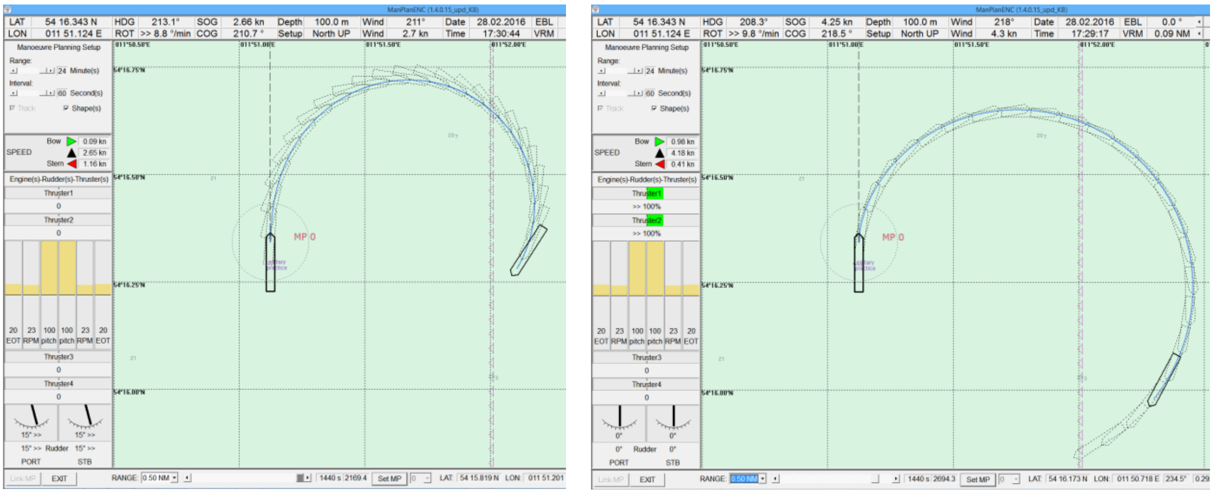


Ship Number [#]	Simulation Run [#]	Ship Speed Performance L/V [s]	EngineOrder_1	EngineOrder_	Stopp way [m]	Stopp way/LPP	Stopp time [s]	Reversing time [s]	Reversing speed [kn]	Final RPM [1/min]	Final Pitch [%]	Course deviation [°]	Heading deviation [°]	Drift Angle [°]	Starting Speed [kn]	Vector Time [s]
1	21	369.1864	-1000	100	34.10	0.14	69.00	9.00 9.00	1.28 1.28	-66.703 -6...	100.00 10...	0.000	-0.000	0.000	1.28	51.60
1	22	127.0059	-1000	200	143.85	0.59	104.00	15.00 15.0...	3.70 3.70	-90.045 -9...	100.00 10...	0.010	-0.000	0.010	3.73	74.88
1	23	76.0076	-1000	300	287.17	1.18	130.00	22.00 22.0...	6.10 6.10	-90.119 -9...	100.00 10...	0.007	-0.000	0.008	6.24	89.46
1	24	51.5396	-1000	400	482.95	1.98	157.00	29.00 29.0...	8.82 8.82	-90.361 -9...	100.00 10...	0.010	-0.000	0.011	9.20	102.01
1	25	40.0725	-1000	500	769.39	3.15	200.00	37.00 37.0...	11.03 11.0...	-89.964 -8...	100.00 10...	0.024	-0.001	0.025	11.84	126.36
1	26	32.9929	-1000	600	965.31	3.96	216.00	44.00 44.0...	13.00 13.0...	-89.731 -8...	100.00 10...	0.009	-0.001	0.010	14.38	130.53
1	27	28.209	-1000	700	1078.64	4.42	216.00	51.00 51.0...	14.67 14.6...	-89.680 -8...	100.00 10...	0.013	-0.001	0.014	16.81	124.70
1	28	25.9185	-1000	800	1234.30	5.06	231.00	55.00 55.0...	15.63 15.6...	-90.253 -9...	100.00 10...	0.006	-0.001	0.007	18.30	131.11
1	29	23.376	-1000	900	1430.64	5.86	249.00	62.00 62.0...	16.62 16.6...	-89.787 -8...	100.00 10...	0.028	-0.001	0.028	20.29	137.06
1	30	21.3577	-1000	1000	1607.68	6.59	263.00	68.00 68.0...	17.49 17.4...	-89.893 -8...	100.00 10...	0.025	-0.001	0.026	22.21	140.72
1	31	369.1864	-300	100	38.83	0.16	92.00	9.00 9.00	1.28 1.28	-41.448 -4...	100.00 10...	0.002	-0.000	0.002	1.28	58.75
1	32	127.0059	-300	200	208.52	0.85	198.00	15.00 15.0...	3.70 3.70	-41.589 -4...	100.00 10...	0.071	-0.000	0.071	3.73	108.54
1	33	76.0076	-300	300	453.76	1.86	280.00	22.00 22.0...	6.10 6.10	-41.376 -4...	100.00 10...	0.017	-0.000	0.018	6.24	141.35
1	34	51.5396	-300	400	771.72	3.16	350.00	29.00 29.0...	8.82 8.82	-41.478 -4...	100.00 10...	0.014	-0.001	0.015	9.20	163.01
1	35	40.0725	-300	500	1103.51	4.52	406.00	37.00 37.0...	11.03 11.0...	-41.483 -4...	100.00 10...	0.040	-0.001	0.041	11.84	181.23
1	36	32.9929	-300	600	1358.93	5.57	437.00	44.00 44.0...	13.00 13.0...	-41.586 -4...	100.00 10...	0.026	-0.001	0.027	14.38	183.75
1	37	28.209	-300	700	1557.25	6.38	455.00	51.00 51.0...	14.67 14.6...	-41.620 -4...	100.00 10...	0.023	-0.001	0.024	16.81	180.04
1	38	25.9185	-300	800	1712.83	7.02	470.00	55.00 55.0...	15.63 15.6...	-41.511 -4...	100.00 10...	0.013	-0.001	0.014	18.30	181.94
1	39	23.376	-300	900	1908.58	7.82	488.00	62.00 62.0...	16.62 16.6...	-41.344 -4...	100.00 10...	0.040	-0.001	0.041	20.29	182.85
1	40	21.3577	-300	1000	2085.48	8.55	502.00	68.00 68.0...	17.49 17.4...	-41.587 -4...	100.00 10...	0.045	-0.001	0.047	22.21	182.55

Fig.2: Results of SIMOPT program for series of stopping manoeuvres for cruise ship AIDAblu (Computing time 17 s): Top: Result table for several Ahead speed rates from EOT = 10 to 100 % and two Astern power variants with EOT = -100% and -30% (SIMDAT); Bottom: Stopping diagram for distances (solid lines) and respective times for speed vector length (dotted lines)

2.2. Effect of rudders and thrusters on swept path and pivot point

For many situation specifically in narrow fairway and limited space the manoeuvring space and the swept path is of utmost importance. Fig.3 shows that the swept path for turning manoeuvres with rudder is much bigger than for thruster manoeuvres.



LAT 54 16.343 N | HDG 213.1° | SOG 2.66 kn | Depth 100.0 m | Wind 211° | Date 28.02.2016 | EBL
LON 011 51.124 E | ROT >> 8.8 °/min | COG 210.7 ° | Setup North UP | Wind 2.7 kn | Time 17:30:44 | VRM
Range: 24 Minute(s)
Interval: 60 Second(s)
☑ Track ☑ Shape(s)
SPEED Bow 0.09 kn, 2.65 kn, Stern 1.16 kn
Engine(s)-Rudder(s)-Thruster(s)
Thruster1 0
Thruster2 0
20 EOT | 23 RPM | 100 pitch | 100 pitch | 23 RPM | 20 EOT
Thruster3 0
Thruster4 0
15° >> | 15° >>
15° >> Rudder 15° >>
PORT STB
RANGE: 0.50 NM | 1440 s | 2169.4 | LAT: 54 15.819 N | LON: 011 51.201

LAT 54 16.343 N | HDG 208.3° | SOG 4.25 kn | Depth 100.0 m | Wind 218° | Date 28.02.2016 | EBL 0.0 °
LON 011 51.124 E | ROT >> 9.8 °/min | COG 218.5 ° | Setup North UP | Wind 4.3 kn | Time 17:29:17 | VRM 0.09 NM
Range: 24 Minute(s)
Interval: 60 Second(s)
☑ Track ☑ Shape(s)
SPEED Bow 0.98 kn, 4.18 kn, Stern 0.41 kn
Engine(s)-Rudder(s)-Thruster(s)
Thruster1 >> 100%
Thruster2 >> 100%
20 EOT | 23 RPM | 100 pitch | 100 pitch | 23 RPM | 20 EOT
Thruster3 0
Thruster4 0
0° | 0°
0° Rudder 0°
PORT STB
RANGE: 0.50 NM | 1440 s | 2694.3 | LAT: 54 16.173 N | LON: 011 50.718 E | 234.5° | 0.29

Fig.3: Ship path during turning with rudders or thrusters with SAMMON Design & Planning tool in forward motion EOT = +20% Ahead: Left: Turning with Rudder STB 15°, Thruster 0%, Right: Turning with bow-Thruster 100% STB, Rudder 0°

If the turning is generated by means of rudder, it is producing a lift force like a wing of an airplane but in the horizontal plane: the force is pointing outward to port side. Then a drift angle ß sets in and now the ship hull acts as a "wing" with lift force to starboard at the fore part of the ship; this force is creating a so called "unstable moment" which tries to increase the drift angle. When therefore the turning motion r develops, it causes centrifugal forces acting on the centre of gravity of ships and hydrodynamic masses. Due to the rotation a damping force sets in, acting like a "curved profile" and producing a moment in opposite direction to balance the unstable moment in the circular motion. It is a similar effect as "counter rudder" to counteract the initial rudder moment plus the unstable moment until an equilibrium is found in steady state turning on a circle.

The development of the Turning Circle Manoeuvre ends up in Steady State Conditions with an equilibrium in balancing the Transverse Forces and Moments. If the ship starts turning with a bow thruster, then a drift angle does not occur – it is not required (or even becomes negative in case the thruster is to powerful!) to shift the ship "inward" from initial course because thruster force is pointing inward. The drift angle and the rate of turn have an impact on the position of the pivot point (PP); the PP is located where the crossflow speed (or the ships transverse motion respectively) is zero.

Where is its position and which effects are driving the PP position? In Fig.4 some examples are shown for turning manoeuvres in ahead and astern motion and with rudder or thrusters. The following conclusions can be drawn:

- PP position is flexible and depends directly on ships motion, i.e. the ratio between drift and turning. E.g. for turning circle its position is starting at mid ship for beginning of turn and moves forward when the drift sets in; it remains in the fore part, on average 1/3 ship length behind the bow for rudder manoeuvres and aft for bow thruster manoeuvres.
- Under wind impact there might already be a wind drift additionally to the drift due to the rudder effect during turning, e.g. for turning under wind: the pivot point is far ahead when the turning starts in comparison to the turning without wind
- Because its position changes, therefore the PP is not suitable as reference point for discussion of acting forces – better use the Centre of Gravity for understanding dynamic effects!

- For small drift angles, the PP is at mid ships and therefor only minimum manoeuvring space is required, specifically as minimum swept path.

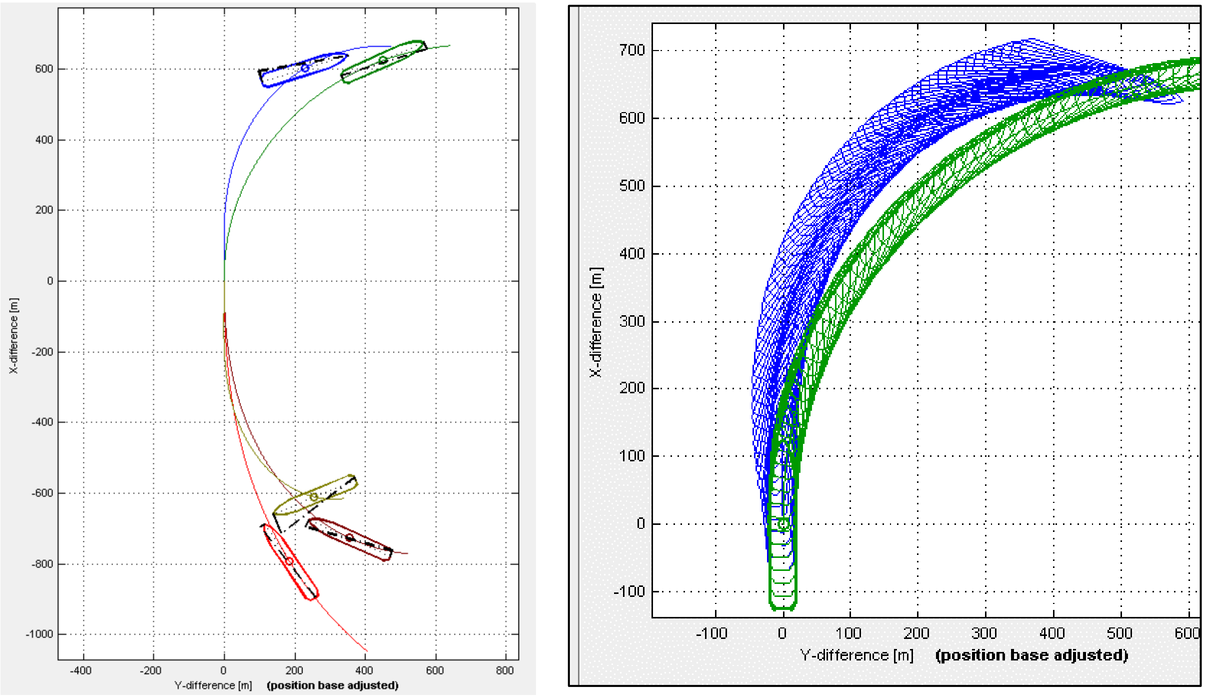


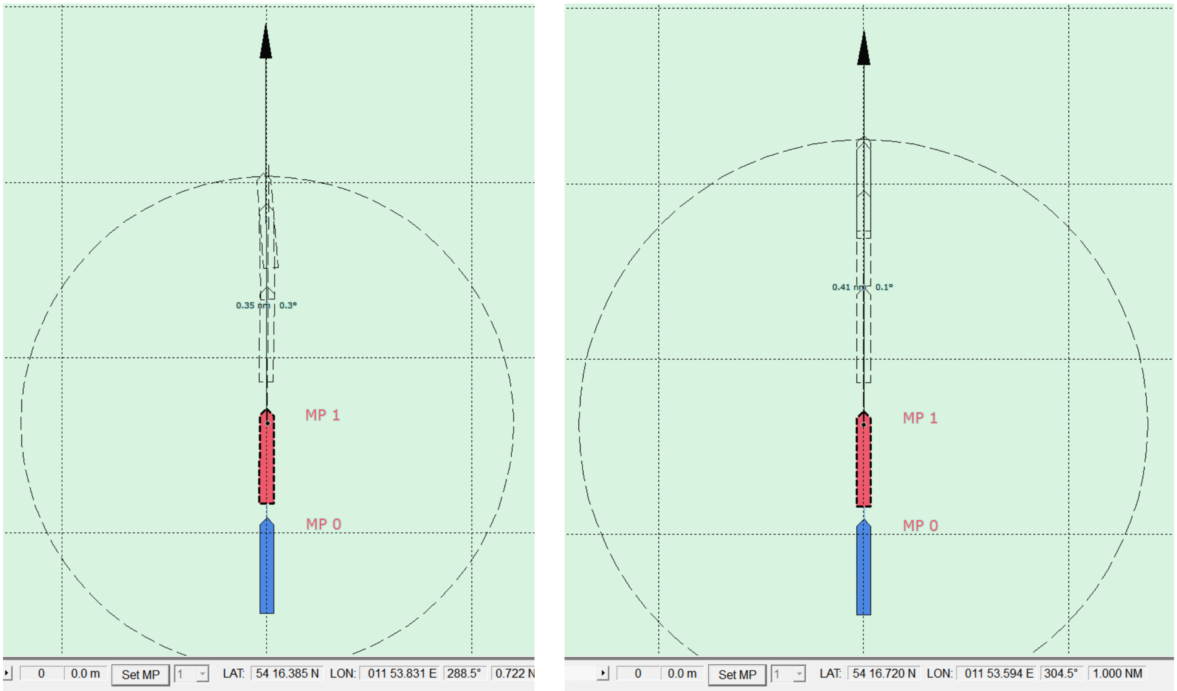
Fig.4: Ship path and location of pivot point (left) and sample of swept path (right) during turning of ship with rudders or thrusters with SIMOPT & SIMDAT: Forward motion Engine Ahead EOT = +20%: Blue: Rudder 20°STB, no Thruster, Green: Bow Thruster 100% STB; Astern motion with Engine Astern EOT = -20%: Red: Rudder 20° STB, Brown: Stern Thruster 100% STB, Grey: Bow Thruster -100% PT

More effects on ship handling characteristics explored by SAMMON can be seen for wind and current in *Benedict et al. (2016)*, for location and controlling of pivot point in *Benedict (2016)*, and for operation from the shore in *Krueger et al. (2015)*.

2.3. Effect of split engines and rudders for twin screw – twin rudder ships

Many cruise ships and ferries have and twin screw – twin rudder systems. Normally these systems are operated in synchronous mode for continuous operations during long voyage segments, but for manoeuvres in ports, there are some advantages to split the engines and propellers to control them separately. For stopping of ships, the distance can be reduced by split engine manoeuvres, as it can be seen from Fig.5: Starting from the same speed with split engines shows a shorter distance for Full Astern, because one engine is already running astern and therefore reversing times can be avoided.

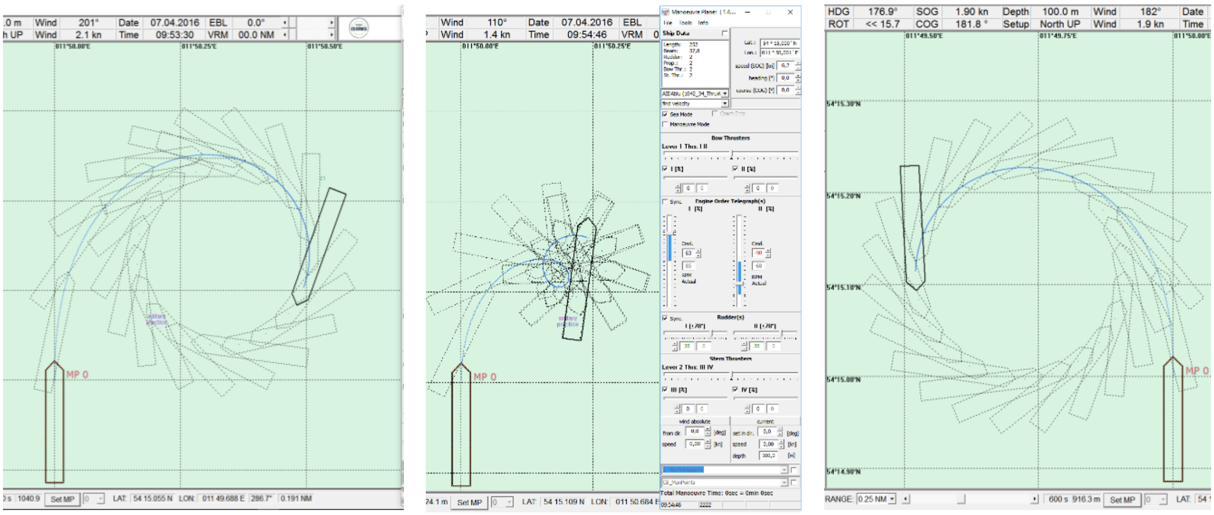
For steering capability the split mode also reveals some advantages because the rudder inflow from the ahead engine causes higher rudder forces to be used for course keeping (e.g. under strong wind) than synchronised engines. In addition, the turning can be improved, Fig.6, where the following conclusions can be drawn: From condition with split engines the turning circle is smaller to the side where the prop is reversed, the ship reacts faster and reaches smaller circular motion radius. The improvement of turning comes also from the stronger speed loss with split engines to that side, therefore the ratio of rudder forces to the hull forces is higher. However, if the ship is turning to the opposite side the turning capability is reduced: This is why the ship needs a rudder angle PT -4.4° to balance the ship already on straight track – that means the effective rudder change is nearly 40° when turning to STB, but only 30° to PT side.



0 | 0.0 m | Set MP | 1 | LAT: 54 16.385 N | LON: 011 53.831 E | 288.5° | 0.722 N

0 | 0.0 m | Set MP | 1 | LAT: 54 16.720 N | LON: 011 53.594 E | 304.5° | 1.000 NM

Fig.5: Two different final situations after Full Astern to EOT = -100% from the same initial speed of 11.4 kn with different initial EOT settings: Left: split engines STB +70%, PT -20%, Rudder 1.7° - Result: Stopping distance = 0.35 nm, Right: sync engines, STB = PT = +48%; Rudder 0° - Result: Stopping distance = 0.41 nm



Wind 201° | Date 07.04.2016 | EBL 0.0°
Wind 2.1 kn | Time 09:53:30 | VRM 00.0 NM

Wind 110° | Date 07.04.2016 | EBL
Wind 1.4 kn | Time 09:54:46 | VRM

HDG 176.9° | SOG 1.90 kn | Depth 100.0 m | Wind 182° | Date
ROT << 15.7 | COG 181.8° | Setup North UP | Wind 1.9 kn | Time

Fig.6: Turning manoeuvres from Initial Speed 6.2 kn with constant speed rate on straight track to demonstrate the difference between sync and split engines: Left: Standard turning manoeuvre with full rudders 35°STB with standard sync engines from EOT 30% both STB and PT; Centre: with full rudders 35°STB with split engines PT +63% ahead, STB -50% astern; Right: with full rudders 35°PT with split engines PT +63% ahead, STB -50% astern

3. Use of fast time simulation for simulator Briefing

3.1 Task description – introduction, conventional Briefing and NEW CONCEPT

During the exercise briefing, the navigational officer is introduced into the harbour area, the starting situation and the environmental conditions within this area on a conventional sea chart, Fig.7. The objective is to bring the ship through the fairway channel of Rostock Port from North, to turn the ships and heading back through the channel to berth the ship with Port Side at the Passenger Pier.

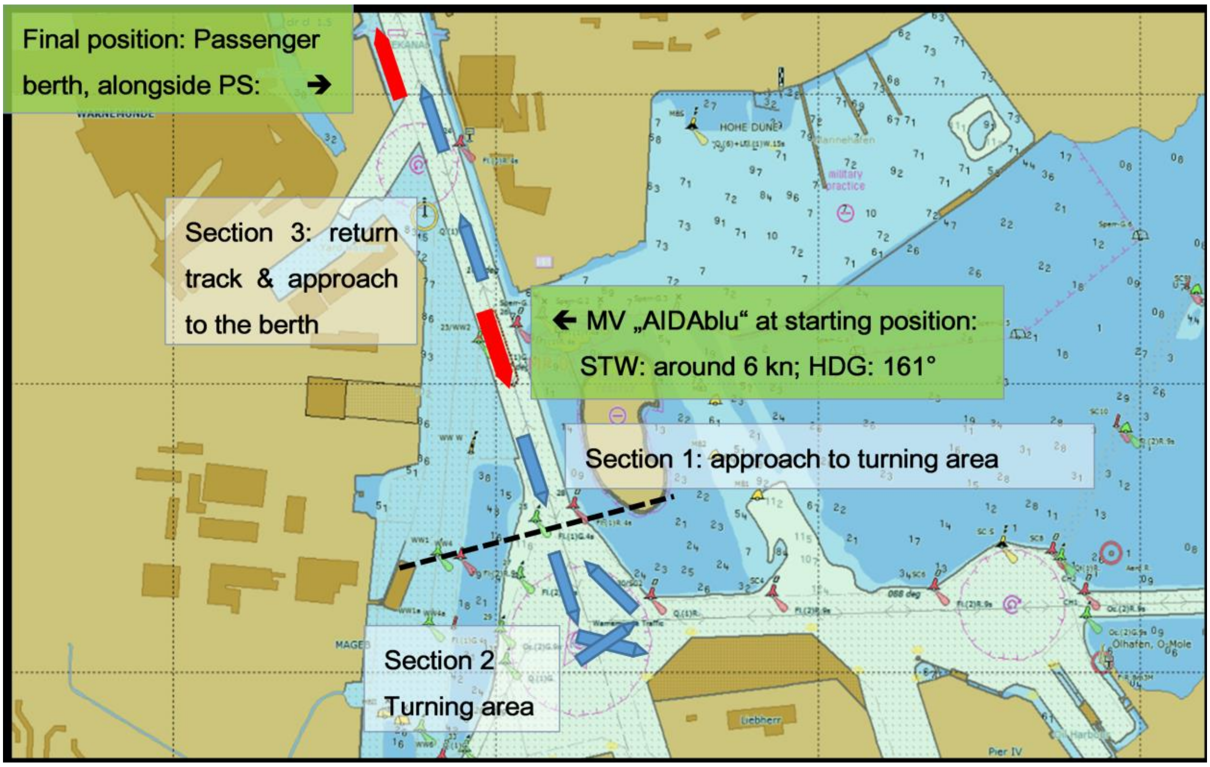


Fig.7: Exercise area and environmental conditions in Port of Rostock for berthing scenario, divided into two sections for planning the manoeuvres and completed by guessing for desired positions as ship shapes only.

The respective harbour area is divided into manoeuvring sections, which are following a specific aim:

1. Section 1: ship speed should be reduced until she is ready to be turned, SOG should be around 3 kn to be prepared for section 2.
2. Section 2: the ship should be turned and adjusted to go back in the fairway on opposite course to the final berth.
3. Section 32: the ship should be stopped and berthed.

In the conventional briefing, only these rough indications of the manoeuvring status can be used to develop a potential strategy for berthing the ship. In conventional berth plans only ship contours are used to be positioned in drawings with WORD or POWER POINT - The specific manoeuvres and settings of engine rudder and thrusters cannot be discussed in detail because specific manoeuvring characteristics can hardly be used for the specific situations. And real time simulation is too time consuming. The fast time simulation allows for new methods for individual exercise preparation with self-developed manoeuvring concepts:

- Drafting Manoeuvring Concept in more detail as Manoeuvring Plan with the Design and Planning tool;
- Optimisation of the concept by several planning trials with that tool,
- Pre-Training with Trial and Training Tool to try out the concept with real time simulation on a laptop

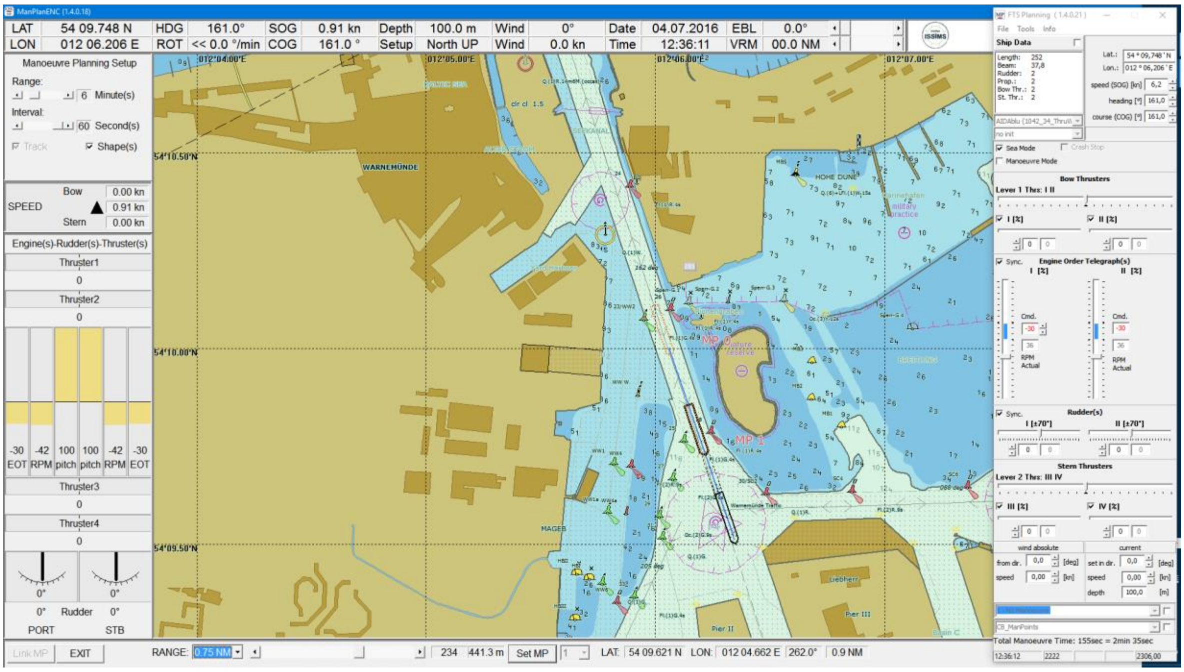
3.2 Briefing by means of the “Manoeuvre Planning & Design Module”

3.2.1. Basic exercise with no wind and current

With the new fast time Simulation there is the chance for designing a Manoeuvre Plan as a detailed strategy with the specific settings at distinguished positions called the Manoeuvring Points MP. Some basic functions and interface displays for the Fast Time Simulation within the Design and Planning Tool are shown in the next figures. Fig.8 explains the method in a sea chart environment represented by an interface, which combines

- the electronic navigational chart ENC window (centre),
- the interface window for the steering panel of the ship (right) for adjusting the controls for the selected manoeuvring point MP and the
- interface to display the status of the current actual ship manoeuvring controls (left) at the position of the next manoeuvring point MP which is indicated as ship shape in red colour in the ENC.

In the following, the course of actions is described in a series of figures to make a full manoeuvring plan by means of the control actions at the manoeuvring points MP – this will be done first for easy conditions with no wind and current to explain the procedure of fast time planning: In Fig.8 the initial position MP 0 is to be seen where the instructor has set the ship in the centre of the fairway. The ship has already been moved by the slider at the ENC bottom to set the next manoeuvring point MP 1: there the stopping manoeuvre is started with EOT -30%. The prediction already shows that the ship would lose speed according to the handle positions.



ManPlanENC (1.4.0.18)

LAT 54 09.748 N | HDG 161.0° | SOG 0.91 kn | Depth 100.0 m | Wind 0° | Date 04.07.2016 | EBL 0.0°

LON 012 06.206 E | ROT << 0.0 °/min | COG 161.0 ° | Setup North UP | Wind 0.0 kn | Time 12:36:11 | VRM 00.0 NM

Manoeuvre Planning Setup

Range: 6 Minute(s)

Interval: 60 Second(s)

☑ Track ☑ Shape(s)

SPEED: Bow 0.00 kn, 0.91 kn, Stern 0.00 kn

Thruster1 0

Thruster2 0

-30 EOT, -42 RPM, 100 pitch, 100 pitch, -42 RPM, -30 EOT

Thruster3 0

Thruster4 0

0° Rudder 0°

RANGE: 0.75 NM | 234 | 441.3 m | Set MP | 1 | LAT: 54 09.621 N | LON: 012 04.662 E | 262.0° | 0.9 NM

FTS Planning (1.4.0.21)

Ship Data

Length: 252

Beam: 37,8

Rudder: 2

Prop.: 2

Bow Thr.: 2

St. Thr.: 2

AIDAblu (1042_34_Thru...

no init

Lat.: 54 ° 09,748 ' N

Lon.: 012 ° 06,206 ' E

speed (SOG) [kn] 6,2

heading [°] 161,0

course (COG) [°] 161,0

☑ Sea Mode ☐ Crash Stop

☐ Manoeuvre Mode

Bow Thrusters – Lever 1 Thrs: I II

☑ I [%] 0 0 ☑ II [%] 0 0

☑ Sync. Engine Order Telegraph(s) I [%]: Cmd. -30, RPM Actual 36; II [%]: Cmd. -30, RPM Actual 36

☑ Sync. Rudder(s) I [±70°] 0 0; II [±70°] 0 0

Stern Thrusters – Lever 2 Thrs: III IV

☑ III [%] 0 0 ☑ IV [%] 0 0

wind absolute: from dir. 0,0 [deg], speed 0,00 [kn]

current: set in dir. 0,0 [deg], speed 0,00 [kn], depth 100,0 [m]

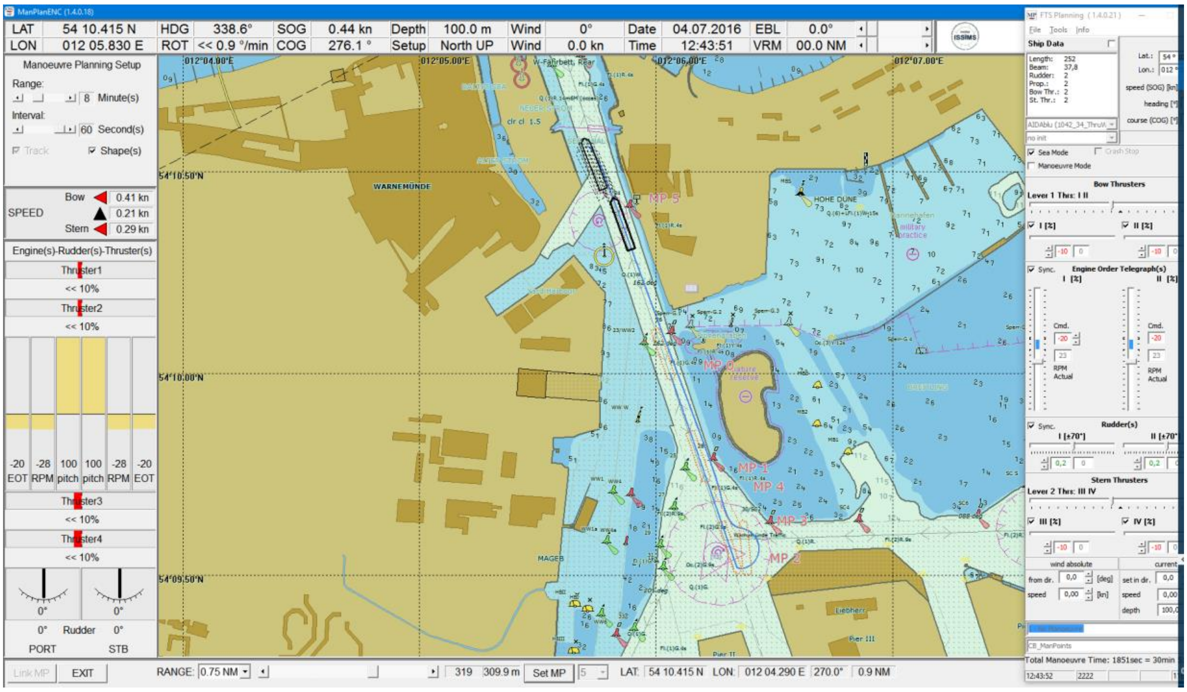
CB_ManPoints

Total Manoeuvre Time: 155sec = 2min 35sec

12:36:12 | 2222 | 2306,00

Fig.8: Fast time planning in sea chart: Initial ship position at MP0 and prediction for the stopping manoeuvre at MP1: The prediction already shows that the ship reduces speed to the set handle positions.

In Fig.10 the ship is nearly stopped and turns by means of the thrusters – the contour is shifted to a position where the thrusters are stopped and the engines speed up to return to the fairway with opposite course. In Fig.11 the vessel is brought close to the berth and at MP5 the engines are reversed to reduce speed and to stop the ships at a position parallel to the berth to be shifted by thrusters to the pier from the next MP 6. Afterwards the plan needs a further MP in order to reduce the transversal speed shortly before berthing.


ManPlanENC (1.4.0.18)

LAT 54 10.415 N | HDG 338.6° | SOG 0.44 kn | Depth 100.0 m | Wind 0° | Date 04.07.2016 | EBL 0.0°

LON 012 05.830 E | ROT << 0.9 °/min | COG 276.1 ° | Setup North UP | Wind 0.0 kn | Time 12:43:51 | VRM 00.0 NM

Manoeuvre Planning Setup

Range: 8 Minute(s)

Interval: 60 Second(s)

SPEED Bow 0.41 kn, 0.21 kn, Stern 0.29 kn

Thruster1 << 10%

Thruster2 << 10%

-20 EOT, -28 RPM, 100 pitch, 100 pitch, -28 RPM, -20 EOT

Thruster3 << 10%

Thruster4 << 10%

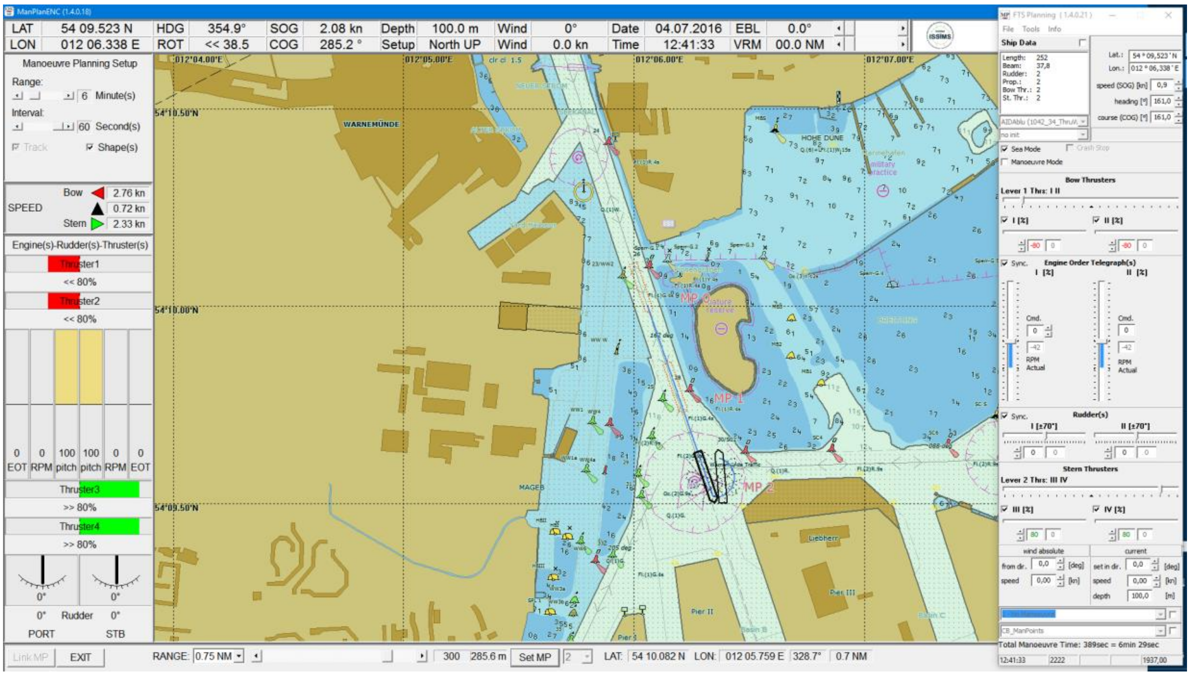
0° Rudder 0°

PORT STB

RANGE: 0.75 NM | 319 | 309.9 m | Set MP | 5 | LAT: 54 10.415 N | LON: 012 04.290 E | 270.0° | 0.9 NM

Total Manoeuvre Time: 1851sec = 30min

Fig.9: Final part of the manoeuvring plan: The vessel is brought into a position parallel to the berth to be shifted by thrusters to the pier from the next MP6


ManPlanENC (1.4.0.18)

LAT 54 09.523 N | HDG 354.9° | SOG 2.08 kn | Depth 100.0 m | Wind 0° | Date 04.07.2016 | EBL 0.0°

LON 012 06.338 E | ROT << 38.5 | COG 285.2 ° | Setup North UP | Wind 0.0 kn | Time 12:41:33 | VRM 00.0 NM

Manoeuvre Planning Setup

Range: 6 Minute(s)

Interval: 60 Second(s)

SPEED Bow 2.76 kn, 0.72 kn, Stern 2.33 kn

Thruster1 << 80%

Thruster2 << 80%

0 EOT, 0 RPM, 100 pitch, 100 pitch, 0 RPM, 0 EOT

Thruster3 >> 80%

Thruster4 >> 80%

0° Rudder 0°

PORT STB

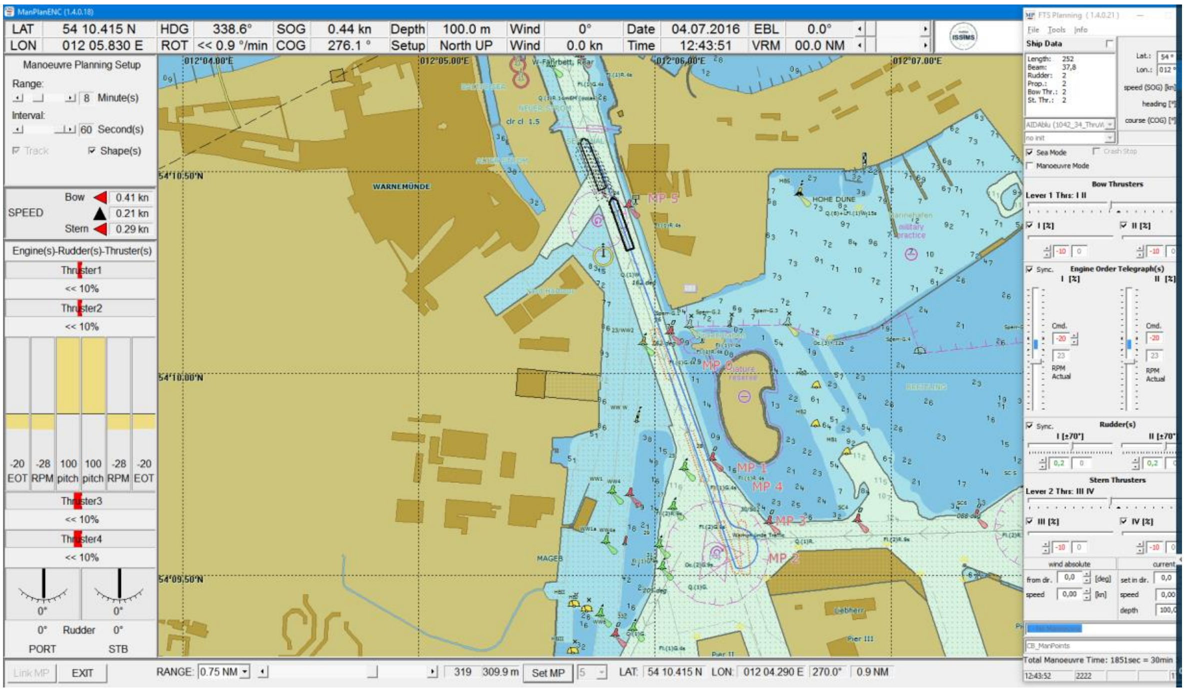
RANGE: 0.75 NM | 300 | 285.6 m | Set MP | 2 | LAT: 54 10.082 N | LON: 012 05.759 E | 328.7° | 0.7 NM

Total Manoeuvre Time: 389sec = 6min 29sec

Fig.10: Ship position at MP2 and prediction for the turning manoeuvre: The prediction shows that the ship is turning due to the set handle positions of Bow and Stern Thrusters with 80%.

3.2.2. Advanced exercise with strong wind

The full potential of the fast time simulation can be seen for challenging weather conditions. In Fig.12 the scenario is now to be solved for 25 kn wind from 61°. The initial position is the same as in the previous example but the first task for the trainee is to find the balance condition in the fairway: after some attempts, a drift angle of about 16° and rudder angle 3° was adjusted and the ship contour was shifted to the buys at the entrance of the fairway.



ManPlanENC (1.4.0.18)

LAT	54 10.415 N	HDG	338.6°	SOG	0.44 kn	Depth	100.0 m	Wind	0°	Date	04.07.2016	EBL	0.0°
LON	012 05.830 E	ROT	<< 0.9 °/min	COG	276.1 °	Setup	North UP	Wind	0.0 kn	Time	12:43:51	VRM	00.0 NM

Manoeuvre Planning Setup
Range: 8 Minute(s)
Interval: 60 Second(s)
☑ Track ☑ Shape(s)

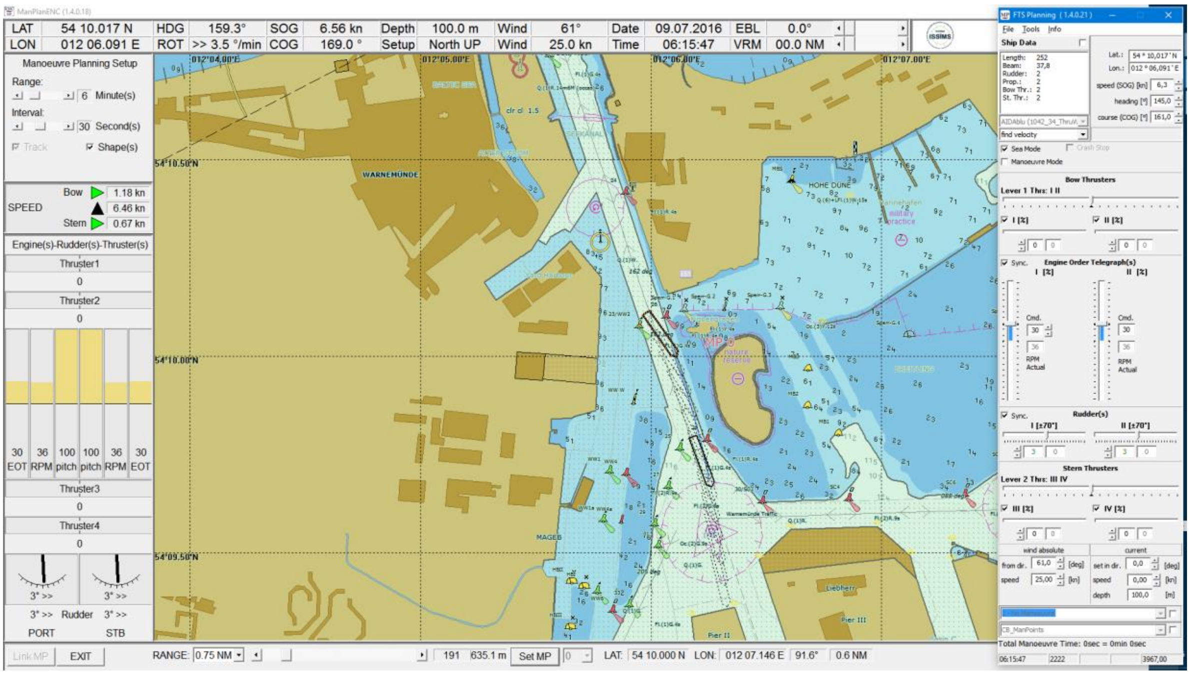
SPEED
Bow 0.41 kn
0.21 kn
Stern 0.29 kn

Engine(s)-Rudder(s)-Thruster(s)
Thruster1 << 10%
Thruster2 << 10%
-20 EOT, -28 RPM, 100 pitch, 100 pitch, -28 RPM, -20 EOT
Thruster3 << 10%
Thruster4 << 10%
0° Rudder 0°
PORT STB

RANGE: 0.75 NM 319 309.9 m Set MP 5 LAT: 54 10.415 N LON: 012 04.290 E 270.0° 0.9 NM

FTS Planning (1.4.0.21)
Ship Data
Length: 252
Beam: 37,8
Rudder: 2
Prop.: 2
Bow Thr.: 2
St. Thr.: 2
Total Manoeuvre Time: 1851sec = 30min
12:43:52 2222

Fig.11: Final part of the manoeuvring plan: The vessel is brought into a position parallel to the berth to be shifted by thrusters to the pier from the next MP6



ManPlanENC (1.4.0.18)

LAT	54 10.017 N	HDG	159.3°	SOG	6.56 kn	Depth	100.0 m	Wind	61°	Date	09.07.2016	EBL	0.0°
LON	012 06.091 E	ROT	>> 3.5 °/min	COG	169.0 °	Setup	North UP	Wind	25.0 kn	Time	06:15:47	VRM	00.0 NM

Manoeuvre Planning Setup
Range: 6 Minute(s)
Interval: 30 Second(s)
☑ Track ☑ Shape(s)

SPEED
Bow 1.18 kn
6.46 kn
Stern 0.67 kn

Engine(s)-Rudder(s)-Thruster(s)
Thruster1 0
Thruster2 0
30 EOT, 36 RPM, 100 pitch, 100 pitch, 36 RPM, 30 EOT
Thruster3 0
Thruster4 0
3° >> Rudder 3° >>
PORT STB

RANGE: 0.75 NM 191 635.1 m Set MP 0 LAT: 54 10.000 N LON: 012 07.146 E 91.6° 0.6 NM

FTS Planning (1.4.0.21)
Ship Data
Length: 252
Beam: 37,8
Rudder: 2
Prop.: 2
Bow Thr.: 2
St. Thr.: 2
Lat.: 54 ° 10,017 ' N
Lon.: 012 ° 06,091 ' E
speed (SOG) [kn] 6,3
heading [°] 145,0
course (COG) [°] 161,0
find velocity
wind absolute from dir. 61,0 [deg] speed 25,00 [kn]
current set in dir. 0,0 [deg] speed 0,00 [kn] depth 100,0 [m]
Total Manoeuvre Time: 0sec = 0min 0sec
06:15:47 2222 3967,00

Fig.12: Fast time planning in sea chart under wind 25 kn from 61°: Initial ship position at MP0 and prediction for future track under drift angle

The next manoeuvring segment is for stopping and turning in Fig.13: On the left side it can be seen, that in case the ship would be plainly stopped here as in the previous exercise she would heavily drifting with the wind. Therefore, the engines are split to support the turning by the STB engine while the PT engine goes astern. In the final part of the manoeuvre, the crucial segments are difficult because of the strong wind on the return track on opposite course: in Fig.14 the ship enters the fairway now from south and because of the strong wind from the bow there is a need to adjust heading, course and rudder. It is advantageous to split the engines because the rudder is more effective when one engine goes with more power. In addition, the ship is better prepared to stop because one engine is already going astern and does not need additional reversing time. On the right side of the figure, the stopping manoeuvre is to bring the ship into a position parallel to the berth. In Fig.15 the thrusters and rudders are used with full power to counteract the wind effect for the final berthing, the approaching speed of the drift motion towards the pier is below 0.8 kn (for 30 kn it would be over 1.5 kn).

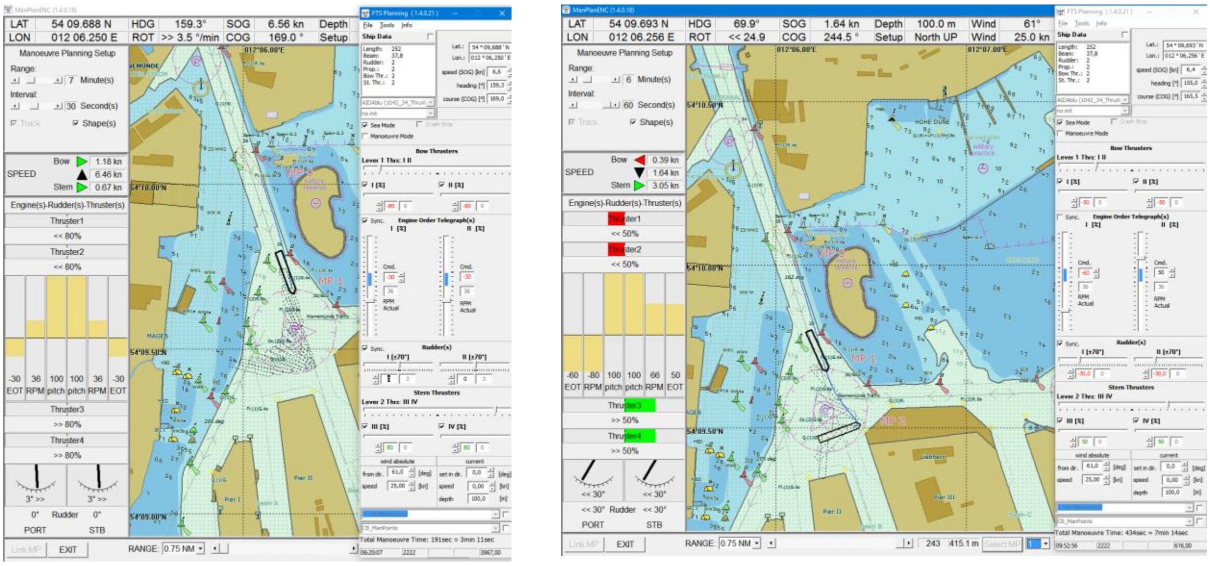


Fig.13: Ship position at MP2 and prediction for the turning manoeuvre with two strategies: Left: turning only with thrusters (same concept as without wind in Fig.10), Right: more powerful solution with split engines and rudder support

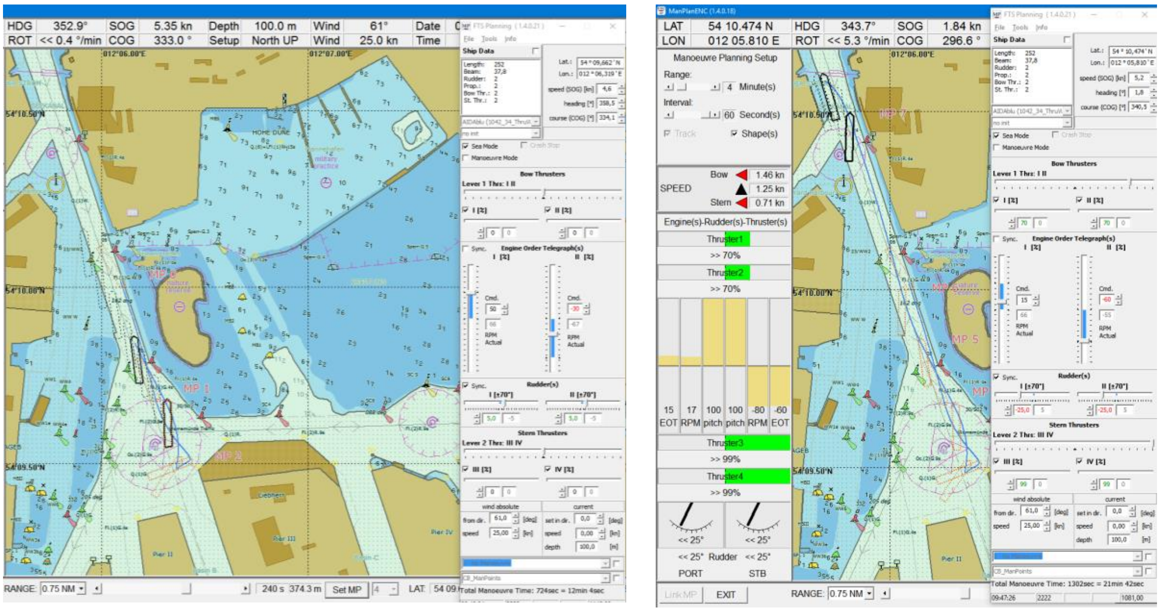
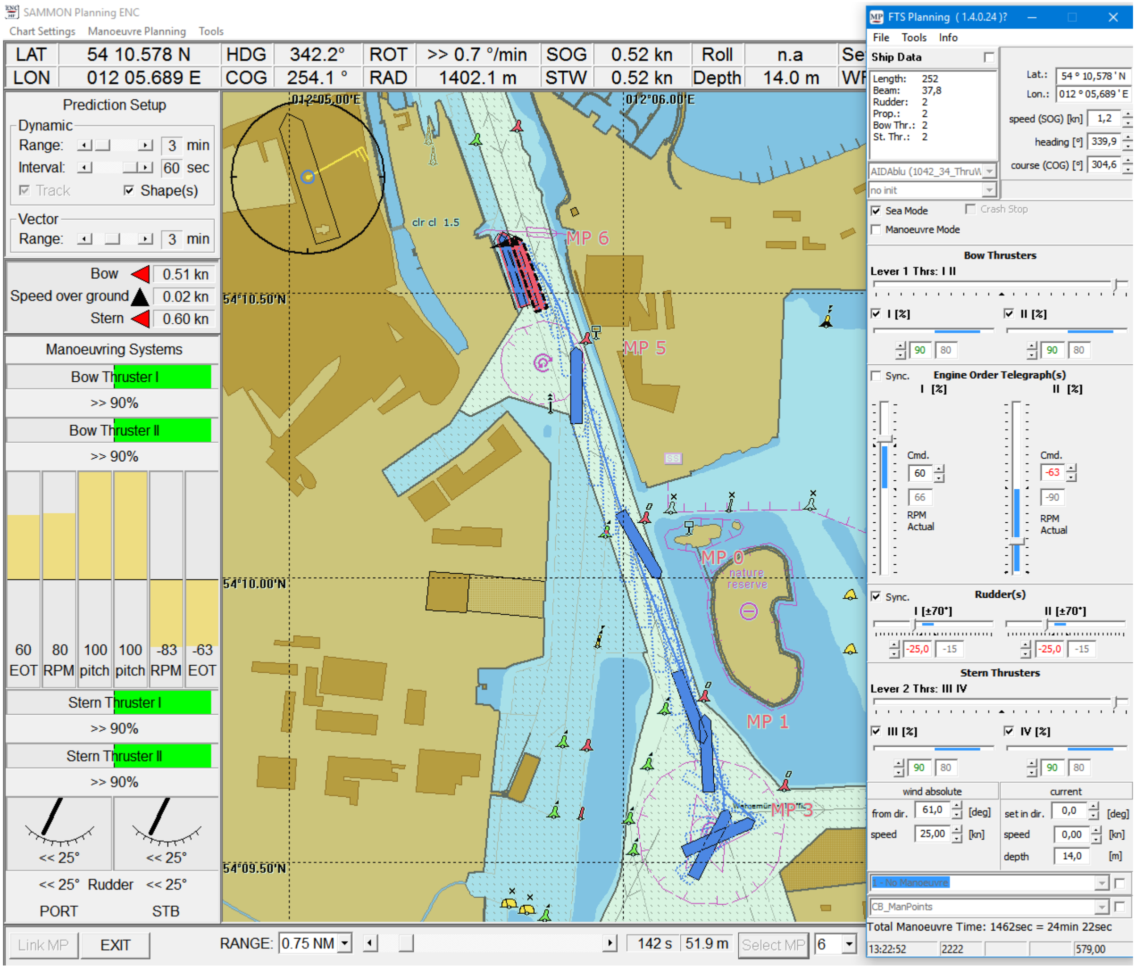


Fig.14: Continuing the manoeuvring plan on the return track on opposite course: Left: the ship enters the fairway now from south and adjust heading, course and rudder with split engines; Right: stopping manoeuvre to bring the ship into a position parallel to the berth

3.3 Briefing by means of the „Manoeuvre trial & TRAINING MODULE“

The Trail & Training Tool is a desktop simulation tool for real time manoeuvring simulation, Fig.14. It contains conning information together with the prediction and it can display the planned manoeuvring track. The centre window shows the ENC together with motion parameter for longitudinal and transverse speed. The ships position is displayed as ship contour where also the track prediction can be indicated as curved track or chain of contours for the selected prediction time. The prediction parameters as range or interval of presentation can be set in the control window at the left side.



SAMMON Planning ENC

Chart Settings · Manoeuvre Planning · Tools

LAT	54 10.578 N	HDG	342.2°	ROT	>> 0.7 °/min	SOG	0.52 kn	Roll	n.a
LON	012 05.689 E	COG	254.1 °	RAD	1402.1 m	STW	0.52 kn	Depth	14.0 m

Prediction Setup

Dynamic Range: 3 min

Interval: 60 sec

☐ Track ☑ Shape(s)

Vector Range: 3 min

Bow 0.51 kn

Speed over ground 0.02 kn

Stern 0.60 kn

Manoeuvring Systems

Bow Thruster I >> 90%

Bow Thruster II >> 90%

60	80	100	100	-83	-63
EOT	RPM	pitch	pitch	RPM	EOT

Stern Thruster I >> 90%

Stern Thruster II >> 90%

<< 25° << 25°

<< 25° Rudder << 25°

PORT STB

Link MP EXIT RANGE: 0.75 NM 142 s 51.9 m Select MP 6

FTS Planning (1.4.0.24)?

File Tools Info

Ship Data

Length: 252
Beam: 37,8
Rudder: 2
Prop.: 2
Bow Thr.: 2
St. Thr.: 2

Lat.: 54 ° 10,578 ' N
Lon.: 012 ° 05,689 ' E
speed (SOG) [kn] 1,2
heading [°] 339,9
course (COG) [°] 304,6

AIDAblu (1042_34_ThruW
no init

☑ Sea Mode ☐ Crash Stop
☐ Manoeuvre Mode

Bow Thrusters
Lever 1 Thrs: I II
☑ I [%] 90 80 ☑ II [%] 90 80

☐ Sync. Engine Order Telegraph(s) I [%] II [%]
Cmd. 60, 66 RPM Actual
Cmd. -63, -90 RPM Actual

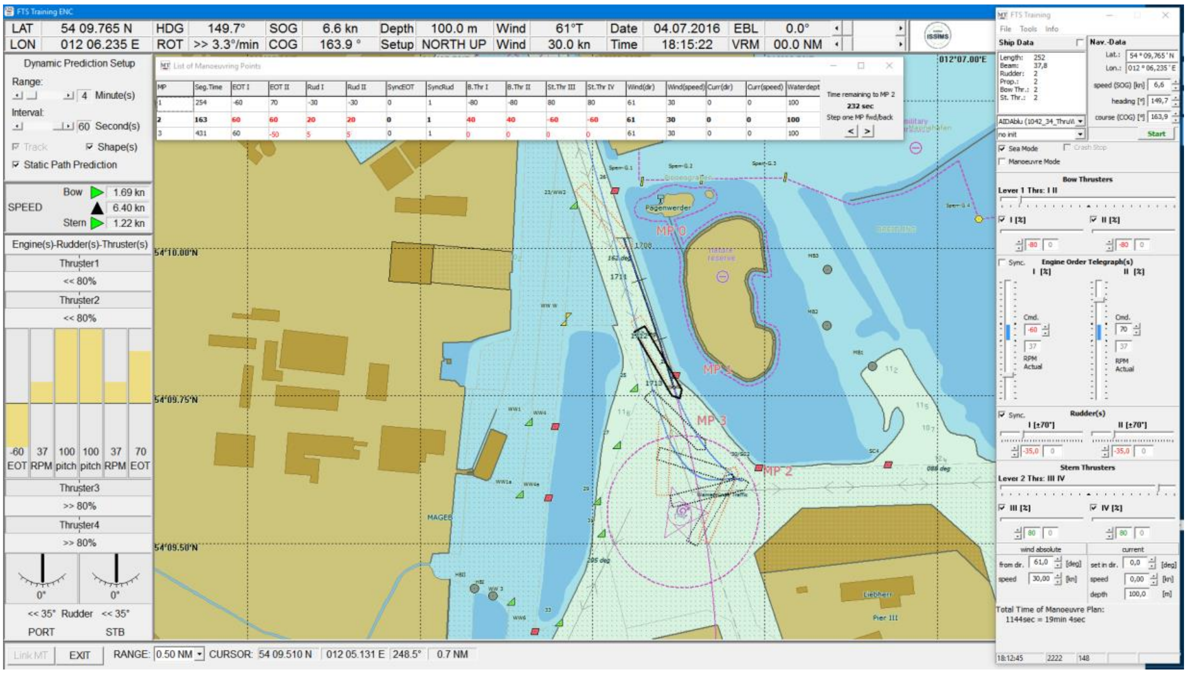
☑ Sync. Rudder(s) I [±70°] II [±70°]
-25,0 -15 -25,0 -15

Stern Thrusters
Lever 2 Thrs: III IV
☑ III [%] 90 80 ☑ IV [%] 90 80

wind absolute: from dir. 61,0 [deg] speed 25,00 [kn]
current: set in dir. 0,0 [deg] speed 0,00 [kn] depth 14,0 [m]

No Manoeuvre
CB_ManPoints
Total Manoeuvre Time: 1462sec = 24min 22sec
13:22:52 2222 579,00

Fig.15: Complete manoeuvring plan with final berthing manoeuvre



FTS Training ENC

LAT	54 09.765 N	HDG	149.7°	SOG	6.6 kn	Depth	100.0 m	Wind	61°T	Date	04.07.2016	EBL	0.0°
LON	012 06.235 E	ROT	>> 3.3°/min	COG	163.9 °	Setup	NORTH UP	Wind	30.0 kn	Time	18:15:22	VRM	00.0 NM

Dynamic Prediction Setup

Range: 4 Minute(s)

Interval: 60 Second(s)

☐ Track ☑ Shape(s)

☑ Static Path Prediction

SPEED Bow 1.69 kn, 6.40 kn, Stern 1.22 kn

Engine(s)-Rudder(s)-Thruster(s)

Thruster1 << 80%

Thruster2 << 80%

-60	37	100	100	37	70
EOT	RPM	pitch	pitch	RPM	EOT

Thruster3 >> 80%

Thruster4 >> 80%

0° 0°

<< 35° Rudder << 35°

PORT STB

List of Manoeuvring Points

MP	Seg.Time	EOT I	EOT II	Rud I	Rud II	SyncEOT	SyncRud	B.Thr I	B.Thr II	St.Thr III	St.Thr IV	Wind(dir)	Wind(speed)	Curr(dir)	Curr(speed)	Waterdept
1	254	-60	70	-30	-30	0	1	-80	-80	80	80	61	30	0	0	100
2	163	60	60	20	20	0	1	40	40	-60	-60	61	30	0	0	100
3	431	60	-50	5	5	0	1	0	0	0	0	61	30	0	0	100

Time remaining to MP 2
232 sec
Step one MP fwd/back < >

FTS Training

File Tools Info

Ship Data

Length: 252
Beam: 37,8
Rudder: 2
Prop.: 2
Bow Thr.: 2
St. Thr.: 2

Nav.-Data
Lat.: 54 ° 09,765 ' N
Lon.: 012 ° 06,235 ' E
speed (SOG) [kn] 6,6
heading [°] 149,7
course (COG) [°] 163,9

AIDAblu (1042_34_ThruW
no init
Start

☑ Sea Mode ☐ Crash Stop
☐ Manoeuvre Mode

Bow Thrusters
Lever 1 Thrs: I II
☑ I [%] -80 0 ☑ II [%] -80 0

☐ Sync. Engine Order Telegraph(s) I [%] II [%]
Cmd. -60, 37 RPM Actual
Cmd. 70, 37 RPM Actual

☑ Sync. Rudder(s) I [±70°] II [±70°]
-35,0 0 -35,0 0

Stern Thrusters
Lever 2 Thrs: III IV
☑ III [%] 80 0 ☑ IV [%] 80 0

wind absolute: from dir. 61,0 [deg] speed 30,00 [kn]
current: set in dir. 0,0 [deg] speed 0,00 [kn] depth 100,0 [m]

Total Time of Manoeuvre Plan:
1144sec = 19min 4sec

18:12:45 2222 148

Link MT EXIT RANGE: 0.50 NM CURSOR: 54 09.510 N 012 05.131 E 248.5° 0.7 NM

Fig.16: SAMMON Trail & Training Tool: Real time simulation and Manoeuvring Prediction integrated into ECDIS with comparison of full dynamic predictions (dotted ship contours) and the simple static prediction (magenta curve) together with planned manoeuvring track (blue line) in (same in Monitoring Tool, except the handle panel))

In Fig.14 the scenario under wind is shown, the ship is just entering the turning area and starts to turn. The table on top of the ENC shows the manoeuvre control settings from the planning and the planned track is shown in blue colour.

4. Execution of exercise and debriefing with fast time simulation

4.1 Use of Simulation augmented support with SAMMON monitoring Tool in Ship Handling simulator

There are several ways to support the execution and debriefing by the FTS. The support during Execution of Exercise is depending on the degree on what the trainee is allowed to use the new manoeuvring prediction technology during the exercise run.

- On a low level the multiple dynamic prediction may be used to gradually let the student know on his potential options for using the controls as a means for good visualisation of quality of manoeuvres – this is only to support the learning process specifically as long as the new technology is not available on the conventional ships
- On the highest level the trainees can make full use of the dynamic prediction and the prepared manoeuvring plan as underlying concept to achieve the best fit with the plan and the exercise result. The full use of the prediction is increasing safety & effectiveness even for advanced trainees
- For instructors (and peer students) multiple dynamic predictions are always a great help because the chances for success of a trainee’s action can immediately be seen or the exercise could be stopped earlier if it is obvious that the trainee will fail.

In debriefing the fast time tools allow for an in-depth assessment of quality of manoeuvring results:

- Assessment of results by comparison with trainees own concept or optimised plan can be shown in the replay function of the Monitoring Tool which can be used with Multiple Prediction functionality; or more in detail within the SIMDAT tool where the time history of the trainees action can be shown graphically e.g. for rudder, thruster and engine activities
- Discussion of alternative manoeuvres at specific selected situations can be supported by the Design & Planning tool by loading any specific situation during the exercise run and to operate the manoeuvring handles differently.

During the exercise, it is possible to take advantage from the Multiple Prediction for the manoeuvres. In Fig.17 the setup is to be seen where the instructor or bring their laptop onto the simulator bridge (where the manoeuvring plan might have been developed), the prediction is controlled via the bridge handles. The same laptop with the Monitoring tool can also be placed at the instructor station.

Fig.17: Using Multiple Prediction in Simulator Training at MSTC of AIDA Cruises Rostock. Left: Portable Setup for Prediction Display in Monitoring Tool on Trainees Laptop on Bridge - the prediction is controlled by the Bridge Handle via WLAN. Right: Prediction Display in Debriefing session (left screen): The dynamic prediction can be used even during Fast Replay to complement the simulator instructor display (right screen)

The benefit of using the FTS is to be seen for several purposes:

- The multiple dynamic predictions shown on the instructors screen are always a great help for instructors and maybe also for peer students looking over their shoulders to learn from the actions of the other trainees in charge on the bridge. They have a better overview on the current situation and the chances for the potential success of a trainee's action can immediately be seen; the exercise could be stopped earlier if it is obvious that the trainee will fail.
- Multiple dynamic prediction may be used to gradually let the student know on his potential options for using the controls as a means for good visualisation of the quality of manoeuvres – this is to support the learning process specifically as long as the new technology is not available on the conventional ships.
- If the trainees are allowed to make full use of the dynamic prediction and also the prepared manoeuvring plan as underlying concept they achieve the best fit with the plan and the exercise result. The full use of the prediction is increasing safety & effectiveness even for advanced trainees and can support to find out the best performance.

4.2 Debriefing of Exercise and Comparison of results with Manoeuvring plan

Several methods of comparison exist for the debriefing after the training by using FTS software. Whilst in the Ship Handling Simulator (SHS) there is the possibility to additionally record the training session using the „Monitoring & Manoeuvring Module“, there's a correspondent option to save the training and planning procedure in the „Trial & Training“ as well as in the „Manoeuvre Design & Planning Modules“. All of the files from the planning and from the execution can be shown together in form of the ship track as well as in diagrams from several parameters over the whole manoeuvring time in the SIMDAT program. The following figures show some possible methods to display the results.

Fig.18 compares simulator results of the trainees with different level of preparation. The achievements of the better prepared trainee are obvious – the planned manoeuvre is very close to the executed track and the actions of the controls were nearly in accordance with the planned procedures. There is not just a reduction of manoeuvring time when applying the Fast Time Simulation tool in briefing and training; the thruster diagrams show also that a well prepared manoeuvre can minimize the use of propulsion units and therefore be more efficient. The great advantage of the Fast Time Simulation is the opportunity to discuss alternatives of manoeuvres and also effects and strategies for different environmental conditions, which might affect the ship unexpectedly at critical positions.

5. Conclusions / Outlook

Fast Time Manoeuvring simulation has proven its benefits for both lecturing and training for improving ship handling knowledge and skills. For the future, the great potential will be investigated to be involved into the real ship operation on-board. The majority of the participants in the ship handling courses expressed their opinion that the Design & Planning Module could be used for preparing berth plan on the ships. There is a high potential for optimisation to reduce manoeuvring time and fuel consumptions /emissions. It is also possible to use the potential of FTS for various analyses (e.g. fairway layout, accidents) to find measures to make shipping safer.

Acknowledgements

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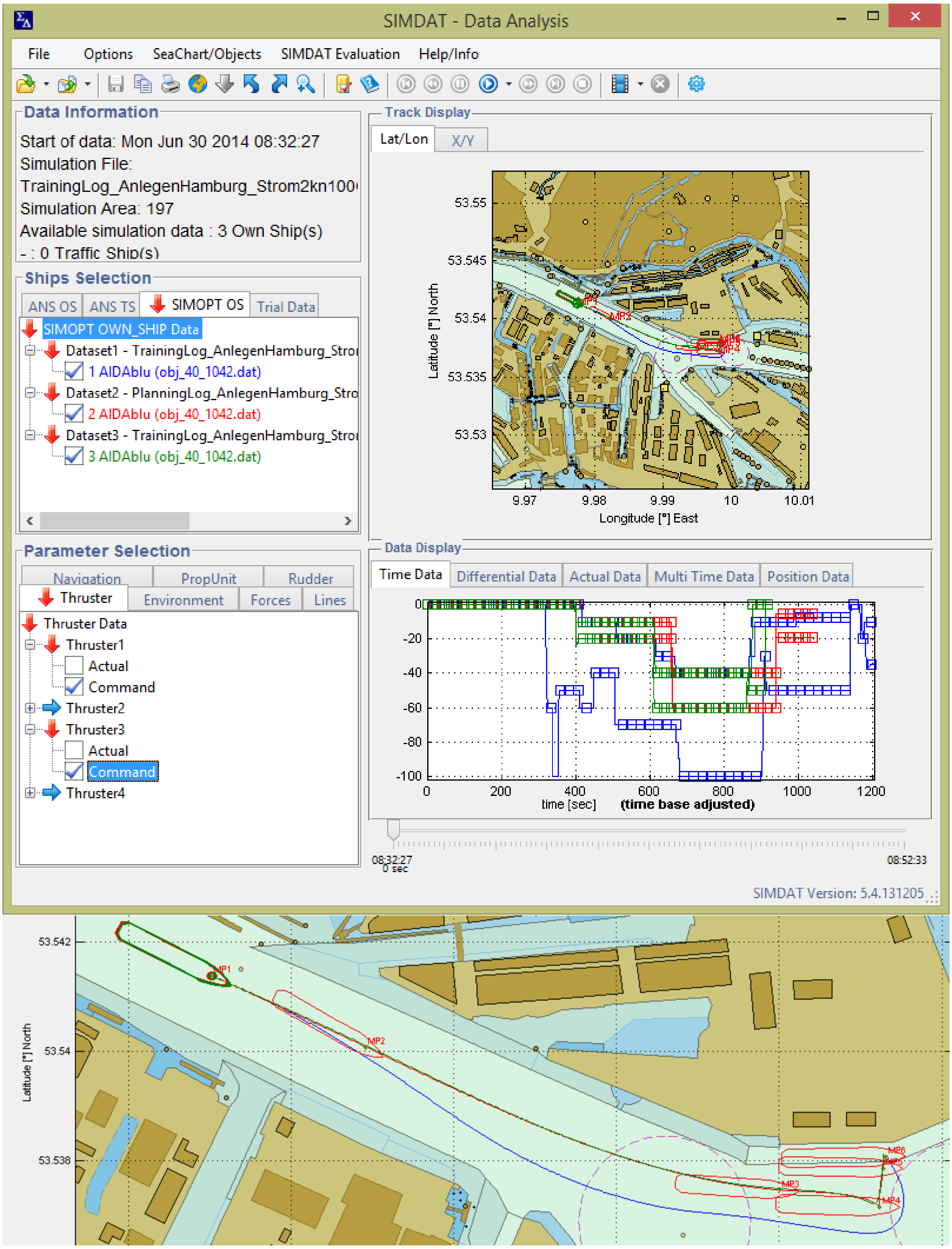

Start of data: Mon Jun 30 2014 08:32:27
Simulation File:
TrainingLog_AnlegenHamburg_Strom2kn100
Simulation Area: 197
Available simulation data : 3 Own Ship(s)
- : 0 Traffic Ship(s)

SIMOPT OWN_SHIP Data
Dataset1 - TrainingLog_AnlegenHamburg_Stro
☑ 1 AIDAblu (obj_40_1042.dat)
Dataset2 - PlanningLog_AnlegenHamburg_Stro
☑ 2 AIDAblu (obj_40_1042.dat)
Dataset3 - TrainingLog_AnlegenHamburg_Stro
☑ 3 AIDAblu (obj_40_1042.dat)

Thruster Data
Thruster1
☐ Actual
☑ Command
Thruster2
Thruster3
☐ Actual
☑ Command
Thruster4

SIMDAT Version: 5.4.131205

Fig.18: Results from two manoeuvring exercises in SIMDAT interface (Top: "Track Display" with contours; Below: "Data Display" for time history for thruster activities, Bottom: extract of sea chart from Track Display) and comparison to the prepared manoeuvring plan (below). Blue: run of the trainee without support by Fast Time Simulation; Green: run of the trainee with full support by pre-planning with Design and Planning Module; Red: prepared manoeuvring plan with manoeuvring points MP

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Path Planning of an Autonomous Surface Vehicle based on Artificial Potential Fields in a Real Time Marine Environment

Yogang Singh, **Sanjay Sharma, Robert Sutton, Daniel Hatton,** Plymouth University,
Plymouth/UK, yogang.singh@plymouth.ac.uk

Abstract

With growing advances in technology and the everyday dependence on oceans for resources, the role of unmanned marine vehicles has increased many a fold. Extensive operations having naval, civil and scientific applications are being undertaken and demands are being placed on them to increase their flexibility and adaptability. A key factor for such vehicles is the requirement for them to possess a path planning subsystem. Most path planning techniques are implemented in self-simulated environments. This study accounts for the use of artificial potential field in path planning of an autonomous surface vehicle (ASV) in a real time marine environment. Path cost, path length and computational time are described to ensure the effectiveness of the motion planning.

1. Introduction

Advanced electronic navigation has become an irreplaceable guide to navigate marine vehicles around the globe. A detailed classification of marine vehicles can be found in Fig.1. ASVs are marine vehicles having small displacement of less than 1 tonnes. An ASV has several applications from ocean surveying to military intelligence gathering which lead to the requirement of safe navigation through obstacles of various shapes and dimensions such as boat, shoreline and docks. These applications require reactive computation of the path based on the rapidly changing conditions.

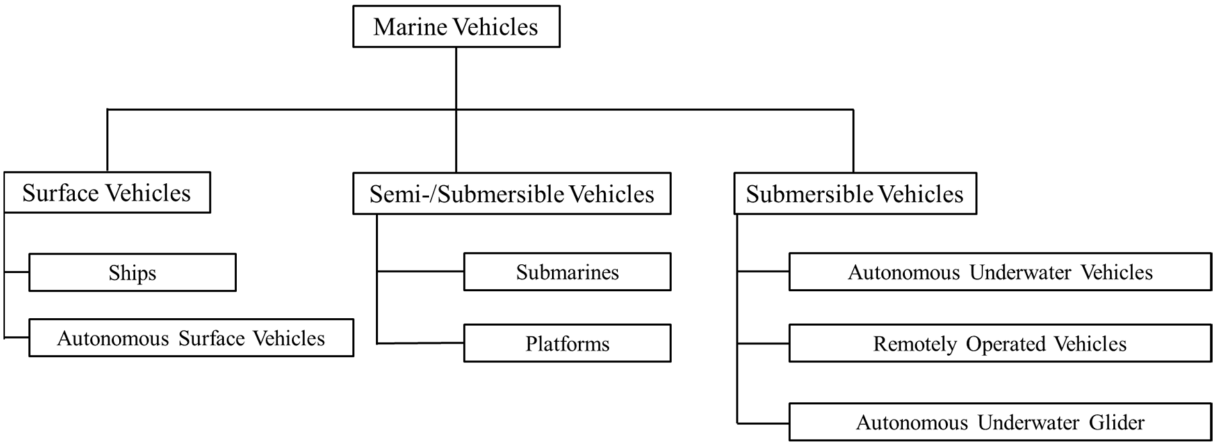


Fig.1: Classification of marine vehicles, *El Hawary (2008)*

A variety of approaches have been developed and applied in marine navigation in recent years. In ASV navigation, there are two kinds of path planning approaches adopted, namely, reactive and deliberative. Reactive approaches are used where the environment is partially unknown while deliberative approaches are used where the marine environment is completely known. The classification of reactive and deliberative approaches can be seen in Fig.2. In this paper, an effort has been to use a reactive approach, namely, an artificial potential field (APF) approach in the path planning of an ASV in a practical marine environment. The main scholarly outcome of this study is to understand the effectiveness of the performance of a reactive approach in a practical marine environment in terms of path length, path cost and computational time. Until now, such approaches have been tested in self-simulated environment. This study makes an effort in direction of developing a reliable path planner which can cope with real time constraints of an ASV.

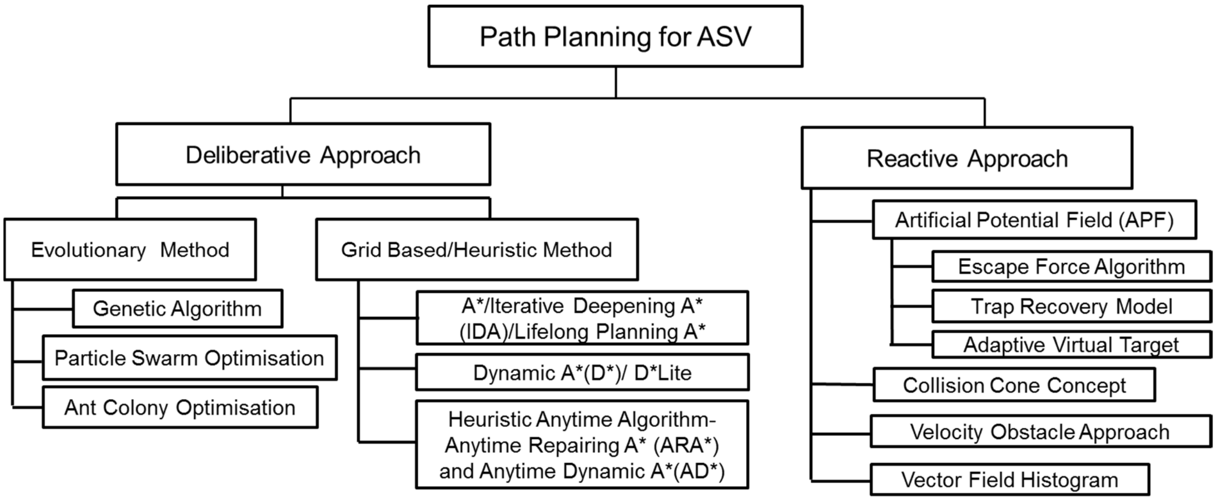


Fig.2: Path planning approaches for an ASV

The plan of the paper is as follows. Section one gives an introduction to the ASV path planning and the major outcome of the present study is outlined. Section two gives an overview of the literature pertaining to APFs in path planning of mobile and marine robots. Section three provides a brief overview of the APF and discussion pertaining to its applicability within the stated problem of ASV path planning. Section four presents the results of the ASV navigation using an APF approach. Conclusions and future work of the study are presented in the final section.

2. Literature Review

In robotics, various reactive approaches such as Collision Cone Concept, *Chakravarthy and Ghose (1998)*, Velocity Obstacle Approach, *Fiorini and Shiller (1998)*, Vector Field Histogram, *Borenstein and Koren (1991)*, and APF, *Khatib (1986)*, have been proposed. As most of the robotics problem is real time, the need to have a very fast and simple motion planner is evident. The simplicity enables fast development and deployment of a robot, whereas the computationally inexpensive nature allows the algorithm to be implemented in robots with minimum sensing capabilities. APF is one of the simplest methods, and the method is capable of autonomously moving a robot in realistic obstacle framework.

After APF was introduced by *Khatib (1986)*, many researchers have attempted to improve the APF, which suffers from trap situation in local minima, oscillations in narrow passage and goals non-reachable with obstacles nearby (GNRON), *Koren and Borenstein (1991)*. *Ge and Cui (2002)* included velocity terms for target and obstacles within APF to compute potential to correct the problem of GNRON. *Baxter et al. (2007,2009)* used APF for multiple robots in order to correct the sensor errors. *Tu and Baltes (2006)* used a fuzzy approach within APF to solve the problem of oscillations within narrow passage. *Fahimi et al. (2009)* used the concept of fluid dynamics within APF to correct the issue of a trapped situation in local minima.

Until now in the literature, very few studies associated with the path planning of ASV have made use of the APF in a practical marine environment. Most of these studies have been conducted in self-simulated environment. The present paper makes an effort to understand the effectiveness of APF in path planning of ASV in a practical marine environment.

3. APF: Concept and Methodology

APF solves the problem assuming all obstacles are a source of repulsive potential, with the potential inversely proportional to the distance of a robot from the obstacle while the goal attracts it by applying an attractive potential, *Kala (2016)*. The derivative of the potential gives the value of the virtual force applied on the robot, based on its movement, *Kala (2016)*. The motion is completely reactive in nature. A schematic of the APF is shown in Fig.3.

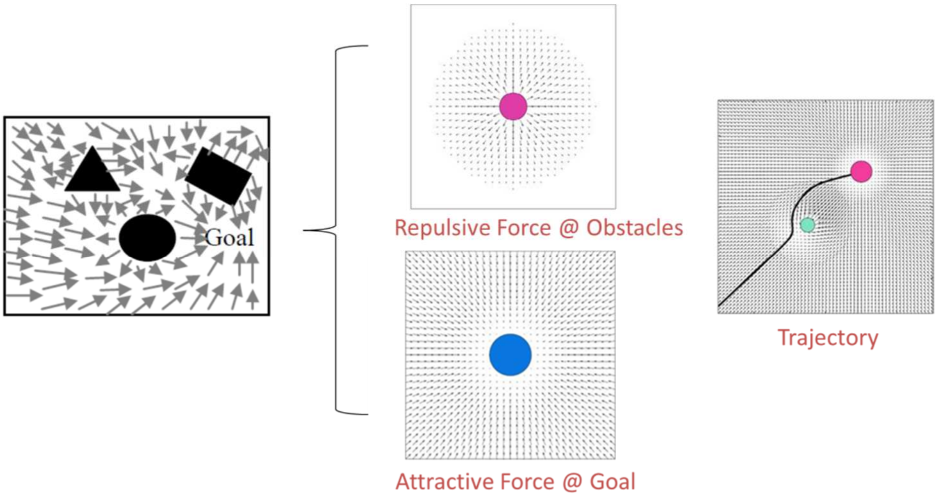


Fig.3: Schematic of the APF

3.1 Attractive Potential

The attractive potential is applied by a single goal to direct the robot towards itself. The attractive potential is directly proportional to the distance between the current position of the robot and the goal. This causes the potential to tend to zero as the robot approaches the goal and hence it slows down as it approaches the goal (*Kala (2016)*). The potential in this study is taken as, quadratic potential, represented in Eq. (1)

$$U_{att}(x) = \frac{1}{2} k_{att} \left\| x - G \right\|^2 \tag{1}$$

where x is the current position of the robot and G is the goal. $\|.\|$ is the Euclidean distance function and k_{att} is the proportionality constant, whereas the degree is taken as 2.

The driving force is a vector whose magnitude is measured through the derivative of the potential function and direction as the line which maximizes the change in potential, which is given by Eq. (2)

$$\begin{aligned} F_{att}(x) &= \nabla U_{att}(x) = k_{att} \left\| x - G \right\| . u(x - G) \\ &= k_{att} \left\| x - G \right\| \frac{(x - G)}{\left\| x - G \right\|} \\ &= k_{att}(x - G) \end{aligned} \tag{2}$$

u() is the unit vector.

3.2 Repulsive Potential

The repulsive potential is applied by obstacles which repel the robot coming close and repelling it to avoid collision. The potential is inversely proportional to the distance so that potential tends to infinity if robot comes near obstacle leading to repulsion. Obstacles at a certain distance d^* are considered in modeling the potential, *Kala (2016)*.

The repulsive potential is given by Eq. (3).

$$U_{rep}(x)=\begin{cases}\frac{1}{2}k_{rep}\left(\frac{1}{\|x-o_i\|}-\frac{1}{d^*}\right)^2 & if\ \|x-o_i\|>d^* \\ 0 & if\ \|x-o_i\|\le d^*\end{cases} \tag{3}$$

Where, x is the current distance of the robot and o_i is the position of the obstacle. $\|.\|$ is the Euclidian distance function and k_{rep} is the proportionality constant, whereas the degree is taken as 2.

The repulsive force is given by Eq. (4), which is a derivative of the repulsive potential

$$\begin{aligned}F_{rep}(x)&=\nabla U_{rep}(x)=-k_{rep}\left(\frac{1}{\|x-o_i\|}-\frac{1}{d^*}\right)\frac{1}{\|x-o_i\|^2}u(x-o_i)\\&=-k_{rep}\left(\frac{1}{\|x-o_i\|}-\frac{1}{d^*}\right)\frac{1}{\|x-o_i\|^2}\frac{(x-o_i)}{\|x-o_i\|}\\&=-k_{rep}\left(\frac{1}{\|x-o_i\|}-\frac{1}{d^*}\right)\frac{(x-o_i)}{\|x-o_i\|^3}\end{aligned} \tag{4}$$

where, *u()* is the unit vector.

3.3 Resultant Potential

The resultant potential is given by sum of attractive and repulsive potential. This final force is henceforth, the derivative of the resultant potential. This is given in Eq. (5).

$$\begin{aligned}U&=U_{att}+U_{rep}\\F&=\nabla U=\nabla U_{att}+\nabla U_{rep}=F_{att}+F_{rep}\end{aligned} \tag{5}$$

3.4 Methodology

In the present study, APF is used for ASV navigation within a practical marine environment i.e. Portsmouth Harbour having a start and goal point as shown in Fig.4.

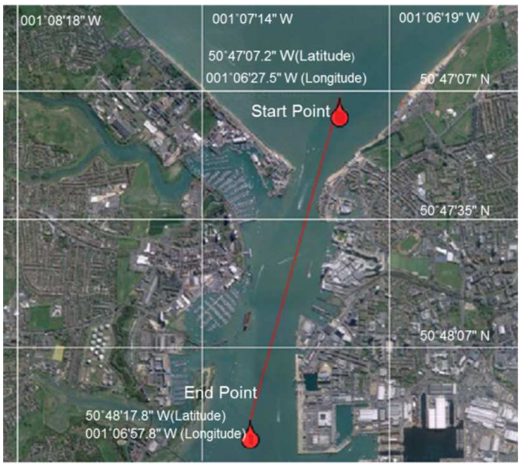


Fig.4: Simulation area- Portsmouth Harbour, *Google Maps*

A binary map of 800 x 800 pixel grid resolution, Fig.5, is taken into account with a ASV available from Plymouth University named, *Springer*, being considered in terms of kinematic constraints for the purpose of path planning. Parameters used in APF for path planning of *Springer* are shown in Table I. *Springer* is shown in Fig.6.

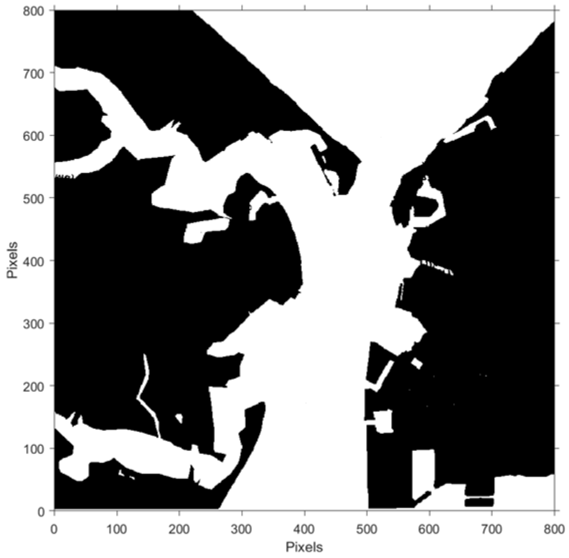


Fig.5: Binary map of the simulation area (1 Pixel = 3.6 m)

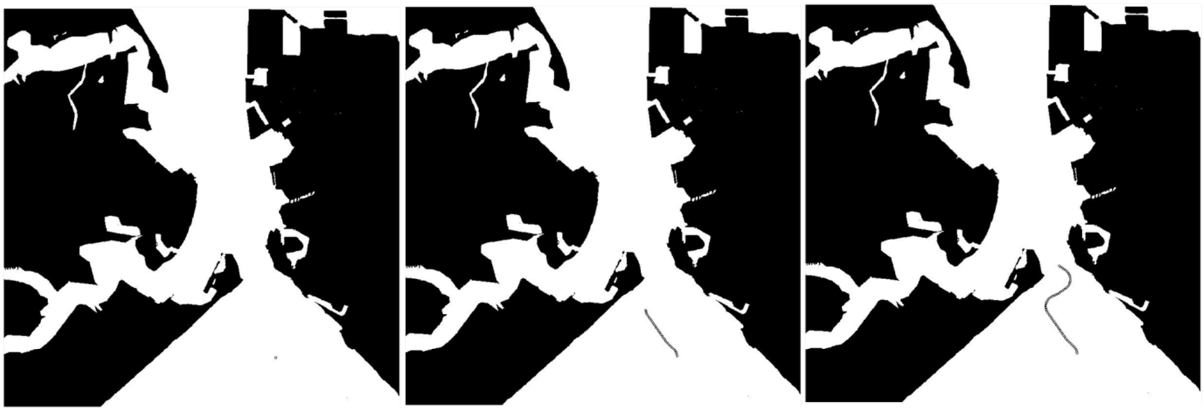
Table I: Parameters used in APF for path planning of *Springer*

Parameters	Values
Attractive Potential Scaling Factor (k_{att})	300000
Repulsive Potential Scaling Factor (k_{rep})	300000
ASV Size	4 m (Length); 2.3 m (Breadth) [Size of *Springer*]
ASV Speed	4 m/s [Maximum speed of *Springer*]
Safety Distance from Obstacles (d^*)	30 pixels
Maximum Turn Rate	10 pi/180°
Initial Heading of ASV	-pi/2

Fig.6: The *Springer* ASV

4. Results

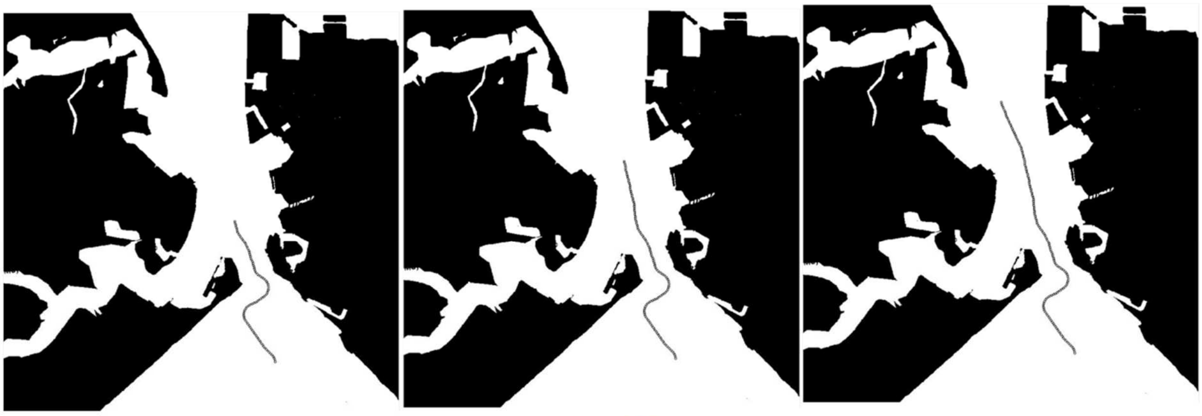
Evaluation of the APF performance for ASV path planning in terms of path length, path cost and computational time is described in Table II. Simulation records movement sequences of the ASV within map. Fig.7 shows the sequence of ASV motion from start to goal point at different time of the motion. The overall trajectory shows that such algorithm is efficient in generating safe path for ASV in a practical marine environment.



t = 0s (@Start Point)

t = 30s

t = 60s



t = 90s

t = 120s

t = 150s

t = 186s (@End Point)

Fig.7: Sequence of ASV motion from start to end point

Table II shows that ASV is able to find a safe trajectory of length 3075 m within 32.608 s which means, less than 1 s is required by ASV to find a path of 1m. Thus a that real time implementation of such algorithm is possible within a practical marine environment. Since the APF is a parameter dependent algorithm, there is a need to find right set of parameters for different case scenarios.

Table II: Performance of APF in *Springer* navigation

Parameters	**Value**
Path Length	3.075 Km
Path Cost (1 Pixel = £20)	854.315 Pixels
CPU Time	32.608 s

5. Conclusions and future work

The paper introduced and discussed APF algorithm for ASV path planning in a practical marine environment. The algorithm is found robust in terms of computational time and real time implementation in a static environment and can be extended in a dynamic environment. Furthermore, international collision avoidance regulation COLREGs can be incorporated within the algorithm to make it suitable for maritime manoeuvring.

APF and its several variants have been widely implemented in path planning of mobile robotics for safe navigation. Although, conventional APF is prone to several disadvantages but recent variants of APF take care of those infelicities. For future work, this can be extended towards navigation of multiple ASVs. This will help in increasing autonomy of ASVs, which is the goal of the future research in ASV navigation.

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Physical Testbed for Highly Automated and Autonomous Vessels

Marius Brinkmann, University of Oldenburg, Germany, marius.brinkmann@uni-oldenburg.de
Axel Hahn, University of Oldenburg, Germany, axel.hahn@uni-oldenburg.de
Bjørn Åge Hjøllo, Navtor AS, Norway, bjorn.hjollo@navtor.com

Abstract

Technology is changing the way of transportation. Thus, the development of new safety-critical driving systems increases the complexity of testing. To facilitate these efforts, suitable engineering and safety/risk assessment methods are required. The maritime physical testbed LABSKAUS implements components such as a research vessel, sensor infrastructure and a reference waterway. This paper describes methods to support the development of new e-Navigation technologies by verification and validation. It gives an overview on the requirements based on the conceptual architecture for driving and reflects current maritime testbeds. Concepts and components of LABSKAUS are presented and evaluated by testing a shore-based bridge.

1. Introduction

Maritime research facilities and industries started developing highly automated and autonomous maritime systems (e. g. autopilots) to provide solutions for the present and future challenges to make seafaring more efficient, safer and sustainable. Based on upcoming technologies or strategies for an optimized information exchange between ship and shore as well as a safe voyage from berth to berth, the (civil) maritime transportation sector faces a time of change to meet the increasing demands of the global logistic processes. For example, *NN (2012)* reports that more than 75% of all worldwide maritime accidents are caused by human factor. Next to the safety argumentation, governmental sustainability plans such as the Paris Agreement establish universal bindings for a global climate deal to reduce emissions, http://ec.europa.eu/clima/policies/international/negotiations/paris_en. There is evidence of a trend towards developing high automated vessel assistance systems with an outlook for the future describing autonomous seafaring to achieve these aims of increased safety and environmental sustainability.

As seen from a technical perspective, the development of automation technology for shipping (as well as other transportation types) involves various disciplines. Components such as sensors, actuators, software and the communication infrastructure technologies form a maritime cyber-physical system (mCPS) that is necessary to enable the development of highly automated and autonomous shipping. While autonomous shipping may affect (human) errors and critical situations, it is a safety-critical issue and needs to follow overarching functional safety related rules. Understanding maritime transportation as a sociotechnical (human and machine) system allows the usage of system-engineering methods. There is the need for a holistic testing approach to consider the sociotechnical system in its environment containing technology, processes, human factors and regulations. Today’s certification tests verify functional properties according to conformance standards (e.g. the range of navigational lights, correct data by AIS system). This does not last for intelligent assistance systems which must evaluate complex situations.

The development of safety-critical systems such as highly-automated and autonomous vessel brings the need to establish a test environment (or ‘testbed’) close to the real world in addition to simulative test environments. New systems can be tested in simulations. Simulators enable the replication of real-life conditions for systems like bridge simulators such as the Korean in Mokpo or big scaled environment planning/control algorithms like the Maritime Traffic Simulator, *Hahn (2015)*. Nevertheless, a prototype must be validated regarding its functionality within a real physical environment to prove the concept for real-life applications. For the evaluation of intelligent assistance systems, a testbed can provide complex maritime situations to analyse the behaviour of the whole system “vessel” considering the components and subsystems.

2. Architecture of Highly Automated and Autonomous Vessels

In the automotive domain, research considering the automation of driving functions has been present since decades. Thus, since 1982 a model describing the aspects of the driver vehicle system has been developed and is described in the following as an adaption for the maritime domain. Fig.1 illustrates the three-layered approach to model driver tasks that builds the basis for highly automated and autonomous driving systems. Despite differences of the maritime domain and the automotive domain such as the criticality of systems or the communication infrastructure, there are common characteristics and the architecture for a cooperative transportation system is similar. In the maritime domain, a common understanding on the architecture of driving does not exist. By using the three-layered approach in Fig.1, which is widely accepted in the automotive domain, there is an adaption possibility for the maritime domain. On this basis, the presented work uses the approach and describes a maritime testbed supporting the test of systems providing functionality on the different levels.

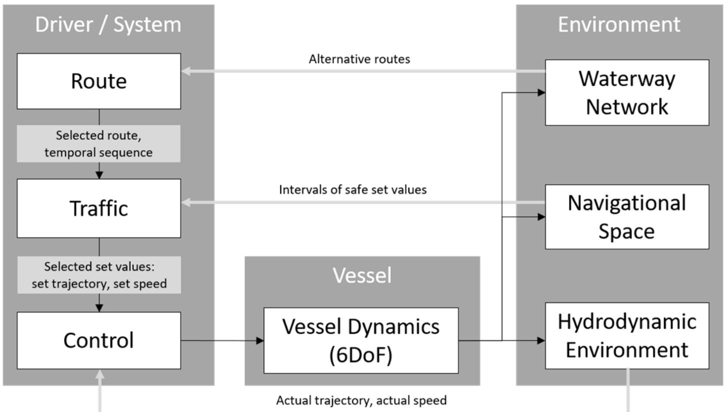

Fig.1: Three-layered approach for driving a vessel

At the highest layer, there is a route component that realises finding and modifying routes based on the waterway network regarding different aspects that determine a good, better or the best route. Going down the three-layered approach, the current traffic situation and limitations such as tide are focused. For this purpose, intervals of safe set values are given to the traffic component to react to the current navigational situation. The lowest layer represents the direct reaction on deviations from the expected state based on the driving surface, e. g. the current trajectory or speed. A testbed for V+V must address the following layers of driving a vessel, Fig.1, to support the testing: navigation, guidance and control. Therefore, the testbed must bring data of the environment necessary for the particular layer. For the navigation layer, the testbed must provide data and information related to the waterway network, e. g. sea lanes or water depth. The guidance layer requires data on the current traffic situation, such as vessels in vicinity or navigational space. The lowest control layer sends commands to the vessel and therefore needs information on the driving surface (water current, waves) to set values such as speed or rudder angle, *Hagn et al. (2016)*.

Beside these functional aspects on steering a vessel, technical aspects that have impact on highly automated and autonomous maritime transportation need to be regarded when designing the testbed. Simplified, in the context of these CPS, there are incoming sensor data that are processed by the system under test and commands that are sent to the actuators. This shortened perspective is also characterised by the components (boxes) and information flows (arrows) in Fig.1. In order to create a highly automated and autonomous vessel, design decisions regarding sensor data fusion, vessel control algorithms and restrictions of communication technology must be addressed. Various sensors such as radio detection and ranging (RADAR), Automatic Identification System (AIS), light detection and ranging (LIDAR) or visual cameras deliver the surveillance information on the environment of a vessel. Sensors such as Global Positioning System (GPS) and Inertial Measurement Unit (IMU) are involved for example to increase the reliability of a vessel's position. For example, the creation of a map with static and dynamic content as well as the prediction of traffic and weather information is a prior function for highly automated/autonomous vessels and therefore the testbed needs to support this by providing data of the environment, *DNV GL (2015)*. Raw data of the sensors described before need to be analysed by components of the automation system based on the layers of Fig.1 to react to a given situation in an automated way. Therefore, those sensors cannot be interpreted in an isolated way but need intelligent data fusion mechanisms to create the perception that a human being has semantically interpreted by his senses in the past. As can be seen in Fig.1, a main requirement for the testbed is to provide the needed data of the environment according to the layer of driving.

For autonomous shipping, an additional challenging circumstance is the communication infrastructure connecting ship and shore. While reliable and area-wide broadband for automotive is not such a big deal, much ocean-based areas are not covered by IP-based communication infrastructure, *Hanhn et al. (2016)*. Driven by the industry, Inmarsat started the initiative called Global Xpress that will deliver globally available, reliable and seamless high-speed broadband and therefore build the basis for internet-based navigation, *IMO (2014)*. This step enables the global IP-based communication of distributed CPS. A continuously surveillance of the self-driving ship from a shore-based station is mandatory. Changes in route and course must be shared. Nevertheless, a stable communication link during a voyage berth-to-berth cannot be guaranteed now in all international waters with the existing communication infrastructure on board, ashore and via satellite, not even with reduced payload. Thus, safety mechanisms should be established that can be used to go in a safe state in the case of an absence of the connection. These safety mechanisms care possibly an emergency stop button or directly remotely control of the vessel based on another communication link, e. g. very high frequency (VHF).

3. Maritime Testbeds

A testbed is an environment in which systems can be evaluated using test methods in realistic simulative and/or real physical scenario. The identified test cases in the form of scenarios are realised with the help of a testbed and the results of the prototypes' behaviour analysed, *Drolia et al. (2011)*. The testbed enables the observation of a system to be tested in a controlled environment. The environment is influenced by various inputs and physical conditions, whereupon objects are observed, investigated and adapted, *Akyildiz et al. (2008)*. The International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA), which is particularly known for the standardisation of sea marks, provides an overview of existing maritime testbeds, a definition of the testbed term and considerations when planning a testbed, http://www.iala-aism.org/products-projects/e-navigation/test-bedsprojects/. In this domain-specific context, a testbed is seen as a controllable infrastructure for the testing of development projects. It is characterised by the attributes of precise, transparent and repeatable. A testbed should not be limited or restricted by special architectures, data structures or existing processes and should involve the actors in the planning, execution and assessment of the testbed.

Maritime Testbeds are used for the V+V of prototypes for the automation of vessels. Therefore, many maritime projects have developed physical testbeds in sea areas for the evaluation of specific technologies, e.g. the North Sea (ACCSEAS), Baltic Sea (EfficienSea, MonaLisa), Adriatic (ARIAD-NA), Ionian Sea (IONO), straits of Malacca (SESAME Straits) and Japan (SSAP). As *Hahn (2015)* stated, these testbeds are specialised to individual use cases. Most of them want to improve planning and coordination of ship movements as well as increase the safety on sea by implementing a specific e-Navigation scenario. From our perspective, a testbed should be designed for general use and not be limited to a specific use case. Referring to the architectural requirements described in chapter 2 for highly-automated and autonomous driving, the existing testbeds cover only a few sub-aspects in a realisation-dependent way. The definition of 'demonstration' is far more appropriate for the efforts of many maritime testbeds. The goal of the presented approach is to provide an open and adaptable generic testbed for multiple reuse in different present and future maritime scenarios.

Generic testbeds are another approach for testing new technologies: Reusable and configurable. Concepts from the automotive industry like the Application platform for Intelligent Mobility (AIM) build an orientation. AIM is a component based testbed for land traffic, *Schnieder and Krenkel (2015)*. It has mobile components like a car fleet or structural components like a research crossway, research railway crossing or reference way Car2X. It also offers driving or virtual reality simulators. These components are test carrier for new technologies. The data gathered can be used later for simulations or other research. If a new traffic observation or management requires a testbed, it can be implemented in the AIM testbed. The virtual reality laboratory is built around a modular mock-up car which allows the integration of new driver assistance systems. This scenario allows evaluating in a static environment. The target of AIM is to be a versatile test environment for broad diversity of land transportation technologies. A major contribution to the previously described scope is a maritime testbed architecture which can realise the previously described requirements of the highly automated and autonomous driving functionality for the maritime domain. This paper describes a similar approach for the maritime domain.

4. Integrated Testbed

4.1 Supporting the Development Process

In this chapter, the approach of a seamless testing environment considering various test methods for the whole development lifecycle will be presented. Since physical testing on rough sea is very costly and complex, the main part of testing is carried out in virtual simulation environments. Nevertheless, virtual tests must be supplemented by tests in the real world. Fig.2 illustrates the holistic perspective on the development process from early stages of requirement engineering to a real physical usage. Each of the development processes can be supported by either virtual and/or physical testbeds. Depending on the respective development process, different test methods are provided for a seamless testing, such as maritime traffic simulations for virtual testing or a mobile bridge and a research vessel for physical testing.

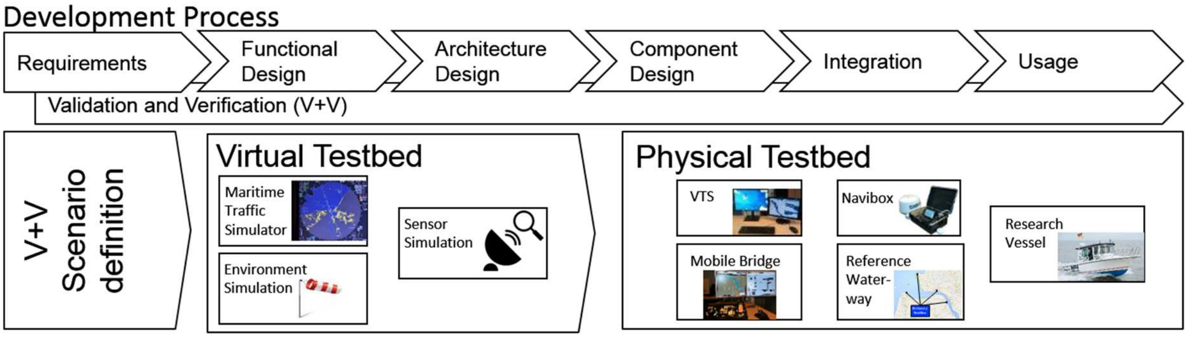

Fig.2: Supporting the Development Process by Testbeds

Firstly, V+V scenario definitions are created on the basis of requirements. When developing safety-critical systems such as highly automated and autonomous driving systems, well established development processes based on a methodological approach are used. Therefore, the key international standard IEC 61508 (Functional safety of electrical, electronic and programmable electronic (E/E/PE) safety-related systems) has been adapted by many industrial sectors as a guideline for development. As an example of the automotive sector, the ISO 26262 ("Road vehicles – functional safety") is an adaption of the IEC 61508 and had hit the light as a draft in 2009. The ISO 17894 ("Ships and marine technology – General principles for the development and use of programmable electronic systems in marine applications") adapts the standard and others for the maritime domain. The IEC 61508 and thus all adaptions focus on safety requirements, hazard analysis, adequate V+V methods and risk assessment. Therefore, the V+V scenario definition based on information of the early requirements and conceptual development process phase is mandatory for a testbed.

A virtual testbed providing complex simulation environments supports the early testing of new maritime technologies. Along the development process, a seamless transfer of the simulated tested technologies into the physical testbed takes place. By using the physical testbed, a real-world assessment can be performed. Depending on the development process, the integrated approach provides elaborated environments for Model in the Loop, Software in the Loop and Hardware in the Loop (MIL, SIL, HIL) testing by providing components such as the maritime traffic simulator for SIL or a research vessel in a reference waterway prototype demonstration, *Hahn (2015)*. This paper mainly addresses the physical testbed, therefore more information on the virtual testbed can be found in *Schweigert et al. (2014)*. In the following, an implementation of the integrated testbed will be presented starting with a description of the components of the testbed.

4.2 Physical Testbed Components

The IALA registered test platform eMIR combines a virtual and physical maritime testbed. The testbed LABSKAUS is the physical part of eMIR and located in the German Bight. Moreover, some components are transportable and can be located everywhere. LABSKAUS covers ship and shore side components and aims to build a basis for testing different functional layers of automation of a vessel according to the requirements described in chapter 2. Addressing all layers of the three-layered approach for driving, systems for various levels of automation such as remote control, remote action planning and finally fully autonomous driving can be tested. Furthermore, the testbed covers Human Machine Interface (HMI) analysis components such as a mobile bridge equipment for testing electronic chart display and information systems (ECDIS) and Integrated Navigation Systems (INS) software on shore and on sea. LABSKAUS can be used for empirical study of maritime automation systems, validation and demonstration of existing systems. In the following paragraphs, all existing components will be described.

- **Reference Waterway -** The Reference Waterway covers the Elbe and Kiel Canal Approach near Brunsbüttel and Elbe estuary around Cuxhaven in Germany. It covers a basic maritime surveillance infrastructure (including AIS, Radar, cameras) and broad band communication via LTE, illustrated in Fig.3. The Reference Waterway is used as an experimental platform and for demonstration of new technologies by offering an observable area for prototype evaluation. Additional, the sensor infrastructure is used for setting up a database with travel pattern and near collisions that can be used as data source for virtual testing. The Reference Waterway can be individually expanded with autarkic stations. Additionally, two AIS receivers are connected to two antennas on top of a building of the Jade University of Applied Sciences in Wilhelmshaven, Germany. Under good conditions they can cover Wilhelmshaven, Bremerhaven till Cuxhaven and the East Frisian Isles till Helgoland to enhance the Reference Waterway. Fig.4 (left) radar and AIS tracks gathered from the sensor infrastructure in Cuxhaven. Fig.4 (right) shows the range of AIS targets of the LABSKAUS infrastructure

Fig.3: Sensor infrastructure of the Reference Waterway

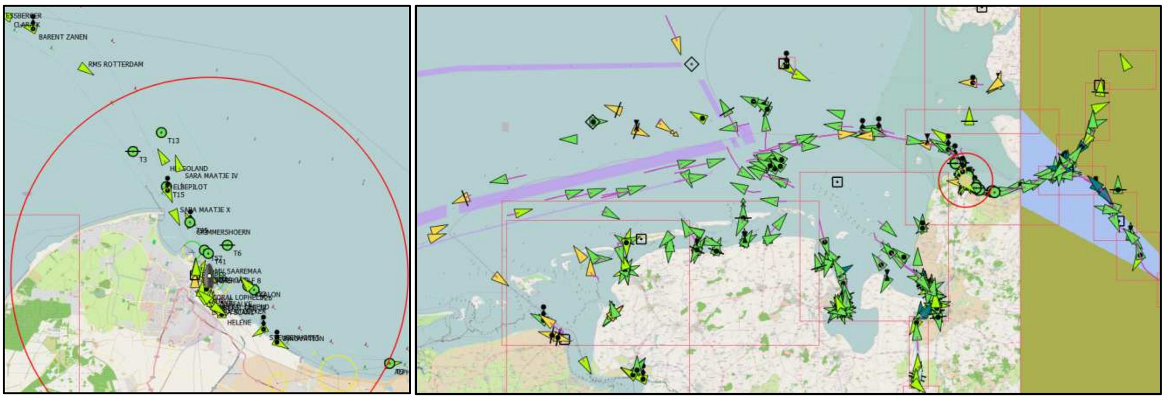

Fig.4: Control centre of the reference waterway (23.02.2016, 10:45)

The main objective of the Reference Waterway is to provide a completely sensor-covered area. This area is monitored and the communication technology allows the data exchange between the components of the testbed and surveillance technology for data gathering.

- **Maritime Control Station -** An experimental Vessel Traffic Service (VTS) system by Signalis enriches the evaluation functionality of LABSKAUS. VTS is an electronic monitoring system for surveillance and, where necessary, the control of ship traffic in a specific area. The VTS uses radar monitoring, VHF radio, AIS data as well as video surveillance of certain areas such as ports. Though it is a mobile unit, it is usually stationed at the Maritime Research Center in Elsfleth. The VTS system represents the onshore area of the HMI components. It can be connected to the reference waterway as well as to a virtual environment for the representation of such a system in the testbed. The VTS is mainly used for HMI research applications to improve the current state-of-the-art designs and new e-Navigation technologies. Especially automated services based on rich databases are interesting research areas of the future, e. g. automatic announcements via radio or integrated information systems on a vessel to the current environmental situation.

- **Research Vessel -** On seaside, the testbed includes the research vessel ZUSE which got modified to act as a highly adaptable vehicle for validation and verification of automated and autonomous technology, e. g. trajectory controller or situational awareness systems. The research vessel ZUSE is fit for high-sea and fully equipped with sensors or actuator control interfaces for the rudder and engine. It provides surveillance information from the environment in vicinity. Beside this, we have a LTE interface that can be used by a prototype to send data to other systems for further monitoring or processing. To better classify and structure the large number of ship sensors in the context of shipping, a classification into movement sensors, environmental sensors and internal ship sensors takes place. This classification should cover all relevant marine sensors.
    - Movement Sensors: Positioning: Compass, Differential Global Positioning System (DGPS); Speed and acceleration: DGPS, Log; Pounding/roll angle and lift: Inertial Measurement Unit (IMU)
    - Environmental Sensors: Above water: Radar, Lidar, video camera; Under water: Echolot, Microphones (acoustic analysis)
    - Internal Ship Sensors: Electronic Control Unit (ECU) for engine information, rudder angle indicator

- **Mobile Bridge -** For the evaluation of bridge component including the HMI, LABSKAUS provides a versatile mobile bridge. Three boxes that are containing computers and two multi-touch displays can be connected to each other and act as an integrated ship bridge system. The mobile bridge provides the Raytheon Integrated Bridge in its standard configuration (other software is optional) and an open source bridge software system. It is linked to eMIR components which provide the required navigational data, such as compass, GPS, AIS, log, lot, radar as well as a broad band of communication systems. The mobile box can be split to allow using it in small spaces, e.g. on a ship. The mobile bridge system allows setting up an experimental bridge on board without interfering with the vessels navigation systems because it collects data from the sensor box or can be used with a virtual testbed as shown in Fig.5. The mobile bridge can use simulated data and later real world data of the reference waterway. In the last step, it can be used on ship in combination with the mobile sensorbox for the fully integrated development. It enables ship steering in conditions which allow to control a ship, e.g. to put the rudder. In addition, it allows the analysis of new human-centred designs for information displays and controls.

Fig.5: Mobile Bridge in the Virtual Testbed

- **E-Navigation Prototype Display -** The testbed for automated vessels contains a ECDIS like ship side application. An ECDIS is a navigation information system that combines data from different navigation sensors and electronic navigational charts. This allows the ECDIS like graphical user interface to display information about the environmental surveillance. For example, the data sources are DGPS, radar, sound navigation and ranging (SONAR), sea charts or electronic navigation cards (ENC) and vessel specific information. By combining various data sources, the system can determine additional information and, for example, dynamically notify by warning messages. For example, if the depth of the vessel is stored, an ECDIS can reconcile this information with the sea charts and use the route to check whether the vessel can pass through this location or not. Beside the ship side ECDIS like application, there is also a VTS like shore side application. The application is called e-Navigation Prototype Display (EPD) and was initially developed by the Danish Maritime Authority. The further development of the EPD will be task of the German institute for computer science OFFIS since 2016. The EPD provides a laboratory platform of an ECDIS like application to demonstrate potential new navigation technologies. There exists an EPD ship and EPD shore that contains sea charts, sensor integration and information visualisation functionalities. The EPD ship acts as a navigation instrument on board of a vessel, whereas the EPD shore provides surveillance abilities for multiple areas in parallel.

4.3 Testbed Architecture

This chapter describes the architecture that represents the design and interfaces of the previously described components of the physical testbed. A realisation of the testbed architecture allows the integration of current and future systems, considering various interoperability levels regarding regulations, processes and technological specifications. The testbed architecture allows the provision of complex maritime situations for the analysis of maritime prototype that will automate a vessel with outlook to autonomous driving. In particular, the technological components of the integrated testbed described in chapter 2 can be appropriately used according to the normative requirements for an approach of the maritime domain, such as ISO 17894.

As illustrated in Fig.6 from a component-oriented perspective, eMIR has co-simulation based components in the virtual part that are linked by a high-level architecture (HLA), such as sensor simulation and environment simulation. The physical part LABSKAUS provides infrastructure such as vessels as well as sensor components located in a reference waterway and a message passing infrastructure for communication over the Internet. Beside this, the physical testbed has a LTE interface that can be used by a prototype to send data to other systems for further monitoring or processing because a wireless link is needed in the physical environment.

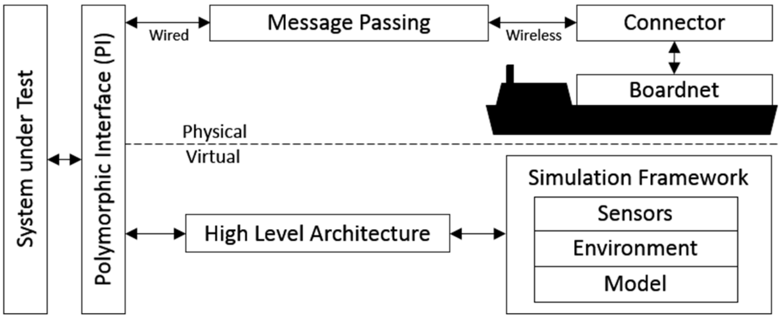

Fig.6: Holistic test platform eMIR

Fig.7 illustrates both the virtual and physical part of the testbed, although the further description only refers to the physical testbed. Nevertheless, this overall perspective is important for the understanding of the seamless integrated testbed. Fig.7 shows the communication infrastructure of the integrated testbed from an architectural perspective. On the left side, the virtual testbed that is not part of this paper as explained before. At the right hand-sight, the physical testbed LABSKAUS is shown. By using a common data model, the virtual and physical testbed have a seamless integration ability. The physical testbed uses a message passing infrastructure for the exchange of data. Further information on the communication infrastructure and data model can be found in chapter 4.4 that will describe the backbone in detail.

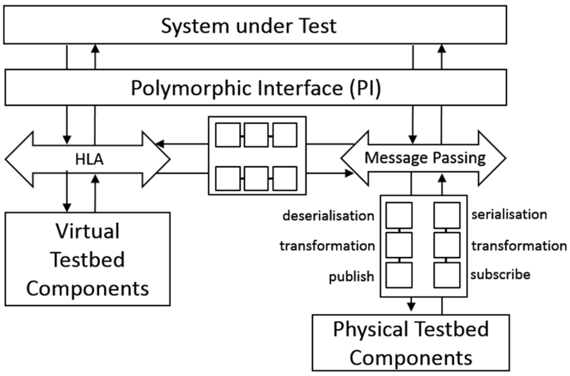

Fig.7: Communication within the Integrated Testbed

Fig.7 shows data handler components that use a data stream management system. For a defined data flow for example of sensor data provided by a radar, dedicated operators (small boxes in Fig.7) are used. Data from the field is deserialised, transformed to S-100 and published on the message passing system RabbitMQ. Components that want to consume the data can subscribe to the RabbitMQ message passing central bus by a subscription operator, transfer it from S-100 into the required format and serialise it into the needed syntax. The operators for consuming data are usually provided by the polymorphic interface to transform it into the needed consuming format, *Hahn (2015)*.

This paper suggests the realisation of the following requirement to create a testbed: Observability, controllable environment, adaptability through technological unrestrictedness, repeatability and functional unbounded. Fig.8 illustrates a functional perspective on the testbed architecture of the physical testbed that aims to fulfil the criteria described before. Basically, there is a prototype that is integrated by an integration platform into the infrastructure that contains environmental components such as sensors and actuators. For this, there are two layers: Management and infrastructure.

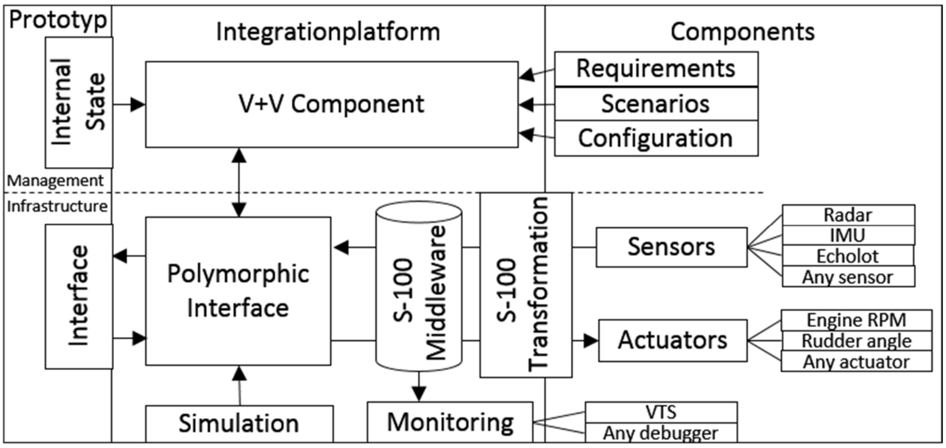

Fig.8: Testbed Architecture of the Physical Testbed

The management layer of the testbed realises V+V concepts such as checking if the incoming and outgoing data of the prototype is valid. On this layer, existing and future approaches for V+V such as ISO 17894 can be realised. Different V+V methods such as requirement-based tests or fault injection tests can be realised by an implementation of the testbed architecture according to normative standards. The V+V component represents the test specific requirements, scenarios and configurations and controls the testbed infrastructure, e.g. by setting input commands according to a scenario specification. For some test methods, the internal state of the prototype system is needed (e.g. runtime verification). Typically, a prototype will not have an interface for this in the functional architecture. Thus, a prototype must add another interface that will be consumed by the V+V component, e. g. a logging procedure. The testbed architecture supports by design tests on different levels, such as the system integration level or software level by providing the polymorphic interface as shown in Fig.8. For a maximum adaption, the polymorphic interface of the infrastructure connects the data flows of the sensor and actuator data to the V+V component that collects input and output data. This input and output data as well as the internal state of the system under test will be analysed according to test methods, such as Failure Mode and Effects Analysis (FMEA).

The infrastructure layer recreates the typical environment of the system under test in a CPS. For this, the core concept of the polymorphic interface offers the ability to integrate prototypes of various technological implementation (e. g. NMEA 0183, NMEA 2000, S-100, IVEF or other interfaces) into the infrastructure of the testbed as further described in chapter 4.4. Beside this, the polymorphic interface listens to the data and commands that are sent between the system under test and the infrastructure and transfers it to the V+V component for further analysis. For the communication link, there exists a middleware using the S-100 data model that abstracts the testbed-specific implementation. The benefit of this testbed architecture is the feature of adaptability by encapsulating the testbed-internal infrastructure by the polymorphic interface in combination with the middleware. In respect to requirements such as heterogenous interface connectivity, loose coupling and bilateral data streams, an essential feature of the maritime testbed architecture is the need for a communication infrastructure connecting elements. For this purpose, software architecture patterns exist, such as communication-oriented or application-oriented middleware. A middleware addresses these requirements by providing a time, space and synchronisation decoupling of distributed systems that work geographically distributed according to the needs of automated/autonomous systems in maritime scenarios.

As can be seen in Fig.8, the testbeds components are sensors such as Radar, IMU, echo sounding or any other sensor as well as actuators such as the revolutions per minute (RPM) of the engine, rudder angle or any actuator. These components are related to the requirements of the three-layered approach of chapter 2 and represent the environment and the vehicle parameters. The native interfaces of these sensors and actuators are heterogeneous, such as NMEA 0183 or NMEA 2000. Therefore, a transformation into the canonical data model of the testbed infrastructure S-100 will be done according to the data handler description in Fig.7. The testbed needs some information to perform the tests. Typically, this information results from requirements and specifications. E.g. pre-conditions, post-conditions, environmental factors and the steps of the scenarios are needed to set up the testbed and perform the test cases. As can be seen in Fig.8, there is a monitoring component that streams information of the testbed infrastructure to a VTS for visual evaluation or any debugger. The non-modified data of the testbed communication infrastructure can be used for diagnosis of errors or analysis of a system's behaviour based on raw data. The detailed implementation of the components of the backbone according to the testbed architecture will be described in the following chapter.

4.4 Backbone

The backbone is a sensor box to integrate the naval sensors, an open communication system based on open source message passing implementation and S-100 conform data representation according to the testbed architecture presented in chapter 4.3.

- **Sensorbox -** The component which integrates the sensors is called 'Navibox'. It is a compact sensor data hub which provides navigational data on board as well as data for maritime surveillance systems. It provides LAN, WLAN and broadband WAN communication facilities. The minimum setup consists of a radar, an Automatic Identification System (AIS) antenna and a wind sensor. The AIS is a core technology based on a radio system for the exchange of navigation information and ship data in the shipping industry. The objective pursued by the use of AIS is to improve the safety and control of shipping by sending various static and dynamic data via radio. All sensors which are sending data appropriate to the communication standard NMEA 0183 or NMEA 2000 and Ethernet can be attached. In case of a different communication standard, an adapter will be implemented to integrate the sensor into the Navibox. The AIS receiver receives all AIS messages from the AIS transceiver equipped systems in a 35-100 km radius dependent on the antenna height. The AIS messages include static, dynamic and journey vessel information. A wind sensor is able to gather wind speed as well as angle and is connected to the NMEA 2000 bus. An Industrial PC (IPC) takes over the sensor stream management and processing. It houses a message passing broker for the publish/subscribe mechanism of the testbed communication infrastructure. The Navibox software gathers and handles all sensor data. A Navibox is configured to be remotely controlled via network (LTE).

  The stationary variant of the Navibox has a sturdy pole to carry the sensor head. Two of the stationary Naviboxes are implemented in the reference waterway located at the roof of buildings that are near to the coast. The setup in Cuxhaven is additionally equipped with optical surveillance technologies to track objects and observe water current/surface behaviour. In the future, an echo sounder will be attached to track movements and ship dynamics under water. An energy autarkic version of the Navibox station is added to run tests on any coast location.

  To collect data at the location of a vessel there is the mobile Navibox. It adds a JRC JRL-21 Differential GPS (DGPS) System that can not only add the position, course over ground and speed over ground, but also the true heading and rate of turn to replace a compass. A chart and multifunctional display allows monitoring sensor data on board. The sensor pole will be attached to a vessel and gathers sensor data independent of the ship navigation electronics.

- **Data Model -** The physical testbed exchanges data based on S-100 over the message passing bus, *DNV GL (2015)*. S-100 is a universal hydrographic data model that was developed by the International Hydrographic Organization (IHO) in 2010. This new standard replaces the past IHO standard S-57 due to a lack of flexibility. For example, a limitation of S-57 is the missing support of complex data type, e. g. gridded bathymetry or time-varying information *Ward and Greenslade (2011)*. S-100 defines specifications for maritime data and is not only a digital data format, but a framework. S-100 shall be used as the new standard for the usage of various data related to the marine environment and safety. Therefore, the design decision to use S-100 for the canonical data model of the testbed infrastructure for automated and autonomous vessels is recommended. To be compatible with international geographic information standards, S-100 is based on the International Standardization Organization (ISO) 19100 series. Therefore, it supports syntactic and semantic interoperability among systems using marine and marine-related geographic information. Currently, S-100 is already used as the basis for several purposes, such as product specifications for Electronic Navigation Chart (ENC), bathymetric data or route information, *Park and Park (2015)*, pp.6574-6575. The backbone of the testbed infrastructure uses the evolving S-100 standard as a uniform (canonical) data model. By defining the semantics of the testbed infrastructure, interoperability within the testbed and all compliant (prototype) systems is ensured.

- **Communication -** LABSKAUS is designed under the paradigm of loose coupling and realised using the open source message passing middleware RabbitMQ, as can be seen from a technology-independent architectural perspective in Fig.9. RabbitMQ is a communication-oriented middleware. A message broker observes the data channels, redirects data and chooses which consumer can access it. This multi-broker setup causes scalability and flexibility of the system. As shown in Fig.9, we realised the system architecture of the infrastructure by using a central broker as an intermediate communication managing component instead of loose coupling since the communication bandwidth is limited in a wireless offshore-onshore link. This allows the following advantage: In case of only one central broker, data from producers on a vessel will only have to send the data to the central broker over a wireless link once instead of multiple time in case of multiple brokers. The central broker is connected to consuming systems on shore by wired links that are not bound to a low bandwidth. As a connection and communication pattern, the middleware software implementation of the testbed backbone uses a publish-subscribe mechanism. This is suitable since message-driven communication of sensors and actuator data streams takes place. The communication of the testbed is controlled by components without requiring application-specific levels such as method calls.

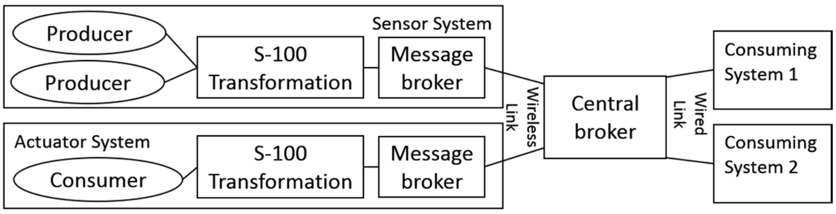

Fig.9: Distributed software architecture of the message passing middleware

- **Polymorphic Interface -** A basic idea for a generic maritime testbed as described in chapter 3 is an open and adaptable design for various kinds of prototypes. For testing navigational equipment, a polymorphic interface offers the ability to integrate prototypes of various technological implementation into the infrastructure of the testbed. The interface is highly flexible and adaptable by supporting various maritime standards, formats and regulations, such as IVEF, NMEA or S-100. The canonical S-100 data model of the infrastructure reduces the complexity of various standards and benefits the polymorphism mechanism. This in combination with a polymorphic interface offers the ability to adapt various domain standards should ease the integration of other components. The polymorphic interface uses S-100 as a reference model represented by a UML diagram. Based on this, a prototype data model specified for example in XML can be interpreted. By the help of XSL Transformation (XSLT), transformation rules are semi-automatically defined that describe semantic interoperability of a prototype and the testbed. Based on the transformation rules that exist in

XML, a platform- and programming-language dependent adapter is generated. An adapter is a design pattern of software engineering and serves as a mediator between interfaces. In the role of the mediator, an adapter adopts translation activities to establish communication and therefore interoperability between incompatible interfaces. These are for example hardware-software or software-software communication links of different specification. A monitoring and debugging communication channel based on S-100 gives the ability to observe a system's behaviour in a V+V scenario. For this, there exists a VTS system that displays vessels and therefore provides observability abilities. By subscribing to the RabbitMQ middleware, the data streams of the testbed can be intercepted and analysed.

5. Use Case – Shore based bridge

The paper shows the capability of the testbed by describing a use case of testing a shore based bridge (SBB) for remote control and action planning. The realisation of this use case takes place in cooperation with the Norwegian e-Navigation technology company Navtor in the 3-year project Cyber-Physical Systems Engineering Labs (CPSE Labs) that got funded by the European Union. Fig.10 shows the realisation of the physical testbed implementation which addresses the requirements of three-layered approach for driving described in chapter 2 required by the SBB. The SBB aims to realise the ability to navigate a vessel remotely over the Internet. The SBB is in Norway while the vessel is based in the North Sea. This testbed implementation will provide an operational environment for testing the SBB functions such as moving planning, vessel monitoring and safety-critical navigation. The SBB covers a shore based ECDIS e-Navigation station implemented by Navtor that receives sensor data from the testbed, such as ship radar, GPS, AIS, voyage data recorder (VDR) or visual camera streams. Based on this infrastructure, a navigator will use multiple data sources for monitoring, navigation, and route planning. The instructions by the navigator will be sent automatically on board of the research vessel ZUSE as waypoints (NMEA 0183 – APB) or direct control commands (rpm, rudder). In case of an autonomous vessel, the updated route will replace the current route in the ship's ECDIS and track pilot and thus directly steer the ship according to the new intended passage plan. The communication infrastructure provides a common operational picture on board of the vessel as well as on shore. In the case of a safety critical situation, the navigator can take control of the ship and set the speed and rudder angle.

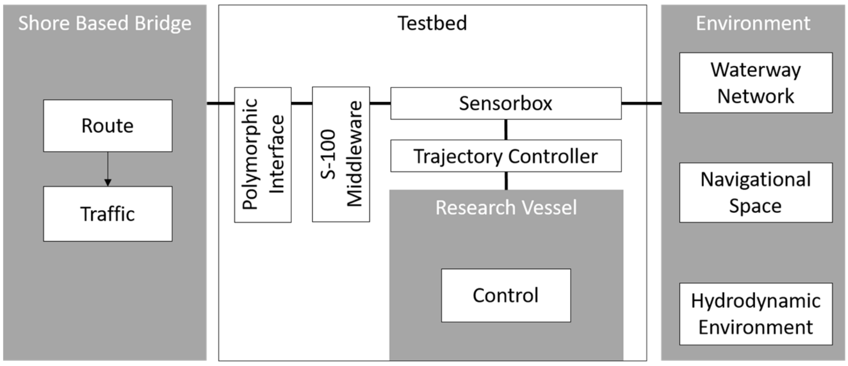

Fig.10: Physical testbed implementation

The SBB can provide navigational functionality by proving a moving planning module. As shown in Fig.10, functionalities on all levels of the three-layered approach for driving are taken over by the SBB. For this, road network information such as sea charts are needed. For the guidance, information regarding navigational space is provided by the sensor box containing environment sensors such as AIS, camera and radar sensors. The control functionality is realised by software handles which send commands over the polymorphic interface to a vessel connector framework of the research vessel. This use case shows the support potential of a physical maritime testbed for the development of highly automated and autonomous maritime systems as described in this work.

6. Conclusion

This paper gives an overview on the implementation and usage of testbeds for highly automated and autonomous vessels. The requirements for a maritime testbed were described that result by the three-layered approach for driving. Furthermore, an overview of present related testbeds was given. This work introduces the test platform eMIR with special focus on the physical testbed LABSKAUS. Firstly, the potential was described from a development perspective to continue describing the individual components of the physical testbed and finally present the complete testbed architecture. LABSKAUS provides components such as a research vessel, reference waterway and mobile bridge aiming to support the V+V by providing services. These testbed components address a wide field of sensor sources, sinks and an infrastructure to build the testbed for V+V. The wide scope of possible tests for highly automated and autonomous technologies offers an open as well as extendable platform for research and industry. Using this approach, various test and demonstration environments can be set up. A use case shows the potential of the presented approach by setting up a test environment for a shore based bridge. The use case realised the remote monitoring and control functionality of a vessel by using a modified ECDIS based in Norway and the physical testbed. In future, the eMIR testbed will be expanded for the development and research of technology for highly-automated and autonomous vessels which seem to be the future of e-Navigation.

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The Key Ship Design Decision - Choosing the Style of a New Design

David Andrews, University College London, London/UK, d.andrews@ucl.ac.uk

Abstract

A paper to COMPIT 2013 presented a description of the ship design process in terms of the important decisions a ship designer makes, consciously or unconsciously, in order to produce a new design. The first real decision that has to be made by the designer in order to proceed was said to be selecting the "style" of the design study or a specific design option. This term was adopted in order to distinguish not just a host of design issues and standards implicit in a given study but also, at this very initial step, the overall characteristics of any particular study. So, the term style could be said to be doubly important. The paper considers the nature of the early ship design process for complex multi-functional vessels, referring to the 2013 paper, and then retracing the origins of the particular use of the term, where it was seen as the last of the five elements in Brown and Andrews' 1980 encapsulation of the ship design issues that matter to the naval architect, incorporated in the term "S to the 5th". This leads on to consideration of the various aspects of design style, many of which could be considered "transversals" as they apply across the naval architectural sub-disciplines and to the component material subsystems comprising a ship. One of the distinctive advantages of the architecturally driven ship synthesis or Design Building Block approach is that it can address many of the style issues in the earliest descriptions of an emergent design study. Examples are provided showing both different top-level style characteristics and how the impact of specific component style aspects can be investigated in early stage ship design using the UCL DBB approach. This enables the paper to demonstrate why the choice of "style" is seen to be The Key Design Decision.

1. Introduction - Style in Early Stage Ship Design

"Style" was explicitly incorporated as a characteristic of a ship design by *Brown and Andrews (1980)* as the fifth "S" in the "S^5" ship design characteristics, the others being Speed (really Resistance and Propulsion), Seakeeping, Stability, and Strength. However the exact nature of style, as a type of information or design characteristic, that set it apart from other characteristics (or even the sub-disciplines of naval architecture), such as Speed or structural strength, was not so clear. *Pawling et al. (2013)* proposed at COMPIT 2013 that the design issues generally grouped under style, see below, are conceptually different to the other naval architectural disciplines not because many are unsuited to mathematical analysis (the same was once true of Seakeeping or structural vibration analysis) but because style is a cross-cutting concept, in that a decision on an aspect of style explicitly influences a wide range of solution features. Stylistic information also has the key property of being able to accommodate uncertainty, containing both "hard" knowledge (such as adoption of specific structural standards) and "soft" knowledge (such as guidance on ship internal layout). Such knowledge can then be conceptually connected or grouped. In addition, style choices may also be reflected in the weighting factors chosen given multiple criteria when the ship designer is selecting a design preference.

An example of a transversal style choice would be the level and extent of survivability adopted in a naval ship design. A decision on the level of survivability can influence a wide range of overall and detailed design features, such as the choice of signatures and defensive systems (to prevent a hit), the spacing of bulkheads (to resist weapon effects and subsequent flooding), the mutual arrangement of compartments (to protect vital spaces and aid in recovering from damage) and structural details (to resist the result of underwater shock on the structural hull girder). This particular example also illustrates another feature of style in that it is cross cutting across the responsibilities of the engineering disciplines involved in a ship design (such as naval architecture, marine engineering and combatant system engineering). In this regard, style choices could be said to be particularly critical in decision-making at the crucial earliest stages of complex ship design. It could be argued, however, that the difference between style and the other components of "S^5" is a matter of degree, given that all the aspects of ship design interact to a greater or lesser degree with each other.

2. Style as the Transversals and Categories of Style

The style to be adopted in a specific design option is the key design decision for that option and so is the first design decision (beyond deciding that a certain range of solution options are to be investigated). This is indicated in the overall ship design process representation in Fig.1, taken from *Andrews (2013)*, where each step or decision selection is explained more fully in the appendix to that paper. The term design style was originally proposed to distinguish a host of disparate issues distinct from the classical engineering sciences, such that many of them could be seen to be on the "softer" end of the scientific spectrum drawing on the arts and humanities. Given the first four terms under the "S^5" umbrella are, historically, the principal naval architectural (engineering sciences) sub-disciplines associated with a ship's technical behaviour. Whereas Style was devised to summarise those other design concerns, which for the case of the naval ship are listed in Table I. This very disparate range of issues, have been categorised under some six headings that (ship) designers understand. Thus for example concurrent engineering concerns are encompassed by the topics under Design Issues in Table I.

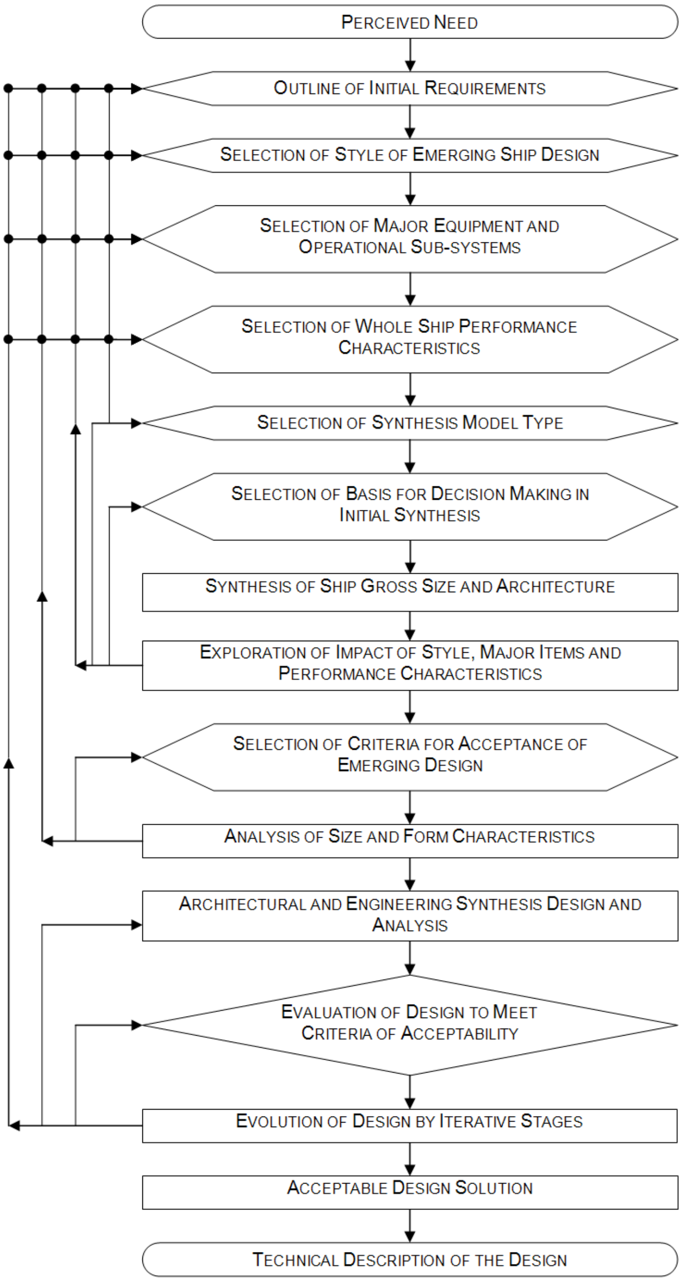


Fig.1: A representation of the overall ship design process emphasising key decisions

Importantly these style issues can make a substantial difference to the final outcome of a design, so their relative impact ought, in the case of a complex ship, to emerge from a proper dialogue between designer and client (or in the naval ship design case, the operational requirements owner). Furthermore, most of these issues have been difficult to take into account early in the design process because, usually, initial design exploration has been undertaken with very simple and, largely, numeric models summarising the likely eventual design definition and giving a (often dubious) feel for the cost to acquire the fabric of the ship, *Andrews (1994)*. That dialogue can now be informed by also having a graphical representation of the ship's configuration and internal architecture, as is reflected in the process summarised by Fig.1. This process reflects the architecturally (rather than solely numerically) driven synthesis propounded in his Design Building Block (DBB) approach, *Andrews (2003)*. At the critical early design stages, such a computer graphics based approach can then enable the ship designer to take account of many of the significant issues, such as those listed in Table I.

Table I: Listing of style topics relevant to a naval combatant design

Stealth	**Protection**	**Human Factors**	**Sustainability**	**Margins**	**Design Style**
Acoustic signature	Collision	Accommodation	Mission duration	Space	Robustness
Radar cross section	Fire	Access	Watches	Weight	Commercial
Infra-red	Above water weapon effect	Maintenance levels	Stores	Vertical centre of gravity	Modularity
Magnetic	Underwater weapon effect	Operation automation	Maintenance cycles	Power	Operational serviceability
Visual	NBC contamination	Ergonomics	Refit philosophy	Services	Producability
	Shock		Upkeep by exchange	Design point (growth)	Adaptability
	Corrosion			Board Margin (future upgrades)	
	Damage control				

The categories adopted in Table I reveal the heterogeneous nature of the specific individual style issues, for a complex naval vessel. Thus the various items under Stealth can be seen to be the many different signatures, which a ship has and then needs to reduce to avoid detection, while the Protection items are largely aspects worth incorporating in the ship to mitigate the results of weapon effects, should the Stealth (and any "hard kill" self defence) fail to be totally effective. However, some of the Protection items are required for normal ship practice, such as corrosion control or for non-weapon considerations, such as collision and fire fighting. The Human Factors aspects are little less coherent (and it might be argued rather more solution oriented than those of the urban architectural theorist *Broadbent (1988)*). These consist of some 21 "human sciences" that he considers are relevant to human habitation – and hence also likely to be appropriate to HF in ships. HF concerns also relate to the important growth area of automation, which along with micro-ergonomics (e.g. console design) has a strong input to the Protection category, specifically in regard to modern bridge design. Sustainability is a major consideration in naval ship design and could be said to be a major driver, and hence a key hidden decision in the ship's style from the beginning of any ship design study. The list of Margins just makes the point that there are many features and considerations beyond simple margins on the weight/VCG to ensure the ship's stability is adequate beyond the day it is accepted into service. Table I also distinguishes those margins required for unplanned (but consistently observed) growth in weight and rise in VCG in-service from Design Margins. The latter are more rightly a Design Issue in Table I, given they address many measures of uncertainty in design estimates. These margins, across all the weight/space groups, are intended to be absorbed, but not exceeded, through out the design and build process to completion.

The last category in Table I is clearly the most broad and heterogeneous. Also, generally, such topics have the biggest impact on the final ship design. But this means they need to be recognised as choices and then properly considered with the owner/requirements team from the beginning of studying any design option. Some of these have been the objects of particular investigations by our research group at UCL and are discussed further in Section 5 as examples of design impact of considering separately some of these particular issues, where each could be as the specific driver of a design from its initiation. It is noticeable that certain of these issues can only be adequately investigated in the Concept Phase if the architectural synthesis assumed in Fig.1 is adopted. The other aspect to most of the Design Issues listed is that they have a qualitative or fuzzy nature. Thus, say, Robustness implies a greater degree of that quality than the "norm" for that type of vessel. This then raises the point that such a "norm" for a given new design option ought itself be defined but is often just accepted (or inferred) as being "current practice" or by the adoption of existing standards. There are also exceptions in the listing of the Design Issues category, like Aesthetics, which for most vessels, other than mega yachts and some cruise ships, is seen to be "a luxury". However, even this can be seen to be a simplification, as in the Cold War there was considerable debate in the US naval ship community as to whether the physical appearance of such a ship was part of it's political "armament", *Roach et al. (1979)*.

Table II: Types of Ship Design in terms of Design Novelty

Type	**Example**
second (stretched) batch	RN Batch 2 Type 22 frigate and Batch 3 Type 42 destroyer
simple type ship	Most commercial vessels and many naval auxiliary vessels
evolutionary design	a family of designs, such as VT corvettes or OCL container ships
simple (numerical) synthesis	UCL student designs
architectural synthesis	UCL (DRC) design studies (see below)
radical configuration	SWATH, Trimaran
radical technology	US Navy Surface Effect Ship of 1970s

The nature of the design of complex ships, such as cruise ships and naval combatants, is such that the need to emphasise the importance and difficulty of early representation of style issues is seen to be a further complication in the practice of designing such vessels. This is due to there being, additionally, a wide range in the practice of such design. This arises from the degree of design novelty adopted in a specific design option, as is indicated by Table II. This shows a set of examples, across the field of ship design, where the sophistication in the design undertaken ranges from a simple modification of an existing ship, through ever more extensive variations in design practice, to designs adopting, firstly, radical configurations and, beyond that, radical technologies. Although in first of the latter two categories of Table II current technology is often adopted, such options are still rarely built, due to the risk of unknowns (usually exacerbated by the lack of a real prototype), while radical technology solutions are even more rarely pursued. In part this rarity arises because such radical technology solutions require recourse to design and, indeed, manufacturing practice much more akin to that appropriate to the aerospace industry. Thus, new major aircraft projects, typically, require massive development costs (including full scale physical prototypes, some tested to destruction) and additionally need tooling and manufacturing facilities to also be specifically designed and then built, before extensive series production of each new aircraft design can commence. This is of course quite unlike most ship design, be it the ubiquitous bulker or the most sophisticated naval vessel. Such distinctions as those of Table II for the design of complex ships suggest any discussion of style needs, at least, to recognise the spectrum of design approach resulting from the novelty of the specific design option being pursued. Such choice on design novelty is key to the initial style choice for a given design study or a variant option in a properly conducted concept exploration, *Andrews (2013).*

3. Examples of Style Choices in Actual Ship Designs

The following are brief summaries of a series of built naval ships, where style in an overall configuration has been a distinct choice and also some more specific style choices have been adopted, reflecting some of the more significant issues amongst those listed in Table I.

- **1st and 2nd Rate Royal Navy (R.N.) Ship Designs**
  In an early study into the nature of ship cost, *Brown and Andrews (1980)* drew on a series of R.N. ship designs to point out that ship classes, which had been specifically designated “First rate” or “Second rate” designs, invariably showed that the latter were poor value for money (VFM). This applied to the Queen Elisabeth Class and Revenge Class Battleships, where the latter ”cheaper” versions were far less effective and clearly less value for money, in their inability to be upgraded over a thirty years life. In WWII, the early convoy escorts, the Flower Class corvettes were again poor VFM compared to the later Castles and Lochs. Post War first and second class frigate classes were produced and, while the former led to the very successful Leander Class, the latter (Blackwoods) were soon disposed of. All these comparative designs are excellent examples of the overall style choice being made from which all the capabilities followed.

- **HMS OCEAN**
  Commercial standards were mandated for this helicopter carrier without this being assessed through any proper concept and feasibility studies, because of the adoption of a false costing based on belief in a potential merchant ship conversion option. The Project Manager (the author in 1986-1990) fought the naval staff over adopting such non-naval standards for an essentially high value unit (given its “cargo” of hundreds of troops plus associated equipment and 12 Commando helicopters). The PM managed to raise the purchase budget but not sufficiently enough to cover the incorporation of limited naval standards. The eventual purchase was subsequently criticised by the Ministry of Defence chief marine engineer as this commercial practice substantially increased the engine support requirement for the fleet (due to this one ship’s unique engine fit). Of course, these support costs were not shown in original cost based decision, given this was obsessed with direct initial procurement cost rather than the “true ownership cost” of the design solution. Interestingly, many have argued that HMS OCEAN has been “good value for money”, however it has not been used in naval warfare (rather than usefully in peace keeping), so the jury must be out as to whether this constitutes, as a “cheap” solution for such a major naval capability. The extent to which many of the detailed “style issues”, largely listed in Table

II, were predetermined by the style choice of a “commercial ship” emphasises the importance of overall design style.

- **RFA ARGUS**
  How ship was a major conversion of a Ro-Ro containership to helicopter training ship. In the acceptance phase the author as Project Manager had to defend to the parliamentary Defence Committee (the HCDC) the payment of huge cost overruns on a Fixed Price contract, *HMSO (1989*). This case proved naval ship acquisition is a lot more than just engineering design and even conversion to a support role such as a training vessel can be demanding. The resultant procurement failure was largely due to several unwise acquisition edicts imposed early on in the project acquisition and resulted from a style choice, which could only be described as incoherent. An important negative lesson on how crucial the style decision can be.

- **Type 23 Frigate**
  This frigate class evolved from the 105m “towed array tug” concept, which then grew in steps (112 m, 118 m) to 123 m general-purpose frigate post-Falklands War (and after the official Concept Phase). It was the first flared R.N. hull form (for radar cross section minimisation reasons) and pioneered a combined diesel-electric and gas turbine (CODLAG) propulsion fit (for ultra-quiet acoustic signature to operate the towed array). Both these features were incorporated from the Concept Design studies and were the two most fundamental ship design decisions, retained from the concept studies despite the very significant growth in size, post-Concept. The style of the design was politically mandated to be short life and “margin less”, when everyone in concept team “knew”, despite the Navy Minister’s edict, this would not be held. Many ships in the class will be in R.N. service for at least 28 years, rather than the mandated 18 years’ ship life, and the through life cost of this shows the impact of an ill thought through key style attribute.

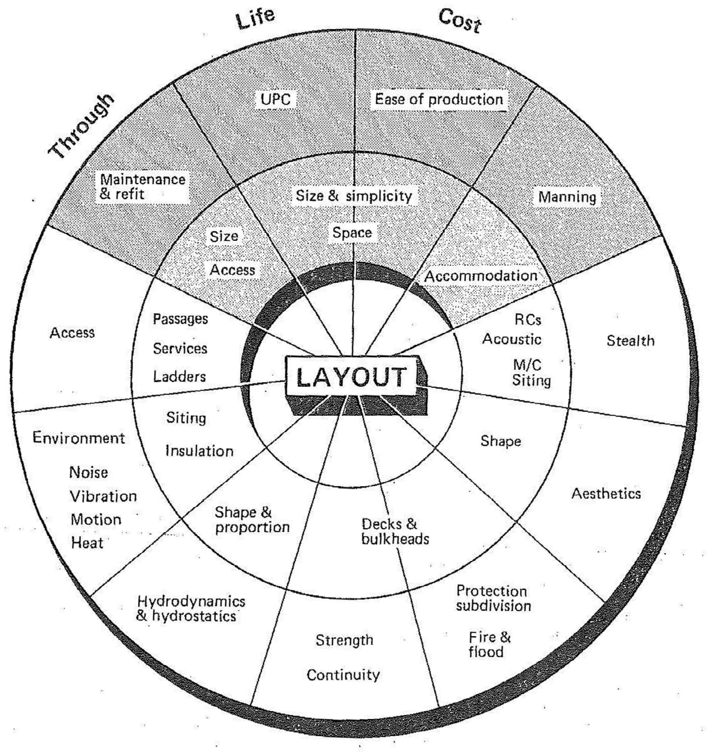
- **Type 31e Light Frigate**
  This is a new “exportable” light frigate concept proposed in a report to the UK Government by the eminent industrialist and naval architect, Sir John Parker. It is seen as an approach to breaking the ever increasing cost of procuring warships and, through adopting more commercial standards and acquisition approaches for a “Second Rate” naval combatant, enabling the Royal Navy to maintain a numerically sufficient surface combatant force, *Parker (2016).* The “style” to achieve this could be seen as a return to Second Rate style and whether the concept in an era of austerity will be more successful than previous Second Rates must await its design development and then its introduction and longevity in service?

4. Style with an Architecturally based Design Synthesis

Many of the style issues listed in Table I should first be exposed in considering the architecture of the ship. This is both in regard to the overall form (not just underwater hydrodynamic and hydrostatics relevant to the first three S^5 aspects) but also the overall configuration (be it multihull or a more typical mono-hull and superstructure configuration), including the internal layout disposition or architecture. The manner in which exploration of ship internal configuration and layout helps to open up many of the more protracted and less readily analysable aspects of ship design, largely under the style designation has been taken further by the author, firstly in his original exposition of the integration of configuration in ship design, *Andrews (1981)* right up to recent outlines of this approach, which have been adopted in current text books of naval architecture, *Tupper (2013)*. This section goes on to address the approach to ship layout or the architecture of ships for several distinct ship types or “styles”, to show the complexity of issues encompassed by style once the architectural component is given its rightful weight in design synthesis and in the rest of early stage ship design.

4.1. The Example of Frigate Architecture

The eminent naval ship designer and historian D K Brown’s paper on “The Architecture of Frigates”, *Brown (1987),* drew on his experience of preliminary warship design and on research undertaken by *Andrews (1986)* and various post graduate students at University College London, *Hutchinson (1981), King (1985)*. Brown's paper was largely a comprehensive survey of many of the aspects and constraints impinging on frigate layout design through the various phases of design (termed levels by Brown), from initial design concept (Level 1) through to detailed General Arrangement (Level 3). The design constraints were indicated in his Fig.4 reproduced as Fig.2, where an outer ring showed “problem areas” directly affecting a frigate's architecture (e.g. access, noise, vibration, hydrodynamics, structural continuity, survivability, stealth, aesthetics and through life issues).



Note: The outer ring lists problem areas which directly affect the architecture of a frigate whilst the inner ring shows material solutions.

Fig.2: Design Constraints affecting Layout, *Brown (1987)*

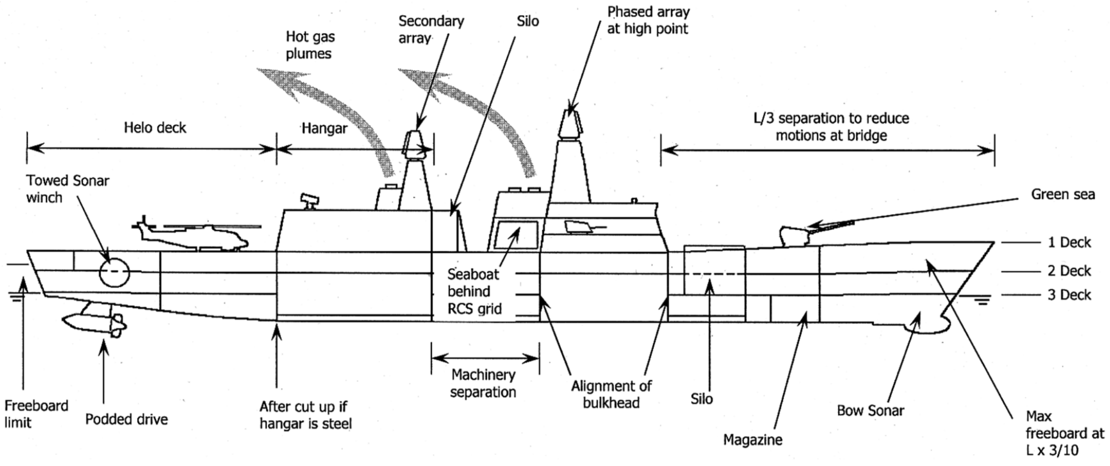


Fig.3: Frigate Layout Considerations, updated from *Brown (1987)* in *Andrews (2003)*

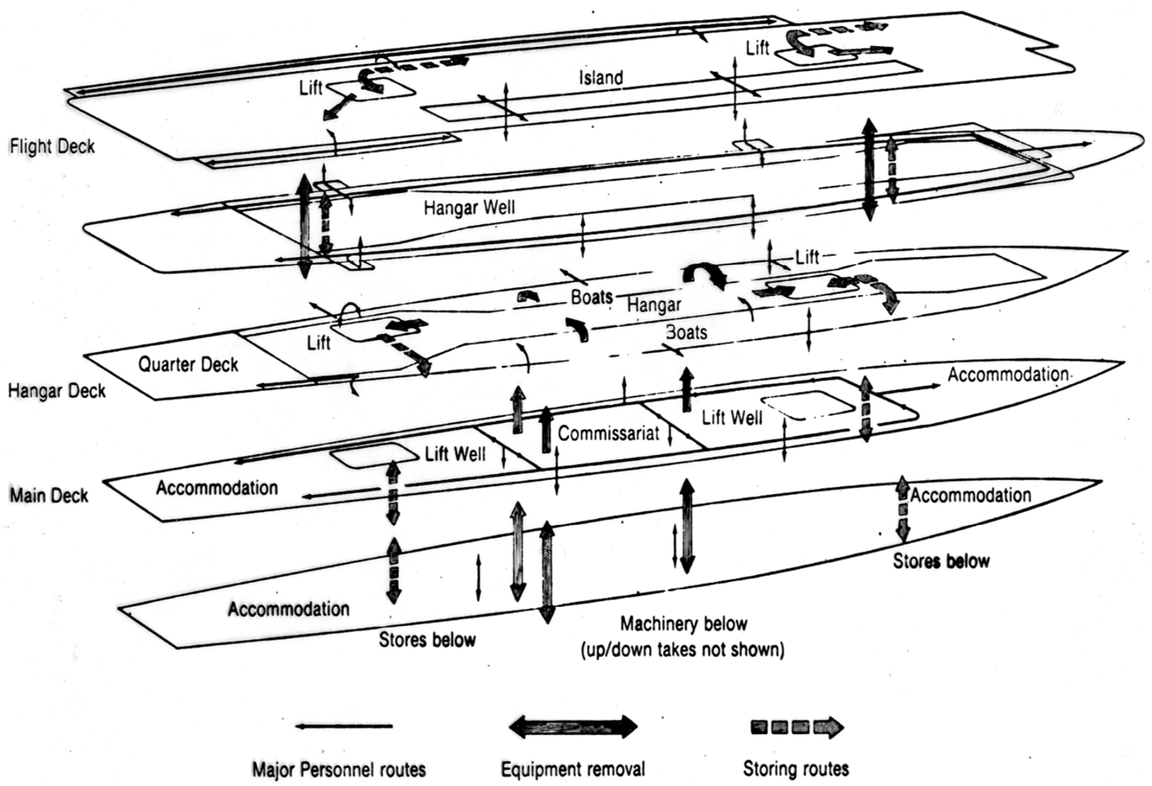


Fig.4: Schematic of INVINCIBLE Class Internal Arrangement, *Honnor and Andrews 1982)*

These can be seen to be a mixture of Style aspects and the naval architecture sub-disciplines, showing the complexity of any taxonomy for such an interdependency of issues. The inner ring of Fig.3 shows elements of the material solution (e.g. accommodation, decks & bulkheads, shape & proportions, passages, ladders, services & machinery arrangements) that are the components of the ship's internal architecture. In keeping with concept of ship style, Brown discussed the range of style-related issues relevant to the layout of a given design (i.e. ship role, modular/cellular features, margins, zoning). He emphasised how, for his Level 1 (for a frigate and similar combatant vessels), the key to the internal layout is the design of the upper or weather-deck disposition of weapons, helicopter arrangements, radars, communications, bridge, boats, seamanship features, machinery uptakes and down-takes, and the access over the deck and into the ship and superstructure. Fig.3 shows an updated version of Brown's frigate configuration, *Andrews (2003)*.

4.2. Configuration Driven Ship Design

Although the author has long postulated that the design of all warships (and most commercial service vessels) should be driven in large measure by their internal (and upper deck) configuration, *Andrews (1981,2003),* it will be recognised that the concept design of certain ship types has to be approached by firstly configuring the spaces required to achieve the primary function(s) of that vessel. Thus, the physical description of a passenger, cruise or ferry ship, can only be produced by commencing with the arrangement of the public spaces and cabins, *Levander (2003).* Similarly the configuration of certain large naval vessels, such as aircraft carriers and amphibious warfare vessels, are driven by the spaces required to accommodate the primary "cargo", whether the hangar and flight deck or the well dock and vehicles decks in those specific cases. A prime example of this aspect was presented on the INVINCIBLE Class carriers, *Honnor and Andrews (1982)* in a diagram reproduced at Fig.4. This shows schematically personnel routes, equipment removal routes and stores routes around and directly below the two decks, which dominate any aircraft carrier design, i.e. the flight deck and hangar deck. That paper discussed the need for access from the main through deck, below the hangar, and around the side of the hangar, taking into account the other spatial demands for machinery inlets, outlets and removal routes, as well as features, such as boat arrangements and ship ventilation. Their paper also pointed out, however, that some important military features also had to be accommodated in the arrangement but had been deliberately omitted from this figure, such as:

- Magazines and weapon movement routes;
- Other important aircraft support spaces and stores;
- The location of ship and force command, control and communications;
- Damage control features.

Although these features would need to be included in order that the evolution of such a complex ship configuration could be properly appreciated, this example - and the previous frigate case – are considered to leave no doubt about the author's contention in regard to the centrality of a ship's architecture in the early design process and in style terms, the essentiality of the three-dimensional functional integration as key to the ship design.

4.3. Design of Unconventional Hull Configurations

A further type of ship style, which necessitates a significantly distinct ship design process is that identified by the penultimate category in Table II. While unconventional hull types are adopted as solutions for ocean going ships relatively infrequently, they should nevertheless be included in the options considered in any comprehensive exploratory stages of a new ship design. In particular, in the case of the normally displacement-borne multi-hulled configurations - like the catamaran, SWATH and trimaran - the architectural design is highly significant. When the initial sizing of ocean-going multi-hulled vessels is considered, to determine dimensions and form parameters, it is apparent that their sizing is not circumscribed by the relatively narrow range of parameters, typical of mono-hulls driven by essentially the Froude wave making effect. Consequently the designer, of say a SWATH or trimaran, has to size these vessels on the basis that it is the configuration of their major spaces and how they are disposed between the hulls and the broad cross deck structure, which constitutes the main driver for determining the vessel's dimensions and principal form parameters, *Andrews (2004)*. As can be seen from Fig.5, the size and shape of the trimaran ship shown are driven significantly by the disposition of the major operational and habitable spaces.

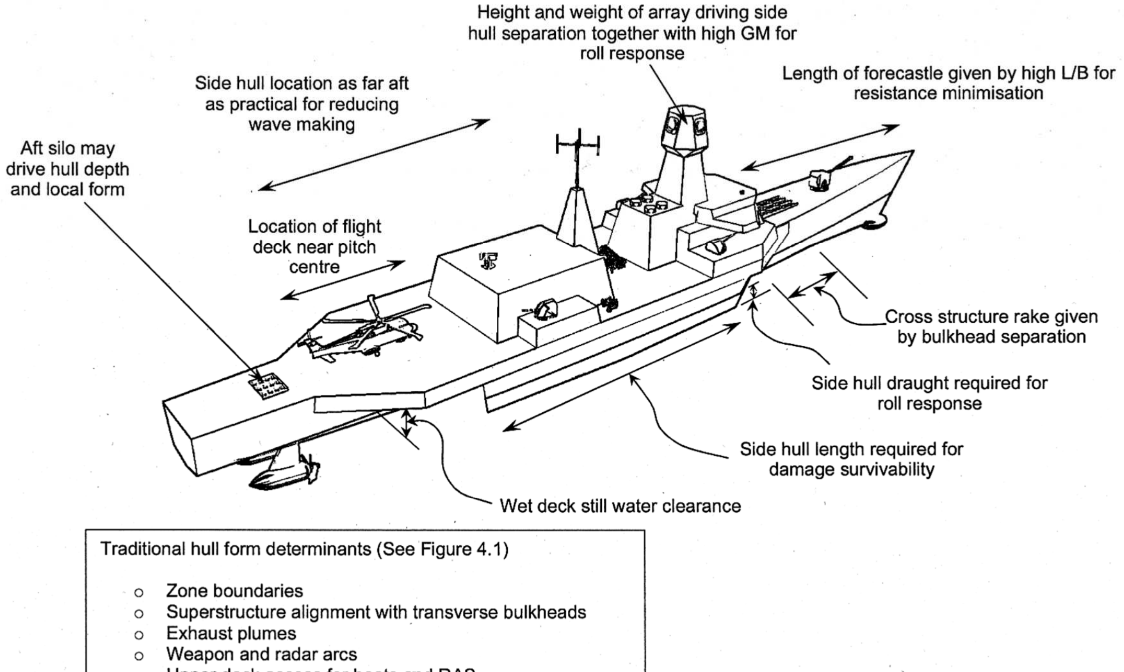


Fig. 5: Trimaran Configuration Drivers for a Combatant, *Andrews (2003)*

5. Examples of UCL Concept Studies exploring aspects of Style

This section gets results of investigations into a selected set of the topics in Table 1, which have been the subject of discrete ship design studies by the author's research team at UCL over the last two decades. The items outlined are not a comprehensive analysis of the Table I topics, but are intended to show how these various design issues are key design choices over which the ship designer ought to be more informed. Thus the designer could make the key first decision step in the ship design process summarised in Fig.1 more overtly and better informed, as a result of such studies for new ship designs.

- **Margins**
  An exploration into the validity of the Design Spiral, as a representation of the nature of ship design especially in ESSD, considered Growth and Board Margins for a naval combatant study, *Andrews et al. (2012)*. Two distinct design styles were investigated: a conventional frigate style and a large hulled/small superstructure variant. The former showed a linear behaviour in solution size with increasing Board Margin, while the latter showed a distinct step change in size with the same variable. Thus the choice of overall style was shown to be key to any such investigations and was only revealed by the use of the DBB approach, rather than simple numerically ship synthesis, which had been undertaken on a frigate study several decades previously.

- **Commercial structure versus Shock Robustness**
  In considering the extent to which commercial standards might be introduced into naval ship design, in the search for reductions in initial (procurement) cost, this UK EPSRC CASE funded project, *Bradbeer and Andrews (2010)* first considered the effect of missile attack on a small frigate built to commercial standards. It was found that survivability was affected by the density of outfitting, which could be considered a style decision, akin to building in robustness or adaptability. A second investigation, *Bradbeer and Andrews (2012)*, looked at the effect of underwater shock and varied the structural style from normal naval scantlings to commercial practice. This meant changing from closely spaced "Tee bar" stiffeners adopted to reduce the structural weight fraction to wider spaced larger bulb and flat bar stiffeners. The survivability to very high (hull lethality) shock levels due to adopting such differing scantling styles, yet with the same longitudinal bending strength, was found to be considerably less for the heavier but less structurally effective commercial style. This is an example of more detailed analysis than would normally be undertaken in ESSD, but reveals that a style decision taken early in design can make a major difference in a key ship's capability, which has been seen to be fundamental in a naval combatant.

- **Design for Production – design style dominated**
  In a research project funded by the UK Shipbuilders and Ship-repairers' Association, *Andrews et al. (2005)* a study was undertaken on both commercial vessel and naval ship ESSD to improve the architecture of ships to reduce the cost of outfitting. This was a novel study in that much of large commercial ship cost is in steelwork, whereas for complex ships, such as the Offshore Support Vessel (OSV) and the Corvette in this study, much of the cost is in outfitting, and hence amenable to architectural exploration. The styles of both ship types were investigated, with rearranged machinery location and more spacious passageways to fleet in modular cabins, respectively, which could be seen as specific style choices.

- **Offshore Patrol Vessel (OPV) configuration Style**
  This ESSD investigation, *Pawling and Andrews (2010)*, was undertaken to show that in addition to the conventional OPV, based on the style of small naval combatants, it was worth exploring more radical ship configurations, such as the OSV commercial design, a trimaran OPV and a very wide stern (Ramform like) mono-hull. These alternative configurations could be seen to be addressing style issues, such as commercial design style and different hull forms, in exploring solutions which might be more appropriate for stowing and deploying sizeable autonomous vehicles, especially launch and recovery from the vessel's stern.

- **Mothership Configuration/operational style**
  A novel solution to the fast Littoral Combatant concept was seen to be the transporting of several small craft on a large fast vessel. This study, *Andrews and Pawling (2004),* presented some five radically different ship configurations with different launch and recovery methods (e.g. crane, heavy lift, well dock and stern gantry). These alternative styles were proposed to explore the operational options but clearly introduced distinct ship configurations which were both synthesised and the compared using the UCL DBB approach.

6. Recent Developments of Research into Ship Style

A further feature of style is that, if it can influence multiple areas of design, then it must itself represent the "grouping" of multiple sources of information in some way. Developing an ontology and taxonomy for style is seen to offer potential advantages to the practice of ship concept design, as it could allow for more efficient storage, retrieval and application of potentially disparate pieces of information or decisions, *Pawling et al. (2013).* It has been proposed that this could be combined with the semi-automatic layout generation methods, such as that developed by TU Delft, *van Oers (2011),* to allow a broader exploration of the impact of stylistic decisions in ESSD than the point based architecturally design approach using DBBs.

From the some of the above examples of ship architecture, it is considered that these can be seen as highly stylistic, in that decisions such as the number of masts on a frigate, or how the various functions might be disposed around an enclosed hangar on an aircraft carrier (see Fig.3) are highly cross-cutting. This is because such style choices can have both direct and indirect impacts on a wide range of overall and detailed design features.

There are seen to be two aspects where a more focused consideration of style might improve ESSD, *Pawling et al. (2013).* Firstly, the development of semi-automatic methods of generating sufficiently detailed designs but based on an initial crude layout, rather than *ab initio* and genetic algorithm based such as the TU Delft approach above, would allow the designer to better focus on the overall style of the arrangement. Secondly, a style taxonomy could be used as a method for describing and storing the data and rules that permit such semi-automatic tools to develop more detailed layouts. The designer could then apply a wide range of changes to a design by selecting a different style (e.g. different survivability levels or extent of through life adaptability – see Table I). These could then be compared to give insights into major design and cost drivers in ESSD.

6.1. Proposed Integrated Approach to better Style driven design

An approach, to better consideration of style choices, was made by the UCL team, in conjunction with its research partners the University of Michigan and TU Delft, *Pawling et al. (2013).* Current early stage design techniques for initial general arrangement definition focus predominantly on spatial compartment allocation. When evolving general arrangements, there is a lack of clarity, which should draw on the selected overall ship style, Fig.1. Given that style can be defined as the combination of whole ship performance metrics and local system metrics (see Table I), information is drawn from different domains, much of which may be ill-defined knowledge (such as HF aspects). Style is representative of design intent and the designer's engineering judgment in the early stages of ship design constraint definition, layout generation, and the evolving layout's evaluations. With the ability to account for style definition, the designer could create concept designs that integrate a larger body of design intent, without the need to explicitly describe its characteristics.

In an effort to incorporate style into the early stages of concept design, an iterative method using three primary levels in the design process was proposed. Fig.6 shows those levels as the style elucidation and input definition level, design layout generation method level, and post-generation style analysis level, respectively. Multiple components of coupled analysis would allow the cross cutting of knowledge to capture style attributes over multiple domains of the design within each level of the suggested process.

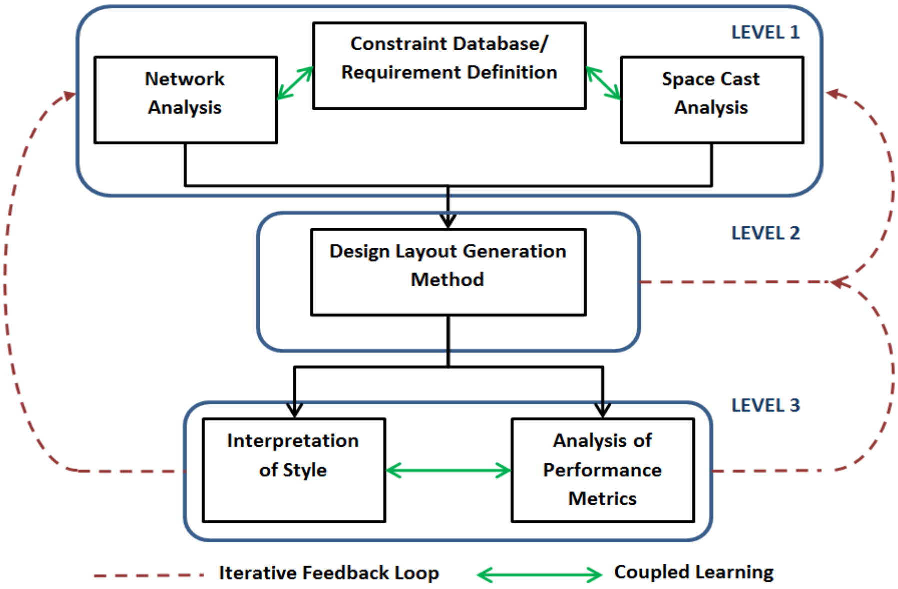


Fig. 6: Integrated approach for style definition in early stage design

The first level of Fig.6 highlights the style choices and the production of the inputs for the design generation method. Capturing the style is done through the explicit and implicit definition of the parameters that will drive the analysis of performance metrics, and their stylistic or architectural features. Definition of these constraints and requirements was not seen to be a trivial process as they evolve throughout the early stages of ship design and then through to detailed design. Constraints and requirements must be defined explicitly before network analysis, *Gillespie (2012), Collins et al. (2015),* or space cast analysis can be performed. At this level, the relationships between spatial, geometric, and global location preferences are iteratively updated with each completed loop of the integrated approach. The relationships could be investigated abstractly through a network analysis, and geometric allocations through a space cast analysis. Insights gained during this definition level could then be used to guide the elucidation process towards the novel definition of style intent in ESSD.

Style at this level of this integrated could identify approach the ill-defined knowledge early in ship design and capture, as inputs, hard to quantify metrics. The definition of style could be carried through to Level 2 and Level 3 of Fig.6, coupling performance metrics to the architectural layout generated to then down select appropriate designs. With proper definition of inputs and a clearly selected ship design style, the parameters of the constraints and requirements would give the potential to produce designs with higher integrity for the subsequent phases of ship design beyond ESSD.

7. Conclusion

The paper has focused on an important part of design decision-making, that of style choice. This has been addressed through discussing actual ship designs in history and specific ship research investigations on discrete ship style related issues, recently undertaken at UCL. A way forward proposed in an early joint paper has been seen as a means to further emphasise this paper’s assertion that choice of overall design style is probably the key design decision. Such a clearer decision choice should be made (hopefully) explicitly at the earliest step in starting any design option to ensure better design exploration and, hence, a better downstream process.

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Big Data Analysis for Service Performance Evaluation and Ship Design

Hideo Orihara, Japan Marine United Corporation, Tsu/Japan, orihara-hideo@jmuc.co.jp
Hisafumi Yoshida, Japan Marine United Corporation, Tsu/Japan, yoshida-hisafumi@jmuc.co.jp
Ichiro Amaya, Japan Marine United Corporation, Tsu/Japan, amaya-ichiro@jmuc.co.jp

Abstract

This paper describes our experiences in big data analysis of on-board ship performance monitoring data for the evaluation of ship's service performance and the feedback to ship design. Full-scale performance monitoring and analysis method devised at Japan Marine United Corporation is presented, which has been developed mainly for the performance evaluation of large merchant ships in service, and which have been found to give satisfactory practical results over a number of years. Monitored full-scale performance data is analysed in a similar way as that employed in ship's speed trials and the results are compared with performance predictions conducted at the design and development stages. Performance evaluations are made for a large bulk carrier. It is shown that by employing the newly developed monitoring and performance analysis method, full-scale performance can be evaluated with high degree of confidence and its results can effectively utilized in the ship design stage.

1. Introduction

In recent years, large-size on-board performance data which cannot be obtained for commercial use in the past has become available for ship's service performance analysis. Whilst these data may not be regarded strictly as Big Data as generally recognized, they possess similar characteristics as Big Data and require special data analysis procedures to deal with. Big Data is usually characterized by 3 Vs including "Volume", "Velocity" and "Variety" which require specific technology and analytical methods for its transformation into value. From the ship performance monitoring point of view, posset ions of 3 Vs-like features can be admitted in the context in the drastic change in technologies in the on-board monitoring. In terms of "Volume", growth in monitoring data size has been noticeable. Until quite recently service performance monitoring, in particular hull performance monitoring, has been conducted mainly from abstract logs or noon-report data with a daily sampling rate. At the present time, however, continuous automatic monitoring has increasingly employed and high-frequency monitoring with sampling rate of 1 Hz and above has been common practice on normal merchant vessels. Along with the increase in sampling rate, a size of monitoring items is also increased from the past normal practice of around 10 items to more than 100 items. As a result, a size of monitoring data has increased by an order of 10^6 and above over the past norm. As for "Velocity", this is generally defined as availability of data in real-time manner. Recent service performance monitoring technology with the use of automatic data transmission capability to shore-side users follows exactly this definition. As for "Variety", this denotes variety of data type and data source. Tendency to collect performance data from normal on-board equipment (such as VDR, EMS) bring about similar challenges concerning the way to deal with the variations in data collected.

To cope with these radical transformations in on-board performance monitoring environment, we have established new monitoring and analysis procedures which can deal with the large size data. For on-board monitoring and automatic data transmission to the shore-side users, we have developed "Sea-Navi" voyage support system for on-board performance monitoring, *Orihara and Yoshida (2010), Orihara et al..(2016)*. Monitoring is conducted continuously of items including ship's position, speed, power, fuel consumption and weather conditions. Monitored performance data are statistically analysed in the on-board sub-system in an automatic manner for the specified duration of time to reduce data size and cost for analysis work. Statistically analysed data are sent shore-side sub-system and examined by means of physics-based rigorous analysis methods as will be described in the present study.

Reverting to the physical nature of ship's service performance, In the course of its normal duties, merchant ships in service are continuously exposed to a variety of disturbances which can in one way or another affects its performance. In a seaway, wind and wave conditions combine to increase the propulsive performance necessary to maintain economical service speed. In addition, intentional steering and manoeuvring motion result in noticeable changes in performance from that in steady advancing on straight course.

The full-scale performance of large merchant ships has long been predicted by extrapolating model-scale tank test results using some combination of correlation factors accounting for the scale effects between model and ship. Whilst this performance evaluation procedures has been effective for some ship types for which full-scale performance can be verified by new-building speed trials conducted in designed laden condition (e.g. tankers) and its results can be readily fed back to prediction at the design stage, accuracy of performance prediction is usually deteriorated considerably for most types of large merchant ships for which new-building speed trials are conducted only in light-load condition. So, for these types of ships, full-scale performance verification is compelled to rely on service performance data.

It has been frequently stated that full-scale on-board performance data are so unreliable and inconsistent that, having in mind that the large amount of work involved for eliminate the effects of many disturbing factors, the detailed analysis of such data is not worthwhile compared to the analysis of new-building speed trials data, but this has not been the author's experience. It is true that the performance data recorded on board is subject to the effects of a variety of disturbances and difficult to apply to detailed analysis on hydrodynamic bases. However, when a sufficient amount of data is available and appropriate analysis methods such as those presented in this paper is employed, high-quality performance evaluation with a comparable accuracy as those from normal new-building speed trials can be obtained. In any case, it is apparent that the final criterion of ship performance must obviously be the results that are consistently monitored and analysed in service, and the ship designer should finally accept this position.

Service performance monitoring and analysis has long history and has been utilized for the management of ship operations over the years. Several works have been done in service performance analysis by utilizing abstract log data, e.g. *Telfer (1926), Clements (1957), Logan (1960)*. In recent years, "Big Data Analysis" like works based on detailed on-board performance monitoring data which is similar to the present work has been reported, *Furustam (2016), Gundemann and Dirksen (2016), Gunnsteinsoson and Clausen (2016), Solonen (2016)*. Most of these reference works are conducted mainly from a ship owner/operator's point of view, and attentions has been devoted to the evaluation of the rate of ship's performance deteriorations due to fouling and wind and wave disturbances with a time after delivery or out of dock. Whilst these evaluations are quite useful for economical operation of merchant ships, from the ship design point of view, more detailed service performance analysis applicable to the verification of design performance predictions.

In normal full-scale ship performance predictions conducted at design stage, ship's performance is evaluated under strictly defined weather conditions. In normal practice at the present day, still-water condition which means no wind and no waves are principal weather conditions for performance evaluation. In addition to it, specifically defined weather conditions such as Beaufort wind force scale based weather conditions are employed for the performance in a seaway. Thus the primary consideration in this paper is placed on the evaluation of full-scale performance under these specifically defined weather conditions and the verification of the design performance predictions.

The next section describes the on-board monitoring system employed in the present full-scale performance analysis method. Then, the physics-based full-scale performance analysis method is described. After that, effectiveness of the proposed full-scale performance monitoring and analysis method is examined by evaluating the analysis results obtained on a bulk carrier in fully loaded condition in both still water and seaway. Analysed full-scale results are compared with performance characteristics predicted at the design and development stage. Brief conclusions are presented in the final section.

2. On-board performance monitoring system

On-board monitoring system employed in this study is “Sea-Navi” voyage support system developed by Japan Marine United Corporation, *Orihara and Yoshida (2010)*. Since their principal features are almost the same, and details of “Sea-Navi” monitoring system is described as a representative in the following.

Typical configuration of “Sea-Navi” monitoring system is shown in Fig.1. This system primarily consists of a suite of sensors (whose combination differs for a particular ship) and a system’s PC to acquire, analyse and display data. Most of hull-related data (ship’s speed, course, heading wind, rudder angle etc.) are obtained from Voyage Data Recorder (VDR) as a LAN output data. Machinery-related data (fuel-oil flow rate, fuel-oil temperature, shaft power etc.) are obtained from engine-room data logger. Ship motions and encountered waves are optional monitoring item and measured by using dedicated motions sensors and a radar wave analyser.

Measured data are merged as a time-series data file of 20-min length containing all the data items. Then, statistical analysis of the time-series data is conducted in the system’s PC. Average, minimum, maximum, standard deviation, significant value and zero up-cross period are calculated all the data items at an interval of 20-minute.

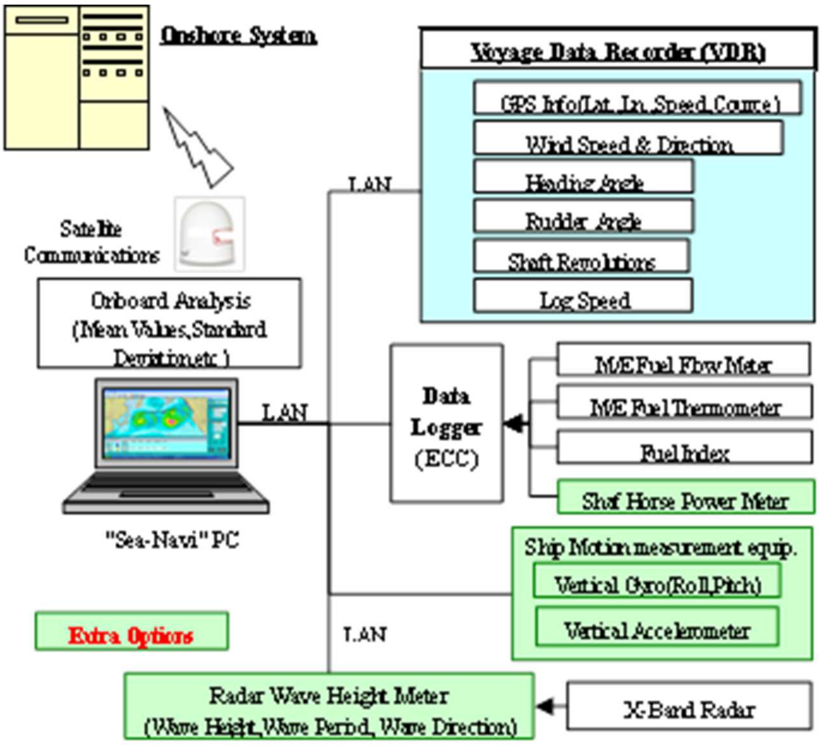

Fig.1: Configuration of “Sea-Navi” on-board monitoring system

3. Full-scale performance analysis method

Monitored performance data are analysed to give results as propulsive power increase due to encountered weather effects on the basis of Beaufort wind force (B.F.) scale. The analysis of monitored data is divided into the following four steps:

(1) Step 1: scrutiny of monitored data.
(2) Step 2: estimation of resistance increases due to encountered disturbances.
(3) Step 3: correction of ship’s performance for the effect of disturbances.
(4) Step 4: evaluation of ship’s performance in standard weather conditions.

3.1. Scrutiny of monitored data

In order to remove uncertainty of data and conduct the analysis under equivalent basis to the extent possible, certain group of monitored data is selected for the analysis. For the performance analysis on still-water condition (i.e. no wind and wave condition), following criteria are specified in the data scrutiny:

1. Propeller revolutions are greater than those corresponding to minimum output of the main engine capable of continuous running to eliminate the data during at excessively slow speeds such as harbour manoeuvres.
2. Difference in propeller revolution during certain duration of time is within certain threshold value of maximum propeller revolution corresponding to MCO to eliminate the data during accelerating or decelerating operations.
3. Average and standard deviation of rudder angle during certain duration of time are within certain threshold values to eliminate the data during intentional steering operations.
4. True wind speed is less than certain threshold value to eliminate data under strong winds.
5. Significant wave height is less certain threshold value to eliminate data in large waves
6. Pitch and roll angle are less than certain threshold values to eliminate data in rough weather conditions

For the performance analysis in standard wind and wave conditions, only (1)～(3) of the above criteria is imposed.

3.2. Estimation of resistance increases due to encountered disturbances

Ship's resistance increases due to environmental and external disturbances such as wind, waves, steering and drifting are estimated.

Resistance increase due to wind (dR_{WIND}) is calculated by

$$dR_{WIND} = \frac{1}{2}\rho_a \cdot A_T \cdot \left\{ C_{AA}\left(\Psi_{WIND,R}\right)\cdot V_{WIND,R}{}^2 - C_{AA}(0)\cdot V_G{}^2 \right\} \tag{1}$$

where ρ_a is the mass density of air, A_T is the transverse projected area above the waterline including superstructure, $C_{AA}()$ is the wind resistance coefficient; $C_{AA}(0)$ means the wind coefficient in head wind, $\Psi_{WIND,R}$ is the relative wind direction, $V_{WIND,R}$ is the relative wind speed, V_G is the ship's speed over ground.

The wind resistance coefficient is based on the data derived from model tests in wind tunnel or data calculated by the method in ISO15016_ 2015, *ISO (2015).*

Resistance increase due to wave (dR_{WAVE}) is presented as a summation of resistance increases due to wind waves and swell and calculated by

$$dR_{WAVE} = \rho_w \cdot g \cdot \left(\frac{B^2}{L}\right)\cdot \left\{ H_{WDWV}{}^2 \cdot C_{AW,WD}\left(\chi_{WDWV}, T_{m,WDWV}\right) + H_{SWLL}{}^2 \cdot C_{AW,SL}\left(\chi_{SWLL}, T_{SWLL}\right) \right\} \tag{2}$$

where ρ_w is the mass density of water, g is the acceleration of gravity, B is the ship's breadth, L is the ship's length, H_{WDWV} is the significant height of wind waves, H_{SWLL} is the height of swell, $C_{AW,WD}()$ is the coefficient for the added resistance due to wind waves, $C_{AW,SL}()$ is the coefficient for the added resistance due to swell, χ_{WDWV} is the encounter angle of wind waves; 0 means head waves, χ_{SWLL} is the encounter angle of swell; 0 means head swell, $T_{m,WDWV}$ is the mean period of wind waves, T_{SWLL} is the period of swell.

$C_{AW,WD}()$ and $C_{AW,SL}()$ are calculated by linear superposition of the directional wave spectrum and the response function of the mean resistance increase in regular waves. Response function of the mean wave resistance increase in regular waves is based on the data derived from tests in ship model basin or data calculated by the method in ISO15016_ 2015, *ISO (2015).*

Resistance increase due to steering (dR_{RUD}) is calculated by

$$dR_{RUD} = (1 - t_R) \cdot F_N \cdot \sin \delta_R \tag{3}$$

where t_R is the deduction factor for resistance due to steering, F_N is the normal force acting on the rudder, δ_R is the rudder angle.

The deduction factor for resistance due to steering is based on the data derived from tests in ship model basin. In cases where a data base is available covering ships of similar type, such data is used instead of carrying out model tests.

Resistance increase due to drifting (dR_{DRFT}) is calculated by

$$dR_{DRFT} = \frac{1}{2} \cdot \rho_w \cdot V_w^{\ 2} \cdot L \cdot d \cdot C_{DRFT,X}(\beta) \tag{4}$$

where V_w is the ship's speed through water, d is the ship's mean draft, $C_{DRFT,X}()$ is the coefficient for the resistance increase due to drifting of the ship, β is the drifting angle of the ship.

t_R and $C_{DRFT,X}()$ are based on the data derived from tests in ship model basin. In cases where a data base is available covering ships of similar type, such data can be used instead of carrying out model tests.

3.3. Correction of ship's performance for the effect of disturbances

After scrutiny of the monitored data, speed/power performance of the ship is corrected for the effect of external disturbances to obtain the performance in the specified weather and operating conditions. Procedure for the performance correction is established based on the resistance and resistance and thrust identity method, *Bertram (2000), ITTC (2011)*. The resistance and thrust identity method is principally based on the assumption that over the normal range of full-scale ship operations, ship's propeller produces the same thrust in a wake field of wake fraction w as in open water with speed $V_w(1-w)$ and that ship's total resistance in a seaway is represented by the linear summation of still-water resistance and resistance increases due to disturbances encountered.

Ship's speed/power performance correcting calculation is made by using ship's resistance/self-propulsive characteristic and propeller open-water characteristic data obtained from tests in ship model basin or theoretical methods which has accuracy equivalent to model tests. For the ease of conduct of the correction, Propeller open-water characteristics are described by the following formulae:

$$K_T(J) = a_T J^2 + b_T J + c_T \tag{5}$$

$$K_Q(J) = a_Q J^2 + b_Q J + c_Q \tag{6}$$

$$\tau_P(J) = a_T + b_T / J + c_T / J^2 \tag{7}$$

where $K_T()$ is the thrust coefficient, $K_Q()$ is the torque coefficient, $\tau_P()$ is the load factor ($=K_T(J)/J^2$), J is the propeller advance coefficient ($=V_A/n_P D_P$), V_A is the speed of flow into propeller, n_P is the propeller shaft speed, D_P is the propeller diameter, a_T, b_T, c_T, are the factors for the thrust coefficient curve, a_Q, b_Q, c_Q, are the factors for the torque coefficient curve.

The correction is based on the resistance increases corresponding to the external disturbances estimated by Eq. (1) to (4). Ship's total resistance is calculated from the monitored ship's delivered power, then the total resistance is corrected by deducing the estimated resistance increases. Finally, corrected speed/power performance is obtained.

The performance correction is conducted for the following 2 standard weather conditions:

(1) Still water condition (no wind and wave condition) for the verification of ship's normally contracted performance.
(2) Beaufort weather condition (wind and wave conditions specified according to the Beaufort

wind force scale, *WMO (1995)*, for the verification of ship's performance in a seaway, Table 1.

Table 1: Beaufort scale based standard weather condition

Beaufort Scale	Wind Speed (m/s)	Sig. Wave Height (m)	Mean Wave Period* (s)
1	0.90	0.1	1.2
2	2.45	0.2	1.7
3	4.40	0.6	3.0
4	6.70	1.0	3.9
5	9.35	2.0	5.5
6	12.30	3.0	6.7
7	15.50	4.0	7.7
8	18.95	5.5	9.1

* : wave period (T_m) is calculated from wave height as $T_m = 3.86\sqrt{H_W}$.

The adaptation of wind speed based B.F. scale as a weather scale for the analysis is based on the consideration that the evaluation of prevailing wind conditions is far more accurate than the corresponding assessment of the wave conditions.

In the following, procedure for the correction of ship's performance into still water condition is described.

First, the delivered power to the propeller ($P_{D,S}$) is calculated from measured shaft power ($P_{S,S}$) by,

$$P_{D,S} = P_{S,S} \cdot \eta_S \tag{8}$$

where $P_{S,S}$ is the measured shaft power, η_S is the shaft efficiency.

The propeller torque coefficient in the monitored condition ($K_{Q,S}$) is calculated by

$$K_{Q,S} = \frac{P_{D,S} \cdot \eta_R}{2\pi \cdot \rho_w \cdot n_s^3 \cdot D_P^5} \tag{9}$$

where η_R is the relative rotative efficiency of the propeller, n_S is the measured shaft speed, D_P is the propeller diameter.

The propeller advance coefficient in the monitored condition (J_S) is determined by Eq. (10) using the torque coefficient $K_{Q,S}$,

$$J_S = \frac{-b_Q - \sqrt{b_Q^2 - 4a_Q \cdot \left(c_Q - K_{Q,S}\right)}}{2a_Q} \tag{10}$$

The thrust coefficient in the monitored condition $K_{T,S}$ is obtained by Eq. (5) using the propeller advance coefficient J_S. Then, the propeller efficiency ($\eta_{O,S}$) is obtained as,

$$\eta_{O,S} = \frac{J_S}{2\pi} \cdot \frac{K_{T,S}}{K_{Q,S}} \tag{11}$$

The load factor of the propeller τ_S is calculated as

$$\tau_S = \frac{K_{T,S}}{J_S^2} \tag{12}$$

Full-scale propeller wake fraction is calculated by

$$1 - w_S = \frac{V_a}{V_w} = \frac{J_S \cdot n_S \cdot D_P}{V_w} \tag{13}$$

where V_w is the ship's speed through water.

The total resistance in the measured condition $R_{T,S}$ is also estimated using the propeller load factor τ_S:

$$R_{T,S} = \rho_w \cdot V_w{}^2 \cdot D_P{}^2 \cdot (1-t) \cdot (1-w_S)^2 \cdot \tau_S \tag{14}$$

where t is the thrust deduction factor.

Propulsive efficiency coefficient $\eta_{D,S}$ is calculated using propeller efficiency and self-propulsion factors as

$$\eta_{D,S} = \eta_{O,S} \cdot \eta_R \cdot \frac{1-t}{1-w_S} \tag{15}$$

The total resistance is corrected by subtracting the estimated resistance increases from $R_{T,S}$ as,

$$R_{T,S,Crct} = R_{T,S} - (dR_{WIND} + dR_{WAVE} + dR_{RUD} + dR_{DRFT}) \tag{16}$$

The corrected load factor of the propeller is determined using corrected as,

$$\tau_{S,Crct} = \frac{R_{T,S,Crct}}{\rho_w \cdot V_w{}^2 \cdot D_P{}^2 \cdot (1-t) \cdot (1-w_S)^2} \tag{17}$$

The corrected propeller advance coefficient is determined by Eq. (18) using the corrected load factor $\tau_{S,Crct}$,

$$J_{S,Crct} = \frac{-b_T - \sqrt{b_T{}^2 - 4c_T \cdot (a_T - \tau_{S,Crct})}}{2(a_T - \tau_{S,Crct})} \tag{18}$$

The thrust and torque coefficients of the propeller is corrected by substituting $J_{S,Crct}$ in Eq. (5) and (6). Then the corrected propeller efficiency is obtained as,

$$\eta_{O,S,Crct} = \frac{J_{S,Crct}}{2\pi} \cdot \frac{K_{T,S,Crct}}{K_{Q,S,Crct}} \tag{19}$$

Corrected propulsive efficiency coefficient is obtained as

$$\eta_{D,S,Crct} = \eta_{O,S,Crct} \cdot \eta_R \cdot \frac{1-t}{1-w_S} \tag{20}$$

Then the required correction for delivered power Δ P is calculated as,

$$\Delta P_{D,S} = \frac{(R_{T,S} - R_{T,S,Crct}) \cdot V_w}{\eta_{D,S,Crct}} - P_{D,S}\left(1 - \frac{\eta_{D,S}}{\eta_{D,S,Crct}}\right) \tag{21}$$

The corrected delivered power to the propeller is obtained as follows

$$P_{D,S,Crct} = P_{D,S} - \Delta P_{D,S} \tag{22}$$

The corrected shaft power is obtained as,

$$P_{S,S,Crct} = P_{D,S,Crct} / \eta_S \tag{23}$$

The corrected propeller speed is obtained from the corrected propeller advance coefficient as

$$n_{S,Crct} = \frac{(1-w_S) \cdot V_w}{J_{S,Crct} \cdot D_P} \tag{24}$$

For the case of the correction of ship's performance into Beaufort standard weather condition, procedure is the same as for the case of still water condition except for the total resistance correction, Eq. (16). For the Beaufort standard weather case, total resistance is corrected only for the difference of the wave effect between actual weather condition and measured-wind-speed based Beaufort weather condition. In Beaufort standard weather condition, wave condition is specified as follows:

(1) Wave height ($H_{WV,BF}$) : calculated from measured absolute wind speed according to Table 1.
(2) Wave period ($T_{m,WV,BF}$) : calculated from measured absolute wind speed according to Table 1.
(3) Wave direction ($\chi_{WV,BF}$) : set same as measured absolute wind direction.
(4) Characteristics : consisted of wind waves only, no swell component.

Thus, the total resistance is corrected by subtracting the estimated resistance increases due to waves and substituting the estimated resistance increase corresponding to the Beaufort standard weather condition ($dR_{WAVE,BF}$),

$$R_{T,S,Crct} = R_{T,S} - \left(dR_{WAVE} - dR_{WAVE,BF}\right) \tag{26}$$

$dR_{WAVE,BF}$ is calculated as a resistance increase due to wind waves of magnitude according to the Beaufort standard weather condition as,

$$dR_{WAVE} = \rho_w \cdot g \cdot \left(\frac{B^2}{L}\right) \cdot \left\{ H_{WV,BF}{}^2 \cdot C_{AW,WD}\left(\chi_{WV,BF}, T_{m,WV,BF}\right) \right\} \tag{27}$$

3.4. Evaluation of ship's performance in standard weather conditions

Corrected ship's performance obtained from the calculations with the procedures described in the preceding section is used for the verification of the performance predictions conducted at the design and development stages. As mentioned earlier, usually ship's full-scale performance is confirmed only for that in trial condition (i.e. lightly loaded condition), thus the actual performance in fully loaded condition (normally design condition) is not verified for most of ship types. In addition, as ship's speed trial conducted before delivery is conducted relatively calm sea condition (usually less than Beaufort wind scale 5), their performance under actual operating condition, that is its performance in a seaway under the influences of external disturbances including wind and waves has not verified so far.

By means of on-board performance monitoring and analysis methods described in this paper, ship's performance in both fully loaded condition and a seaway can be evaluated and readily compared with those predictions. For the evaluation of performance in fully-loaded condition, corrected speed/power performance is compared with the prediction obtained from model test results in terms of so-called speed-power curves. Detailed analysis of the corrected performance enables us to obtain model-ship correlation allowances, that is correction factors for the resistance and self-propulsive factors applied in the performance predictions. For the evaluation of performance under the influences of external disturbances, comparison is usually made in terms of the performance deterioration from the still water (no wind/wave) condition using the indexes such as power increase or speed loss.

4. Examples of service performance analysis of a large bulk carrier

To evaluate the effectiveness of the full-scale performance monitoring and analysis method described in the previous sections, full-scale performance monitoring has been conducted on a large bulk carrier, and measured performance data are analysed according to the present method and verified through the comparison with the prediction results.

4.1. Test ship

A large bulk carrier recently built by JMU (designated as "Ship A" henceforth) is selected as the test ship for the full-scale performance monitoring and analysis. Its dimensions are about 320m in length, about 55m in width and about 30m in depth, respectively. Ship A has been mainly operated on the route between Brazil and East Asia.

4.2. Results and discussion

Evaluation of fully loaded performance is made for Ship A using their laden voyage data of time duration of about 40. To reduce the influences fouling and aging effects in the performance correction, this voyage case is selected from those made within 6 months from the delivery.

4.2.1. Characteristics of monitored full-scale data

Time series of the monitored data is shown in Fig.2 which include encountered weather (wind speed, wave height), rudder angle (average, standard deviation (S.D.)), ship motions (pitch, roll angles), speed through water, shaft power and revolution.

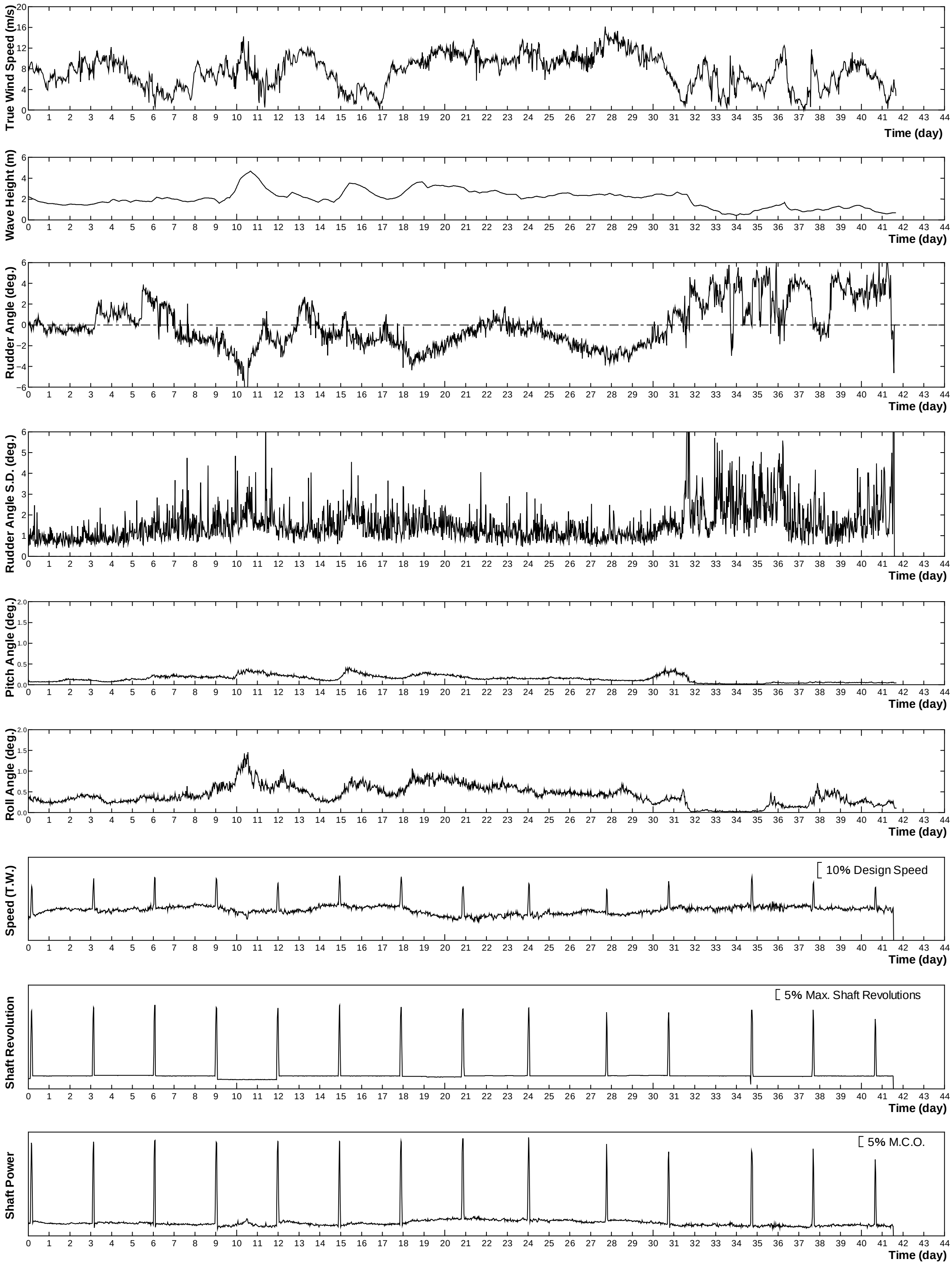

Fig.2: Monitored weather and performance data of Ship A, laden voyage.

All the data shown in Fig.2 is those processed over time duration of 20 min from the raw time series data sampled at 1Hz. Except for the S.D. of rudder angle, pitch and roll angles, 20-minute average data are shown for each measured item. As can be clearly seen from the true wind speed figure (top), encountered weather condition seems to be moderate with an average wind speed of around 6 to 8 m/s corresponding to Beaufort wind scale 4. Spike-like behaviours shown in the figures of shaft revolutions and power are due to short-time speed up for the cleaning of main-engine's turbocharger or soot-blowing procedures conducted at an interval of about 3 days during slow-steaming operations. In total, about 2000 data samples (each processed from 20-min time series) have been obtained.

4.2.2. Evaluation of full-scale performance in still water condition

This case of performance evaluation is intended to evaluate ship's performance in still water condition (no wind and wave condition). Since for most of dry cargo vessels this type of performance in design loaded condition cannot be verified on new-building speed trials as mentioned in the introduction, evaluation from monitoring data is of significant practical importance from ship design viewpoint.

From all the monitored data, data scrutiny is conducted according to the following criteria to select appropriate data for the still-water performance evaluation:

(1) Wind speed is less than 4.0 m/s
(2) Wave height is less than 2.0m
(3) Rudder angle average and its standard deviation (S.D.) are less than 2.0 degree
(4) Shaft revolution is greater than 70 % of maximum revolution
(5) Difference in shat revolutions over 30 minute is less than 5 % of the maximum revolution
(6) Pitch angle standard deviation (S.D.) is less than 0.25 degree
(7) Roll angle standard deviation (S.D.) is less than 0.50 degree

The above data scrutiny is principally intended to select data monitored under small disturbances due to both encountered weather (wind and waves) and intentional steering and propelling machinery operation. By setting the stringent criteria for data scrutiny, high-quality data which requires small corrections for the disturbances can be obtained.

After the scrutiny of the data, about 30 samples are obtained. All and selected data are shown in a form of speed/power relationships in Fig.3 together with the estimated speed/power curve predicted at the design stage. In Fig.3, three types of comparison are shown for I) all the monitored data, II) filtered data according to the above mentioned criteria ((1) through (7)), and III) corrected data reduced to the still-water equivalent condition by eliminating the effects of disturbances according to the procedures described in Section 3.

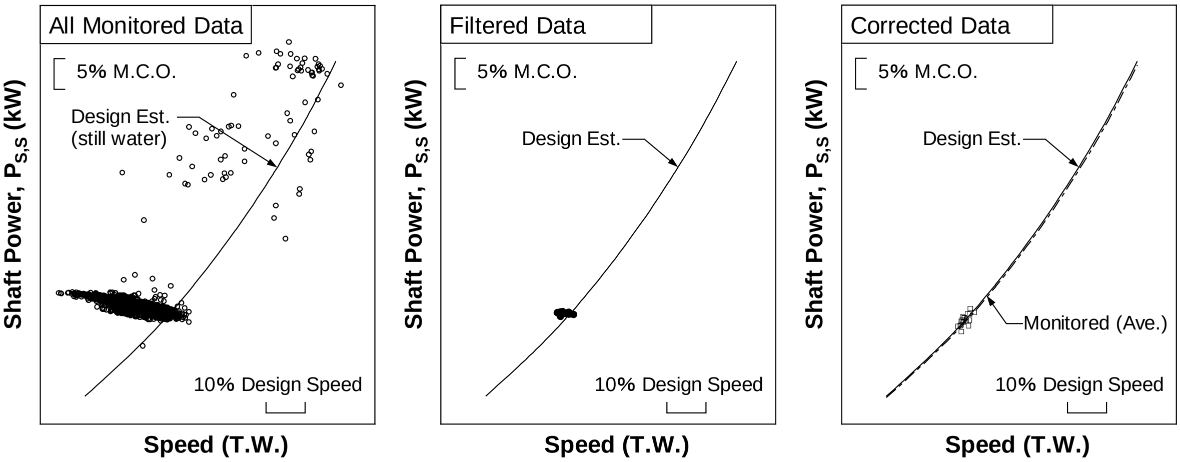

Fig.3: Comparison of speed/power performance of Ship A, laden voyage.

The right figure in Fig.3 shows the corrected speed/power data with the estimated curve. In Fig.3 corrected speed/power curve is included which is calculated using revised model-ship correlation allowances obtained from the full-scale analysis results.

As can be clearly seen in Fig.3, corrected speed/power data and its curve correlate quite well with the design estimated curve. In addition scatter of the corrected data around mean corrected curve is relatively small equivalent to standard deviation of about 1% of ship's design speed.

These favourable corrected results for Ship A imply not only the correctness of the design performance but also the adequacy of the present procedure of performance monitoring and analysis for the means of full-scale evaluation.

4.2.3. Evaluation of full-scale performance in a seaway

Evaluation of the performance in a seaway is made for the test ship using its laden voyage data of about 40 days. Voyage case is the same as selected for the still-water performance analysis.

Fig.4 shows an example of monitored data in a seaway which is divided into groups of wind directions where θ denotes true wind direction relative the ship's heading. Three groups of θ which correspond to head wind ($0^\circ \leqq \theta < 15^\circ$), beam wind ($75^\circ \leqq \theta < 105^\circ$) and following wind ($165^\circ \leqq \theta \leqq 180^\circ$) cases, respectively. Effect of true wind direction (θ) on speed/power performance, that is, reductions in speed loss due to changes in true wind direction can be clearly noticed.

As in the case of still-water performance analysis, data scrutiny is conducted according to the following criteria to select appropriate data for the performance evaluation. In this case the data scrutiny is mainly intended to eliminate the data both under excessive steering and manoeuvring motion and in wave environment different from the Beaufort standard condition

(1) Difference between true wind angle and mean wave direction is less than 45°
(2) Difference between encountered wind-speed based B.F. scale and encountered wave-height based B.F. scale is less than 3.
(3) True wind direction standard deviation (S.D.) is less than 15°.
(4) Rudder angle standard deviation (S.D.) is less than 3°.
(5) Ship's heading standard deviation (S.D.) is less than 3°.
(6) Shaft revolution is greater than 70 % of maximum revolution
(7) Difference in shat revolutions over 30 minute is less than 5 % of the maximum revolution

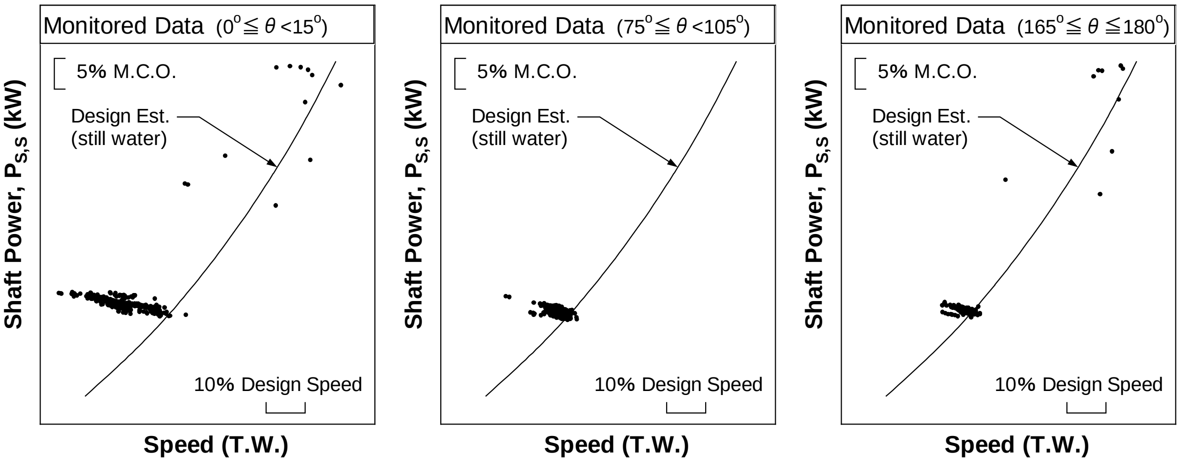

Fig.4: Comparison of speed/power performances between different ranges of wind direction.

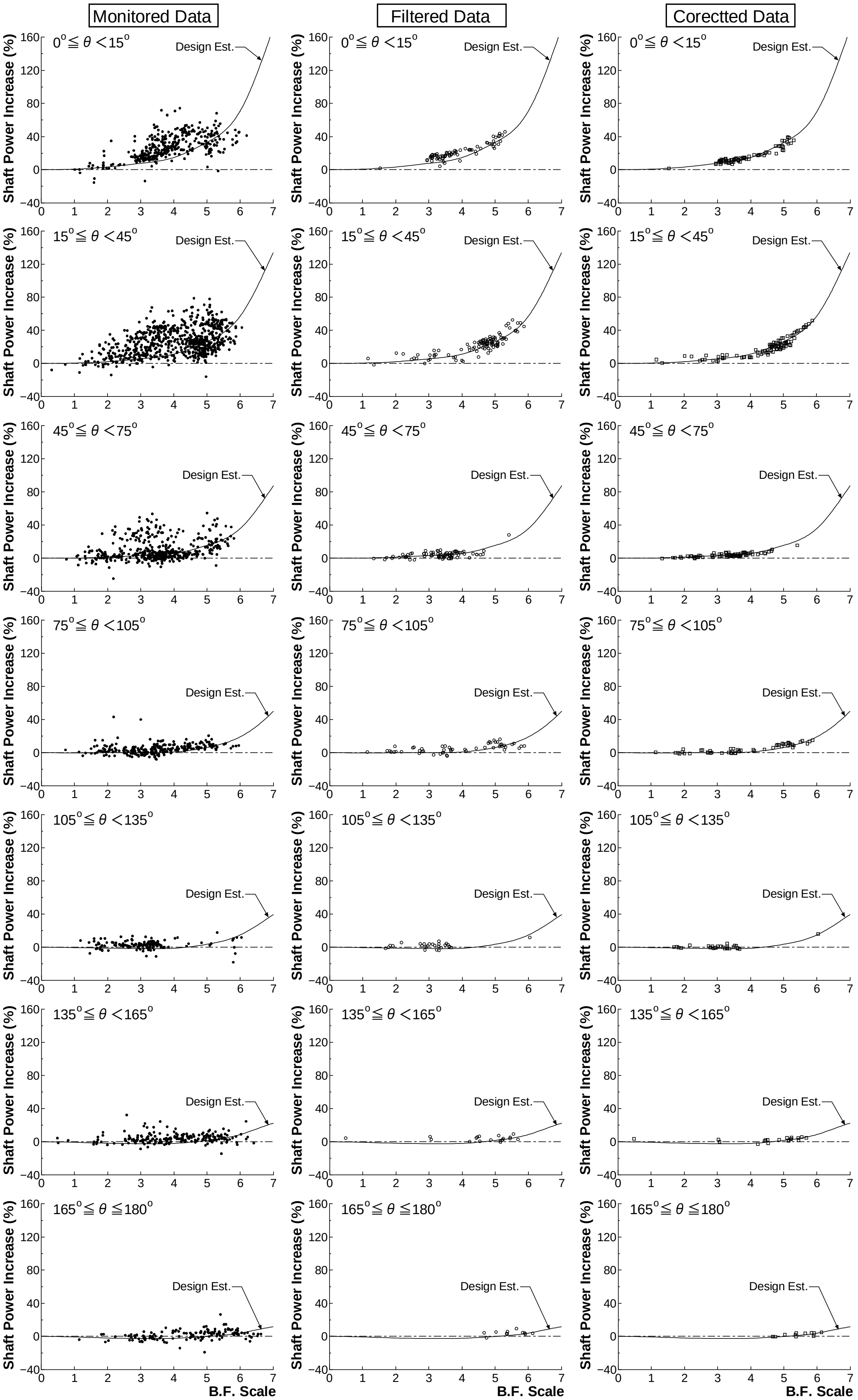

Fig.5: Comparison of shaft power increase for Ship A, laden voyage.

In this case of analysis, ship's performance corrected for the difference of weather disturbances due to waves. That is, resistance increase due to waves is adjusted by substituting the estimated resistance increase under actual wave condition with that corresponding to the Beaufort standard condition based on the encountered true wind speed by means of Eq. (16).

Corrected performance under Beaufort standard weather condition is evaluated in terms of shaft power increase which denotes the percent increase of power relative to the power in still water at same ship's speed through water. Comparison of corrected performance with estimated shaft power increase curve is shown in Fig.5 for a group of wind/wave directions.

In Fig.5, shaft power increase is presented against true-wind speed based B.F. scale. Three types of data consisting of raw monitored data (●), filtered data (○) and corrected data (□) are shown in the left, centre and right graph, respectively. By applying the scrutiny criteria ((1) through (7)), data size is reduced to about 50 percent of original data. Differences between filtered (○) and corrected (□) stand for the effect due to difference in wave conditions between actual weather and the Beaufort standard weather which assumes fully developed wind waves. Principle reasons for the corrections applied in this analysis are the effects of swell and the differences of mean periods and encounter directions of waves. In the case where swell effect is predominant, corrected sea margin is noticeably reduced from the monitored data. On the other hand, in the case where encounter directions of wind and waves differ by large amount, correction can be large because the resistance increase due to waves changes significantly with encounter angle. If the wave encounter direction is small (close to bow) than the encounter wave direction, wave resistance increase is corrected to a smaller value than that corresponding to the actual encountered wave condition.

As shown in shown in Fig.5, corrected shaft power increases correlate quite well with the estimated curves. Also noted is that the corrections of shaft power increase data due to the difference in wave conditions is relatively small which is the order of corrections are less than 10% for most of filtered data. This implies that there exists a noticeable difference in wave conditions between actual weather and monitored wind-speed based Beaufort standard wave condition, and that ship's performance evaluation in a seaway should be conducted by imposing stringent scrutiny criteria considering the actual wave conditions instead of evaluation solely based on wind-speed based Beaufort weather condition.

These reasonable agreements between corrected results with the estimations in terms of shaft power increase in a seaway under wide range of wind and wave conditions imply that ship's performance in service can be estimated using the present prediction approach which is based on the resistance and thrust identity method. Also should be stressed is that the speed/power performance is affected significantly from the effect of encountered waves and that the accurate evaluation of those effect is crucial in enhancing the accuracy of full-scale performance monitoring and analysis.

5. Conclusions

In this paper, full-scale performance of large merchant ships is evaluated by means of newly developed on-board performance monitoring method. Full-scale performance monitoring and analysis method based on on-board performance monitoring has been developed for the performance evaluation of large merchant ships in service. Monitored full-scale performance data is analysed in a similar way as that employed in ship's speed trials and the results are compared with performance predictions conducted at design and development stage. Performance evaluations are made in terms of still-water performance and seaway performance for a variety of 3 merchant ships of large bulk carrier. It is shown that by employing present monitoring and performance procedures, full-scale performance can be evaluated with high degree of confidence and its results can effectively utilized to improve the accuracy of performance predictions at design stage.

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Case Study - Totem Fully Autonomous Navigation System

Azriel Rahav, Totem plus, Ramat HaSharon/Israel, azriel@totemplus.com

Abstract

The Totem Autonomous Navigation System enables a USV to operate on the waters without a crew even when the vessel is without radio contact. The vessel can be operated in a fully autonomous way with route keeping, collision avoidance and danger/obstruction avoidance capabilities as well as interception functionality: (1) The built in, fully approved ECDIS uses vector electronic charts and provides powerful route planning, monitoring capabilities and interception ability. The system can be configured for the task in advance or change the task during the voyage by the control station. (2) The integrated Track control system keeps the vessel on a selected pre-determined route with unlimited number of waypoints. The route can be regular, cyclic, ASR etc. Dangers and cautions along the track are automatically avoided. (3) Collision and Obstruction Avoidance capabilities: the system enables safe sailing by automatically avoiding danger from collisions and obstructions. This aim is achieved by analyzing automatically ALL the targets and obstructions within the selected range around the ship, and applying change of course to steer or speed as required. The stipulations of the COLREGS are taken into account and the advice is complying in full with the COLREGS. The system categorizes the targets according to their status (crossing, overtaking, head-on etc.) and applies the requirements of the COLREGS (Give Way, Stand On etc.) according to the required parameters. The system can handle a multiple vessels scenario. Dangers along the new course are avoided automatically. (4) Interception functionality: This function enables the user of the Control Station (CS) to select a specific target on the map, and instruct the system to intercept it. The system calculates continuously the required Intercept Course and Speed and follows the target according to its changing parameters.

1. Introduction

In a world quickly entering an era of driverless cars, or at least talking about it, it is only a matter of time before the maritime industry will be faced with Unmanned Surface Vessels. Such USVs start from remotely controlled vessels (without autonomous capability) and go all the way to fully autonomous vessels, with a combination of both in the interim.

The incentive for unmanned ships can come from several aspects. The shipping community is faced with rising difficulties to obtain good officers and crews, the life onboard is becoming less and less appealing to young people, cost of crew are always a major expense, unfortunately humans tend to err - and errors at sea result in lives lost and loss of assets. During 2013 alone there were more than 10 collisions between ships, more than 150 seamen lost their lives and more than 1000 tons of heavy fuel polluted the sea - most of those accidents were attributed to Human Error; e.g. Allianz estimates 80% of marine casualties are down to human error, *NN (2015); Rothblum et al. (2002)* estimate 75-96% of marine casualties are caused, at least in part, by some form of human error. Further, certain tasks are best done without risking people, for example patrolling in rough weather or mine sweeping in dangerous waters.

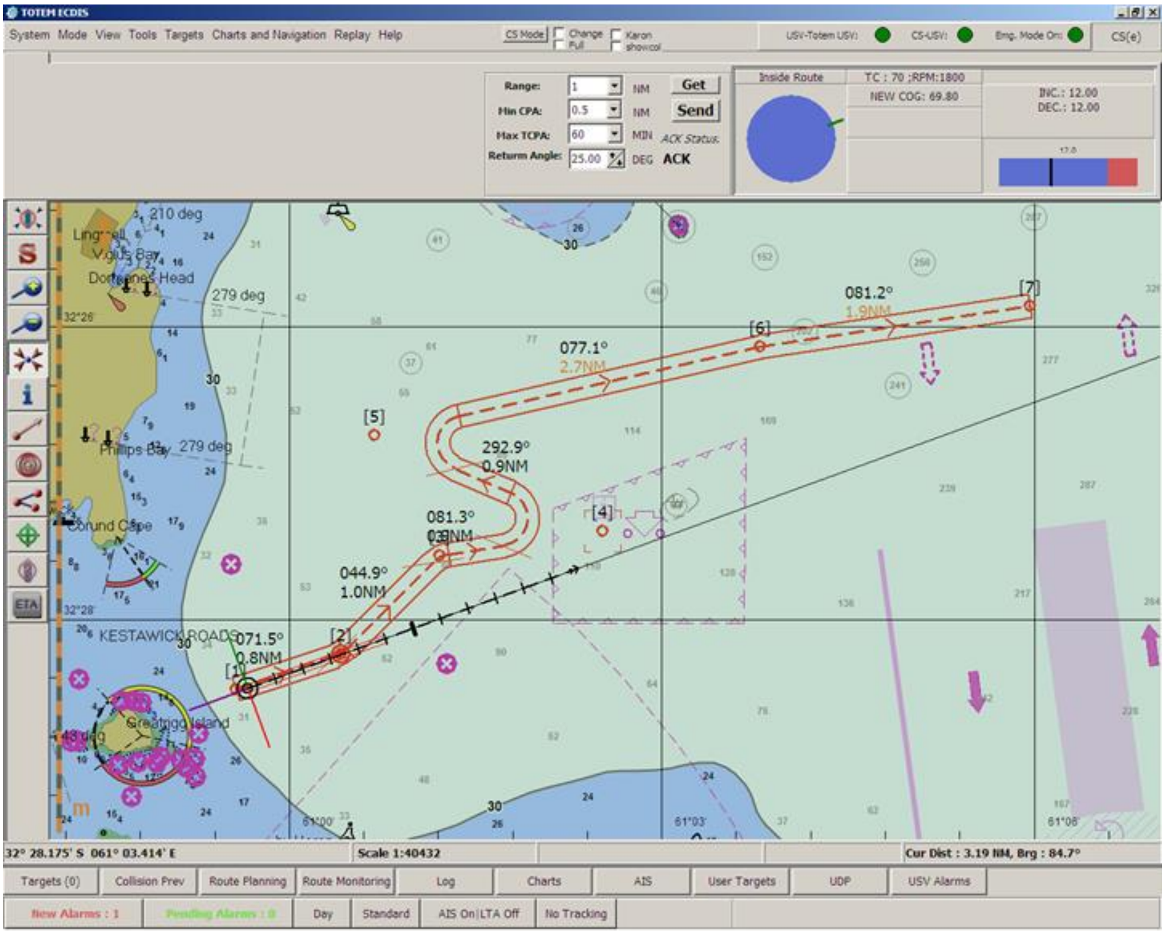
Totem Plus is active in the Autonomous Vessels field for few years, during which the Totem Autonomous Navigation System (TANS) was fine tuned to offer full autonomous control of a fast unmanned craft. The TANS can provide track control for various pre-defined routes, offer obstruction avoidance and collision avoidance by course and speed control, and much more. The system can be fully autonomous but can also be remote controlled from a command center by radio communication.

2. Totem Autonomous Navigation System

Totem Autonomous Navigation System is based on Totem ECDIS, short for “Electronic Chart Display and Information System”, with the additional features of track control, Collision Avoidance, Obstruction Avoidance and other functions required for USV autonomous operation. Further, the system is synchronized between the vessel and the control station ashore, passing information in both directions and allowing the operator in the control station to supervise and take control if required. When needed the operator can take complete control or (more likely) change the setup of the vessel as required – change route, change setup configuration (for example obstruction avoidance parameters) , send the vessel to intercept a moving target and so forth.

The use of a fully approved ECDIS allows the USV to operate with approved marine charts, according to the newest IMO and IHO requirements which require use of ENC charts only. The system can therefore use any ENC chart coded in the S57 or S63 protocol and tested by the S64 protocol. Such charts are also updated constantly by the issuing authority. In the USV there is no need for visual monitor, of course, but the data is used by the system for proper route keeping and obstruction avoidance. The operator in the control station can see the chart, and can add objects or prepare routes as required and pass it to the USV system. Further, the control station system ashore have all the information from the vessel at sea in real time, either from on-board sensors such as GPS or compass, or additional info from other sources such as shore based VTS radars. All the information is plotted on the chart in the control station, including targets information from sensors like AIS and ARPA, or from operator knowledge coming from other sources.

Once configured for a specific task, the vessel can operate on the water without a crew even when the vessel is without radio contact for any reason (Fully Autonomous mode). Route keeping, collision avoidance, danger/obstruction avoidance and “return to base” capabilities are built-in in the system and can work without human intervention. Interception functionality is available for targets chosen by the operator, and the intercept will continue autonomously according to the requested parameters.

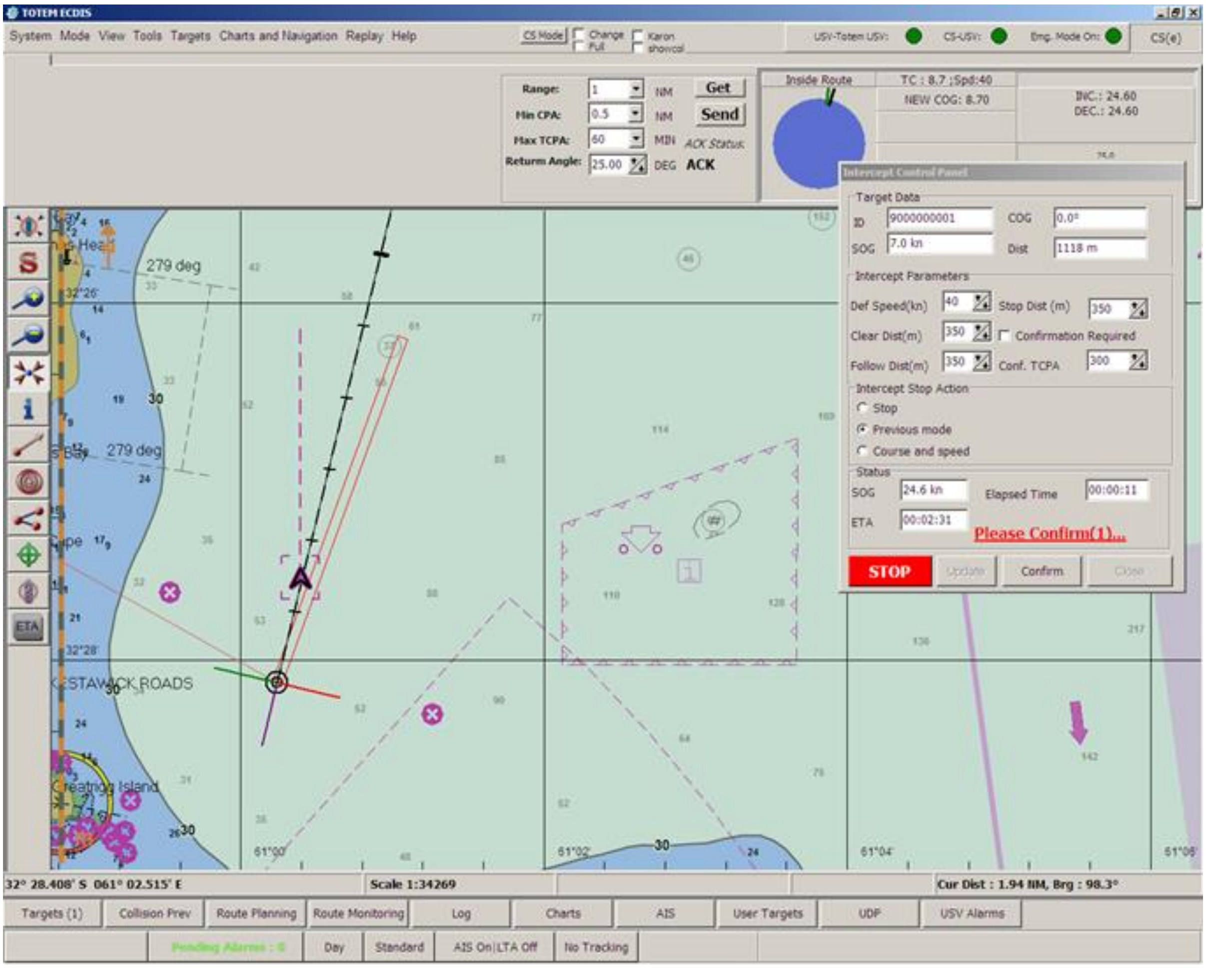


Range: 1 NM
Min CPA: 0.5 NM
Max TCPA: 60 MIN
Return Angle: 25.00 DEG
ACK Status: ACK
TC : 70 ;RPM:1800
NEW COG: 69.80
INC.: 12.00
DEC.: 12.00
32° 28.175' S 061° 03.414' E
Scale 1:40432
Cur Dist : 3.19 NM, Brg : 84.7°
New Alarms : 1
Pending Alarms : 0

Fig.1: Pre-determined route

The integrated Track control system keeps the vessel on a selected pre-determined route with unlimited number of waypoints. The route can be regular, cyclic, SAR etc. Dangers and cautions along the track are automatically avoided, due to the revolutionary collision avoidance system developed by Totem Plus. The system has the capability to analyze automatically all the targets within the selected range around the ship and take action on the best course or the best speed required to keep a certain CPA from all targets. The action taken is in full compliance with IMO's international regulations for preventing Collisions at sea 1972 (COLREGs) and can handle a multiple vessel scenario of up to 100 simultaneous targets. The collision avoidance system is already in operation since 2009 on hundreds of merchant ships as DST (Decision Support Tool) with excellent results, but on a USV it is the part that makes the USV indeed autonomous.

Last but not least, Totem TANS is equipped with a unique Interception functionality that enables the user of the control station (CS) to select a specific target on the chart, and instruct the USV to intercept it by continuously calculating the required intercept course and speed and then follow the target according to its changing parameters.



Range: 1 NM
Min CPA: 0.5 NM
Max TCPA: 60 MIN
Return Angle: 25.00 DEG
ACK Status: ACK

TC : 8.7 ;Spd:40
NEW COG: 8.70
INC.: 24.60
DEC.: 24.60

Target Data
ID 9000000001
COG 0.0°
SOG 7.0 kn
Dist 1118 m

Intercept Parameters
Def Speed(kn) 40
Stop Dist (m) 350
Clear Dist(m) 350
☐ Confirmation Required
Follow Dist(m) 350
Conf. TCPA 300

Intercept Stop Action
○ Stop
● Previous mode
○ Course and speed

Status
SOG 24.6 kn
Elapsed Time 00:00:11
ETA 00:02:31
Please Confirm(1)...

32° 28.408' S 061° 02.515' E
Scale 1:34269
Cur Dist : 1.94 NM, Brg : 98.3°

Fig.2: Interception

3. The USV Katana

Totem Autonomous Navigation System was installed with great success on the Katana, a new Unmanned Surface Vessel (USV) for unmanned combat marine applications, Fig.3. As a multifunction vessel, Katana is compatible with various systems and supports the totally integrated security. The Katana is 12 m long, can go as fast as 60 kn, and is equipped with two Diesel main Engines of 560 HP each.

Fig.3: USV “Katana”

4. Summary

TANS - Totem Autonomous Navigation System - can be embedded into a wide variety of vessels, giving them the capability to sail unmanned and in fully autonomous mode and carry out vessel specific tasks as required. TANS integrates the functionality of approved Electronic Charts, Track Control, Collision Avoidance and Obstruction Avoidance. The experience of Totem Plus in automation and navigation systems during the last 20 years allows the company to offer a mature solution to the USV market.

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Cutting-Edge Underwater Robotics - CADDY Project
Challenges, Results and Future Steps

Marco Bibuli, CNR-ISSIA, Genova/Italy, marco.bibuli@ge.issia.cnr.it
Gabriele Bruzzone, CNR-ISSIA, Genova/Italy, gabriele.bruzzone@ge.issia.cnr.it
Massimo Caccia, CNR-ISSIA, Genova/Italy, massimo.caccia@ge.issia.cnr.it
Davide Chiarella, CNR-ISSIA, Genova/Italy, davide.chiarella@ilc.cnr.it
Roberta Ferretti, CNR-ISSIA, Genova/Italy, roberta.ferretti@ge.issia.cnr.it
Angelo Odetti, CNR-ISSIA, Genova/Italy, angelo.odetti@ge.issia.cnr.it
Andrea Ranieri, CNR-ISSIA, Genova/Italy, ranieri@ge.issia.cnr.it
Enrica Zereik, CNR-ISSIA, Genova/Italy, enrica.zereik@ge.issia.cnr.it

Abstract

This paper describes results from the EU research project CADDY on cognitive autonomous robotics to support divers. The robot communicates with the diver by understanding gestures and acknowledges by light signals and task execution. Validation trials showed feasibility of the approach. In order to successfully achieve these beyond-the-state-of-the-art objectives, a number of specific features and functionalities have been designed and developed from scratch, integrated in the overall CADDY architecture and finally tested for validation. This paper focuses on the development on some of the game-changing techniques needed to face the scientific challenges of the projects.

1. Introduction

The FP7 CADDY (Cognitive Autonomous Diving Buddy) project is funded by the European Commission and was started in January 2014, *Miskovic et al. (2015)*. Seven partner institutions (University of Zagreb, Croatia; National Research Council, Italy; Instituto Superior Tecnico, Portugal; University of Newcastle, UK; Jacobs University, Germany; University of Vienna, Austria; Divers Alert Network Europe, Malta) came together to pursue collaborative R&D work aimed at enhancing cognitive robotics in the underwater arena; specifically, to develop robots capable of cooperating with divers.

The main motivation for the CADDY project, *Bibuli et al. (2016)*, was the fact that divers operate in harsh and poorly monitored environments in which the slightest unexpected disturbance, technical malfunction, or lack of attention can have catastrophic consequences. They manoeuvre in complex 3D environments and carry cumbersome equipment while performing their missions. To overcome these problems, CADDY aims to establish an innovative set–up between a diver and companion autonomous robots (underwater and surface) that exhibit cognitive behaviour through learning, interpreting, and adapting to the diver's behaviour, physical state, and actions.

The CADDY framework, Fig.1, is composed by three components: an autonomous surface vehicle, an autonomous underwater vehicle, and the diver. The autonomous surface vehicle is responsible for communicating with the diver and the autonomous underwater robot, as well as serving as a communication relay link to a command centre. It also plays the key role of navigation aid for the underwater agents – it must adapt its motion to optimize communication efficiency and navigational accuracy of underwater agents. The autonomous underwater vehicle, on the other hand, manoeuvres near the diver, and exhibits cognitive behaviour with regard to the diver actions by determining the diver's intentions and the state of the diver's body.

The CADDY project replaces a human buddy diver with an autonomous underwater vehicle and adds a new autonomous surface vehicle to improve monitoring, assistance, and safety of the diver's mission. The resulting system plays a threefold role similar to those that a human buddy diver should have:

i) the buddy "observer" that continuously monitors the diver;

ii) the buddy "slave" that is the diver's "extended hand" during underwater operations performing tasks such as "do a mosaic of that area", "take a photo of that" or "illuminate that"; and
iii) the buddy "guide" that leads the diver through the underwater environment.

This envisioned threefold functionality will be realized through S&T objectives which must be achieved within three core research themes: the "Seeing the Diver" research theme focuses on 3D reconstruction of the diver model (pose estimation and recognition of hand gestures) through remote and local sensing technologies, thus enabling behaviour interpretation; the "Understanding the Diver" theme focuses on adaptive interpretation of the model and physiological measurements of the diver in order to determine the state of the diver; while the "Diver-Robot Cooperation and Control" theme is the link that enables diver interaction with underwater vehicles with rich sensory–motor skills, focusing on cooperative control and optimal formation keeping with the diver as an integral part of the formation.

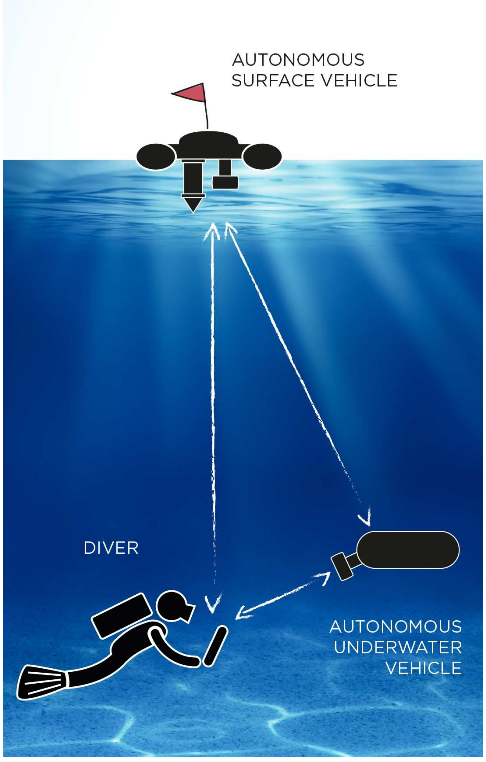

Fig.1: CADDY concept: autonomous underwater and surface vehicle interacting with the diver

2. Main objectives

Within the CADDY Project, three core research themes have been set:

1. **"Seeing the Diver"** research theme focuses on 3D reconstruction of the diver model (pose estimation and recognition of hand gestures) through remote and local sensing technologies, thus enabling behaviour interpretation. High resolution multibeam sonar has been used to detect diver hands (short distances) and the diver at larger distances (>3 meters) and his global pose (direction). Stereo camera in combination with monocular camera has been used to determine both diver pose and hand gestures. Instead of calibrating underwater directly, a technique was developed to estimate the underwater calibration parameters based on the much easier and well understood in-air calibration and basic measurements of the underwater housing used. An innovative body network of inertial sensors called DiverNet has been designed and manufactured to reconstruct the pose of the diver. Wireless version enables acoustic transmission of data processed on the diver tablet. Heart rate and breathing sensor have been integrated with the DiverNet, allowing recording of heart rate, breathing data and motion data during the experiments. Developed Diver State Monitor shows the supervisor in real time diver status using several critical values like: diver

depth, average flipper rate, heart rate, breathing rate, motion rate, PAD space, diver state alarms, and predefined chat messages.

2. **“Understanding the Diver”** theme focuses on adaptive interpretation of the model and physiological measurements of the diver to determine the state of the diver. Artificial neural networks were trained using the DiverNet data do detect different diver activities such as standing, sitting, T-pose, etc. Accuracy of around 90% was achieved allowing to transmit only this high-level diver activity data to the surface. A multilayer perceptron was trained to predict pleasure, arousal and control using breath rate, heart rate and motion rate measurements. This approach proved successful with classification rates reaching from 60% (dominance/control high) to only 18% (pleasure, neutral). Overall classification score was 40%. Language of communication between the diver and the robot based on gestures, called CADDIAN, has been developed – a total of 52 symbols have been defined, together with the “slang” group of symbols for better acceptance by the diving community. A fault tolerant symbolic language interpreter was developed, allowing robust interpretation of the commands issued by the diver to BUDDY. The following set of algorithms have been developed: hand gesture recognition using stereo camera imagery based on feature aggregation algorithm developed to cope with the highly variant underwater imagery; hand detection using multibeam sonar imagery to detect the number of extended diver fingers within sonar imagery; algorithms for diver pose recognition and localization from mono and stereo imagery, and algorithms for diver pose and localization recognition using the sonar to determine diver position and orientation relative to the BUDDY AUV.
3. **“Diver-Robot Cooperation and Control”** theme is the link that enables diver interaction with underwater vehicles with rich sensory-motor skills, focusing on cooperative control and optimal formation keeping with the diver, as an integral part of the formation. Diver-AUV cooperative controller was developed to ensure that the AUV is positioned in front of the diver regardless of the diver’s orientation. Diver-AUV-USV formation control was developed to ensure the surface vehicle is in an area close-by to improve, among other things, the acoustic communications with the underwater agents, while avoiding being on top of them, for safety purposes. Single beacon navigation algorithms based on extremum seeking and Fisher Matrix Inversion approach was implemented for navigation using only ranging devices, without angle measurements. Automatic selection system for the execution of the proper autonomous robotic tasks was developed with the aim of providing a compliant behaviour of the overall robotic system, with respect to the command issued by the diver. Modular framework of the mission controller based on Petri nets was designed and developed with the aim of managing the state tracking, task activations and reference generation that fulfils the requirements to support the diver operations.

In order to successfully achieve these beyond-the-state-of-the-art objectives, a number of specific features and functionalities have been designed and developed from scratch, integrated in the overall CADDY architecture and finally tested for validation. This paper focuses on the development on some of the game-changing techniques needed to face the scientific challenges of the projects.

3. Video-based diver recognition

To comply with the requirement of diver operation support, the overall CADDY system must be able to detect and recognize the diver in the underwater environment. The problem is two-fold: i) the robotic system has firstly to be able to detect the diver pose, in such a way to move and position itself to some specific relative position with respect to the diver (usually the robot is required to stand in front of the diver to guarantee the recognition of hand gesture based commands as well as to be visible to the diver allowing safe operations); ii) the robotic platform requires the capability to recognize the hand-gesture commands issued by the diver in order to trigger the execution of specific mission operations.

3.1 Diver pose estimation

Diver orientation estimation by means of stereo camera imagery was implemented for obtaining a pose estimation measure through computation on-board the AUV to perform a relative positioning with respect to the diver. The direct computation on-board the robotic platform allows to overcome the problem of receiving the pose measurement from acoustic-based devices (sonar or USBL) that may be sensible of underwater disturbances and affected by relevant delay.

The estimation of the diver pose is achieved by a sequence of computation on the imagery data collected by the stereo camera system mounted on the AUV. First, from the stereo images a dense disparity map is generated based on image features. In order to eliminate 3D points belonging to other objects than the diver a clustering algorithm DBSCAN that uses colour and depth is used to over-segment the diver. Then the cluster areas with small number of points are eliminated as they are considered as noise. From this processed disparity map, the final diver point cloud is generated. In this way, we ensure that PCA (principal component analysis) is applied only to the diver and not other parts of the underwater imagery. Then the PCA eigenvector are used as an input to a classifier to determine the diver orientation. The computation sequence is depicted in Fig.2.

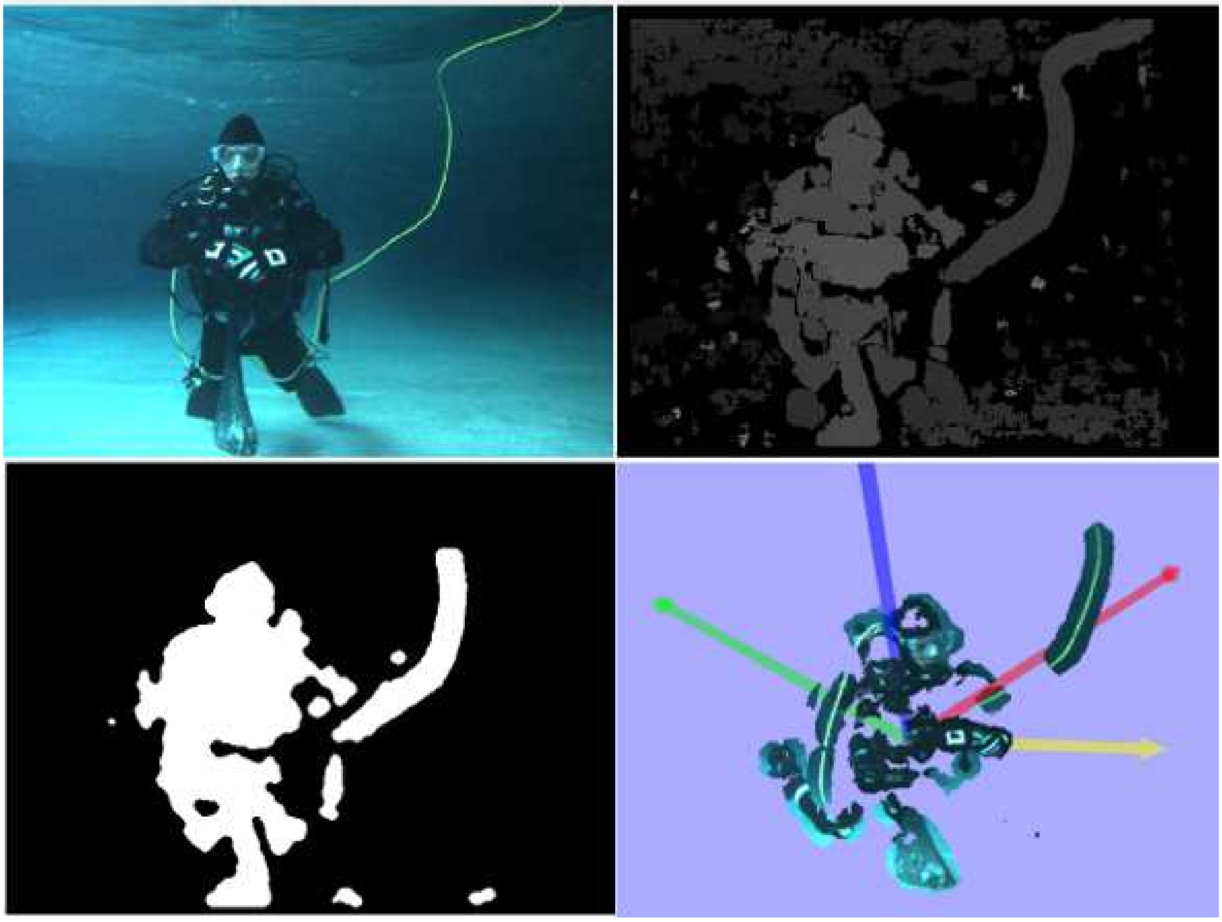

Fig.2: (Top left) One stereo image of diver (Top right); Raw disparity map generated with DAISY descriptor (Bottom left); Generated disparity map after segmentation and filtering (Bottom right); Generated point cloud with RGB eigenvectors and diver orientation shown with yellow arrow.

3.2 Gesture recognition

The Multiple-Descriptor Nearest Class-Mean Forest (MD-NCMF) is a stereo-image based method mainly relying on a feature aggregation algorithm developed to cope with the variant underwater imagery. The main idea behind this approach is that different image descriptors are robust against different type of distortions; thus, by aggregating their information without compressing them, a classifier can be made more robust and accurate. However, 3D information generated from the stereo images is used to create saliency areas to locate the hands, as well as Haar-cascade classifiers; then the classification of the gesture is done using only 2D information as shown in the pipeline scheme of Fig.3. It is also important to mention that during the research and experimentation process, different QR and color markers were tested on the diver’s gloves. Nevertheless, image quality and light attenuation prevents their use for gesture classification; on the other hand, they provide enough image texture to generate 3D information and facilitated the hand detection process.

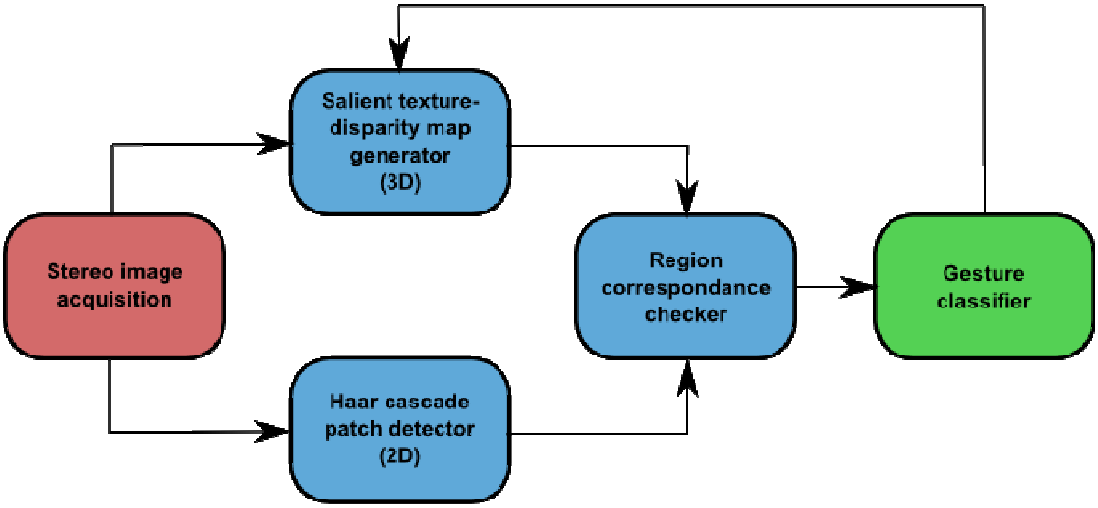

Fig.3: General framework diagram for hand gesture recognition. The different stages of the process are colour coded. (Red) Image acquisition (Blue) Hand detection (Green) Gesture Classification

One of the main requirements of CADDY is to classify each gesture in real time, meaning that the diver should only perform a gesture for a couple of seconds for the system to identify it. To achieve this, state of the art methods use learners for object detection which are commonly a group of weak decision trees combined with a variant of AdaBoost, *Viola and Jones (2001)*. These methods arrange their classifiers in cascades according to their complexity, where each successive classifier evaluates only the samples that were accepted by the preceding ones. If at any stage a sample or sub-window is rejected, no further processing is performed (see Figure 8). Taking advantage of the fact that a very small percentage of the sampled subwindows are positive (diver's hands ≈ 0.01%), most of them are rejected in the first stages and real time detection can be achieved. It is also possible to compute more complex features like Histogram of Oriented Gradients (HoG) as in *Dollr et al. (2014)*, but it increases the processing time's order of magnitude from 10^{-1} to 10^{1} seconds.

In the literature, there is not a consensus of how many positive and negative samples the dataset for cascade classifiers should have. This factor depends on the quality of the data and the variance of the samples and as already established, underwater environments are highly dynamic and create several artifacts on the images. Likewise, the creation of a dataset for field applications such as this one is hard to obtain; the environment cannot be so easily manipulated to create image samples with all possible transformations.

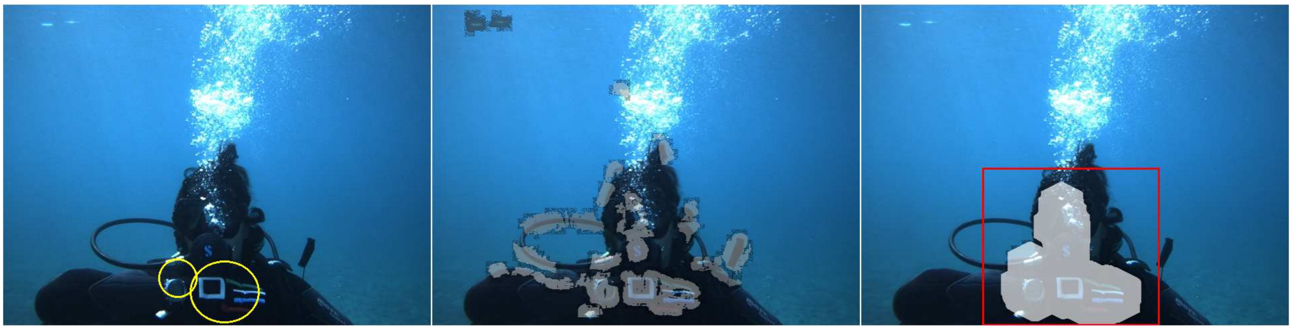

Fig.4: (Left) Hand detection using 2D features in Haar cascades (Middle) Disparity map generated from stereo camera (Right) Processed disparity map for hand detection using 3D information

Considering that cascade classifiers achieve high recall rates directly from the first classification stages; we only trained them with less than 8 stages to underfit the data, such that the detection of the diver's hand is guaranteed at the cost of having a great number of false positives. The analysis of different experimental results shows that fewer stages lead to higher recall and more false positives. Large number of stages increase precision but fail to detect the hands if the image is highly distorted. Thus, precision is compromised to boost detection. To filter out the wrong detections, these subwindows are passed to another classifier based on the method of randomized trees. Fig.4 reports the results of hand detection through the application of the proposed methodology.

4. Interpretation of gestures

This objective of developing an interpreter of a symbolic language refers to the integration of the different modules for the mission generation based on diver gestures. This encompasses the following tasks: gesture recognition, identification of valid phrases (parsing), generation of missions and feedback delivery to the diver via a tablet. The main purpose of the integration is to build a fault tolerant system against human errors (gestures badly performed or with no correct syntactical structure) and software errors (misclassification of gestures).

Within this background a language of communication between the diver and the robot based on gestures, called CADDIAN, has been developed. The language is based partly on the consolidated and standardized diver gestures. The choice of rendering CADDIAN, to all intents and purposes, backward compatible with the current method of communication used by divers, has been made in the hope of fostering its adoption among communities of divers.

CADDIAN is a language for communication between the diver and the robot, therefore the list of messages/commands identified is strictly context dependent. The first step of its creation has been the definition of a list of commands/messages to be issued to the AUV: currently the number of messages is around fifty-two units. The commands/messages are divided into seven groups: Problems (8), Movement (at least 13), Setting variables (10), Interrupt (4), Feedback (3), Works/tasks (at least 14) and Slang. This latter group has been introduced in the second version of CADDIAN for a better divers’ acceptance: the Slang group is a subset, which is an intersection of the previous groups.

After defining the commands, a communication protocol with error handling has been developed which ensures a strict cooperation between the diver and the robot. Thanks to this protocol, the diver can know the progress of a task/mission that has been requested to the vehicle and to understand whether it has been completed, while the robot can show the diver which CADDIAN message it understood during the communication.

The gesture sequence interpretation is implemented through a parser (Syntax Checker) that accepts syntactically correct sequences and reject the wrong ones. The parser accepts commands or messages, which are, to all intents and purposes, sequences of gestures. Each gesture can be represented by a symbol. In this way, a message/command is a sequence of symbols/gestures delimited, at the beginning, by a symbol of “Start communication” and, at the end, by the same symbol or by a symbol of “End of communication” (see Fig.5). According to which symbol has been found after the initial one (i.e. “Start communication”), the Syntax Checker goes on by applying the CADDIAN syntax rules. More details on the CADDIAN language definition and implementation can be found in *Chiarella et al. (2015).*

Fig.6 shows the diver executing a sequence of recognized gestures; when the “End of communication” gesture is detected, the complete gesture sequence is fed to the Syntax Checker module to validate or reject the required command (“Go down 2 meters” in the proposed example). A validate command sequence will then trigger the mission control module to execute the proper tasks to comply with the required action.

5. Action execution

The aim of providing a compliant behaviour of the overall robotic system, with respect to the command issued by the diver, is made available through the development of an automatic selection system for the execution of the proper autonomous robotic tasks.

First of all, the basic CADDY functionalities have to be mapped into subsets of tasks that can be provided by the robotic platforms. In order to define the primitives-tasks matching, an additional high-level task set has to be defined as cross-interface between the primitives and robotic task sets.

A preliminary definition of the three sets is reported in the following:

- *functional primitives* represent the macro-actions that the robotic platform must carry out to support the diver operation and that are strictly related to the current functional mode (slave, guide, observer). The primitives are triggered by the recognized gestures;

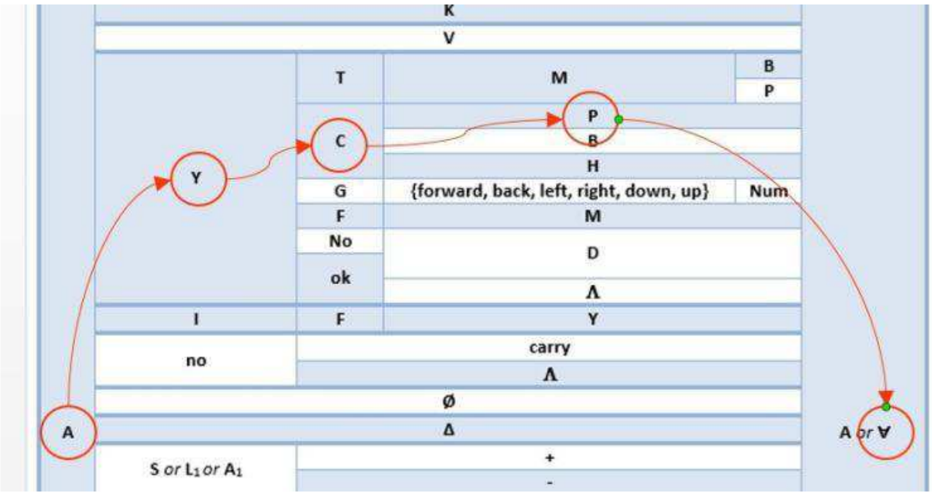

Fig.5: "Table of possible sequences" - table representation of command “A Y C P ∀” (“Come to the point of interest”).

Fig.6: “Go down 2 meters” gesture sequence executed during trials

- high-level logical tasks are the interface between the primitives and the operative task provided by robot. This logical task set is common in the overall architecture and will provide the required functionalities activating the proper low-level tasks that are currently made available by the employed robotic platform;
- low-level robotic tasks are the actual implemented autonomous functionalities on the target robot, e.g. speed regulators, heading and depth controller, etc. Depending on the low-level task availability, the CADDY compliant mission control system will properly select which high-level functionalities can be activated allowing, in turn, the enabling of the required primitives to fulfil the mission operations.

For the automatic selection, activation and inter-task conflict management, a Petri net based execution control system has been developed. The system is configured by means of a set of configuration files that specify, on one side, the capabilities of the robot in terms of autonomous tasks and, on the other side, the set of high level functionalities that the CADDY system has to provide for the diver support. A real-time Petri net engine models the logical interconnections among the tasks and primitives and, depending on the specific actions commanded by the diver, automatically handle the activation/deactivation of the proper task sets.

The primitives are linked to the support action that the diver can require by means of the gesture-based language: once a gesture or a complex sequence of gestures is recognized and validated, it is sent to the mission controller that will activate the proper primitive to start the support operation. Each primitive activates as set of high-level tasks that represent the logical functionalities required to fulfil the required operation. The high-level logical tasks activate in turn a set of robotic tasks that enable and execute the physical operations on the real robot devoted to the support of the diver operations.

The system is able to promptly react to the gesture commands, recognizing in real-time (1-2 s) the issued hand signs and in turn executing the related actions. Fig.7 shows the behaviour of the robot executing a “go up” command after successful gesture recognition and interpretation.

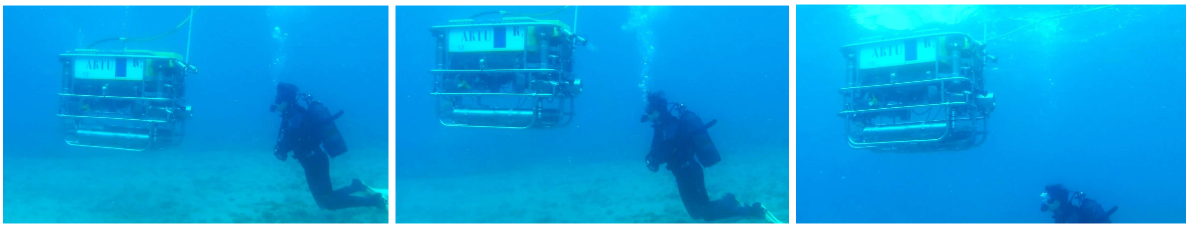

Fig.7: The robot executing a “go up” command

6. Validation trials

The validation trials, needed to assess the full system functionalities, were performed from 10.10.2016 to 21.10.2016 in Biograd na Moru, Croatia. The trials focused on different functionalities testing based on divers’ requirements, to stress the overall framework in a very realistic operative scenario. The following specific objectives were defined to validate the CADDY functionalities:

- Dive guide
    - to guide the diver efficiently to find/detect the object/objects located on the known position even in the case of unfavourable diver behaviour and willingness to cooperate;

- Dive slave
    - to geo-reference objects of interest and collect data for object identification, geo-referenced image or 3D image;
    - to recover selected objects, i.e., to take it to the surface;

- Dive observer
    - to monitor/supervise diver states and mission progress in real-time during the mission;
    - to trigger alarm on e.g. high breathing rate.

Five professional divers with different backgrounds (scientific, public safety, commercial and recreational divers) performed five complete trials. Having in mind that work was done in real environment with the robotic prototypes and novel, CADDY developed applications, thus not with off-the-shelf thoroughly tested products and software, some technical problems were expected. Nevertheless, the complete set of results from the missions were sufficient to evaluate and validate work done in the scope of the CADDY project.

Specifically, the objective of each trial required:

- to guide the diver (by means of the robotic system) along a two-transect path - “dive guide” evaluation;
- to stop at a first target point to command, via hand gesture, the robot to take a picture of an object posed on the seabed (Fig.8) - “dive slave” evaluation;
- move to a second target point to: i) simulate physiological awareness situations (accelerated breathing and body motion) to trigger alarm to the ground station and test communication protocol with the diver (through underwater tablet) (Fig.9) – evaluation of “dive observer”; ii) collect an object posed on the seabed, place it on the robot, then command the robot to bring the object to the remote station (Fig.10) - further “dive slave” evaluation.

Buddy successfully guided the diver to the designated locations where targets were found. Dive guide functionality was achieved using the so called “pointer” algorithm, by which the robot indicates with its position the correct direction that diver has to follow in order to reach the desired location. The cooperative motion of the diver and the robotic framework is plotted in Fig.11.

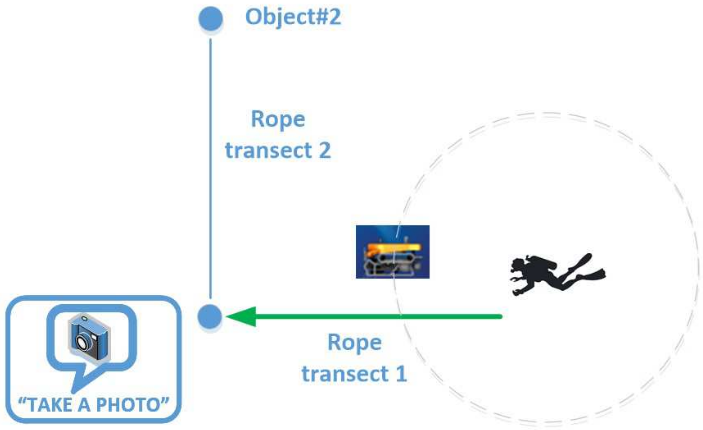

Fig.8: Diver guided along transect 1; then a “take a photo” command is issued to the robot

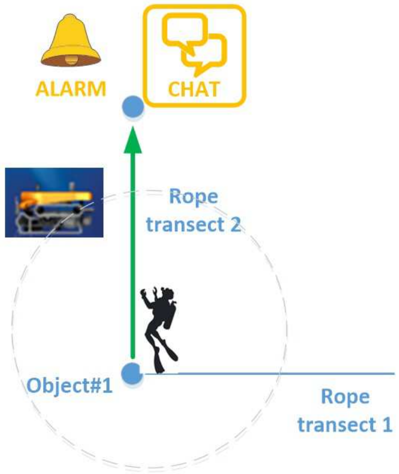

Fig.9: Diver guided along transect 2 where physiological situations are simulated

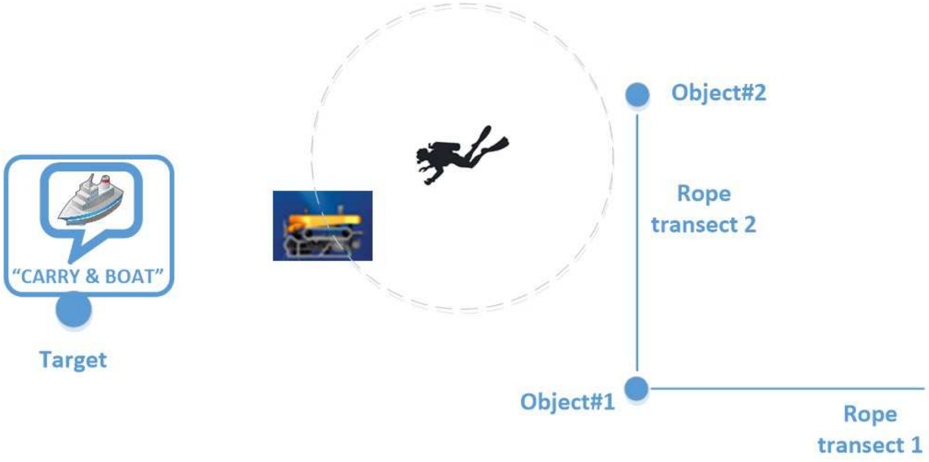

Fig.10: Diver collects object from seabed and command robot to carry it to the remote station or boat

During the trial, divers have autonomously decided to identify and geo-reference some objects of interest. Photo of the objects were taken (Fig.12 and 13) on divers’ command using the gesture-based CADDIAN language and images were collected and georeferenced by linking the images with the AUV’s position data. During one mission, command "take a photo" was not recognized by the robot; after analysis, the conclusion was that the mission was carried out in shallow waters around mid-day and the zenith position of the sun generated more challenging light conditions for the gesture recognition.

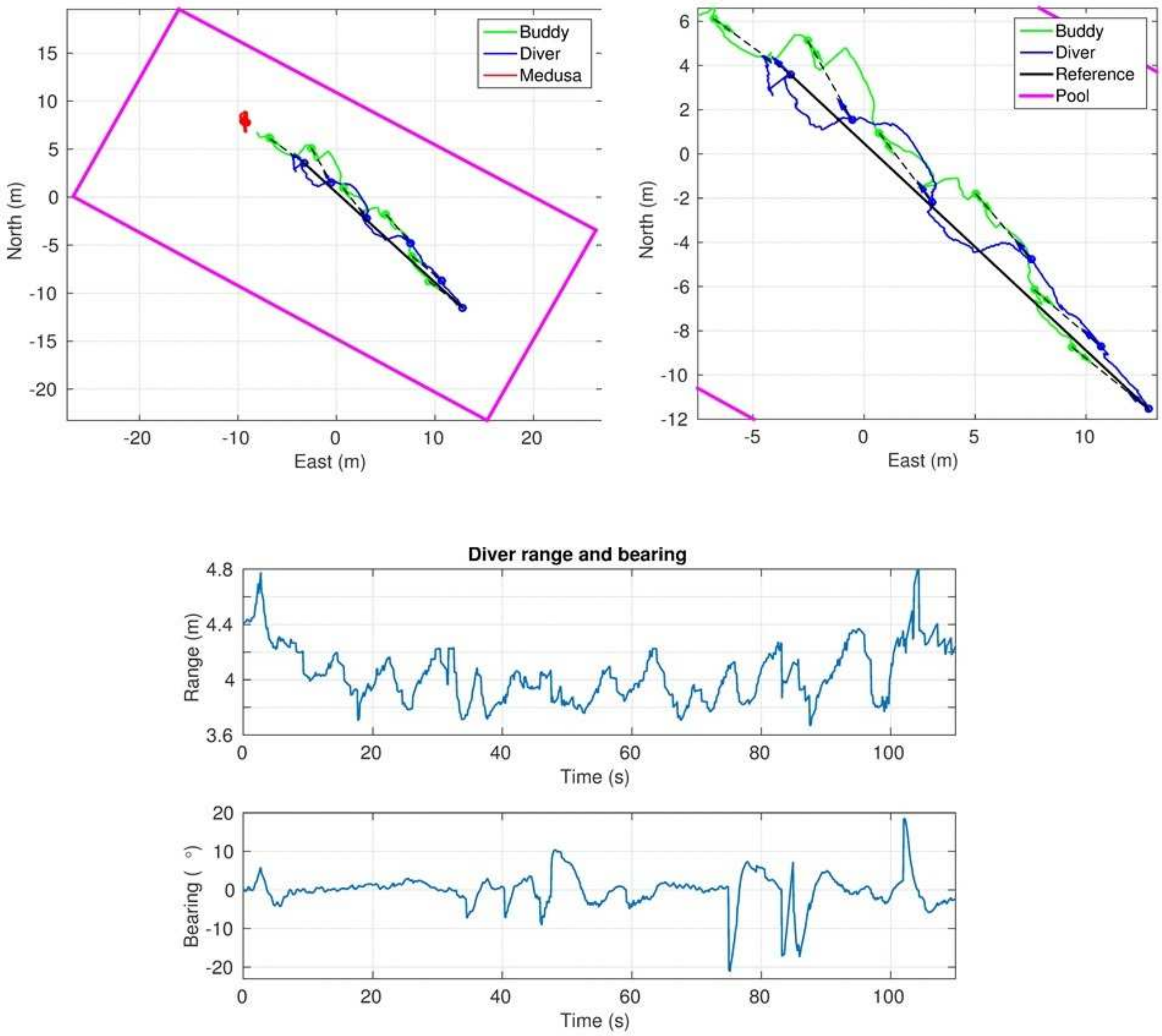

Fig.11: Motion of diver and robotic platforms (top images); plot of range and bearing between diver and AUV (bottom image)

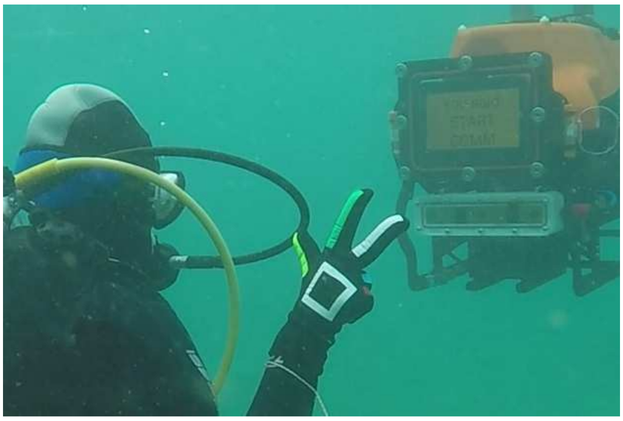

Fig.12: Diver issues “take a photo” command

Fig.13: Photo of the target object on seabed

After the action of taking the photo, diver is guided to the second target point where some physiological awareness situations are simulated by the diver accelerating her/his breathing and executing jerky movements with the body and limbs. Thanks to the DiverNet the changes in the physiological state are sensed and transmitted to the remote station where alarms are triggered. Remote station initiates a communication with the diver, using a simple chat service to send messages to the diver, that can read the messages on its own underwater tablet. The diver can also reply selecting response amid a set of preset messages. The ground station console with physiological state visualization and chat service is shown in Fig.14.

```
2016-10-20 10:39:03.311830 | Heart rate alarm!!
2016-10-20 10:38:57.854516 | Breathing rate alarm!!
2016-10-20 10:38:52.312943 | Breathing rate alarm!!
2016-10-20 10:38:46.801813 | Breathing rate alarm!!
2016-10-20 10:38:41.249222 | Breathing rate alarm!!
2016-10-20 10:38:35.516297 | Breathing rate alarm!!
2016-10-20 10:38:29.535598 | Breathing rate alarm!!
2016-10-20 10:38:23.907035 | Breathing rate alarm!!
2016-10-20 10:38:18.101169 | Breathing rate alarm!!
2016-10-20 10:38:12.550655 | Breathing rate alarm!!
```

Diver: Ok
Topside: Normal operation.
Diver: Ok
Topside: Issue alarm.
Diver: Ok
Topside: Issue alarm.
Topside: Issue alarm.
Diver: Alert

Fig.14: Remote station console used to monitor diver physiological state and to communicate via chat messaging service

Fig.15: Object collected by diver

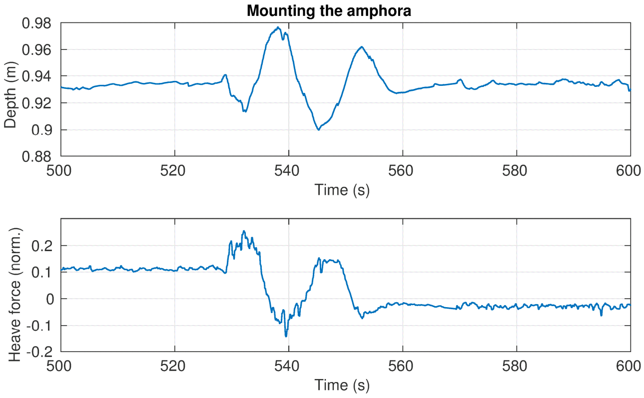

Fig.16: AUV trim change indicates that object was loaded on vehicle

At the second target point the diver can easily locate an object of interest, Fig.15, posed on the seabed. The diver can then collect the object, loading it onto the AUV; from the robot's telemetry it is possible to detect the object loading which causes a trim change in the vertical motion due to the weight and buoyancy changes, Fig.16. Once the object has been loaded on-board the robot, diver can execute the gesture sequence to require the robot to carry the object to the remote station or boat. Once recognized, the command sequence triggers the automatic guidance functionalities of the robot allowing the autonomous navigation, surface and reaching of the final position for the object delivery. The motion of the robot during the "carry" operation is reported in Fig.17.

Furthermore, in order to collect subjective evaluation of the CADDY system, a questionnaire was prepared for the divers that participated to the validation trials. The conclusions drawn from the questionnaires related to CADDY performance and divers comfort are:

- Communication with the surface was easy and efficient. It was easy to handle the tablet and the menu of the program was well arranged. Messages displayed were understood immediately and reaction time was satisfying. The same is valid for surface-diver communication, which was rated as easy and efficient by the mission supervisors;

- The communication between BUDDY and me was rather satisfying. Based on experience with diving with human buddy, divers expected communication success rate of 100% and rapid reaction to their instruction. Although divers were generally satisfied with the communication with the BUDDY using CADDIAN they expected communication performance similar to the one with the human diving buddy. The problem with the gesture recognition at mid-day ambient light emerged during one mission, which affected the system performance and diver satisfaction with the diver-BUDDY communication, resulting in lower related rates;
- Divers rated mental and physical workload demand as very low. This was very important fact that system did not introduced extra mental or physical demand on divers;
- Divers rated performance and frustration level from medium to low. Frustration can mainly be attributed to communication;
- BUDDY did not disturbed divers and kept and maintain comfortable distance from them;
- Divers would like to use CADDY system in the future and found the work with the system comfortable.

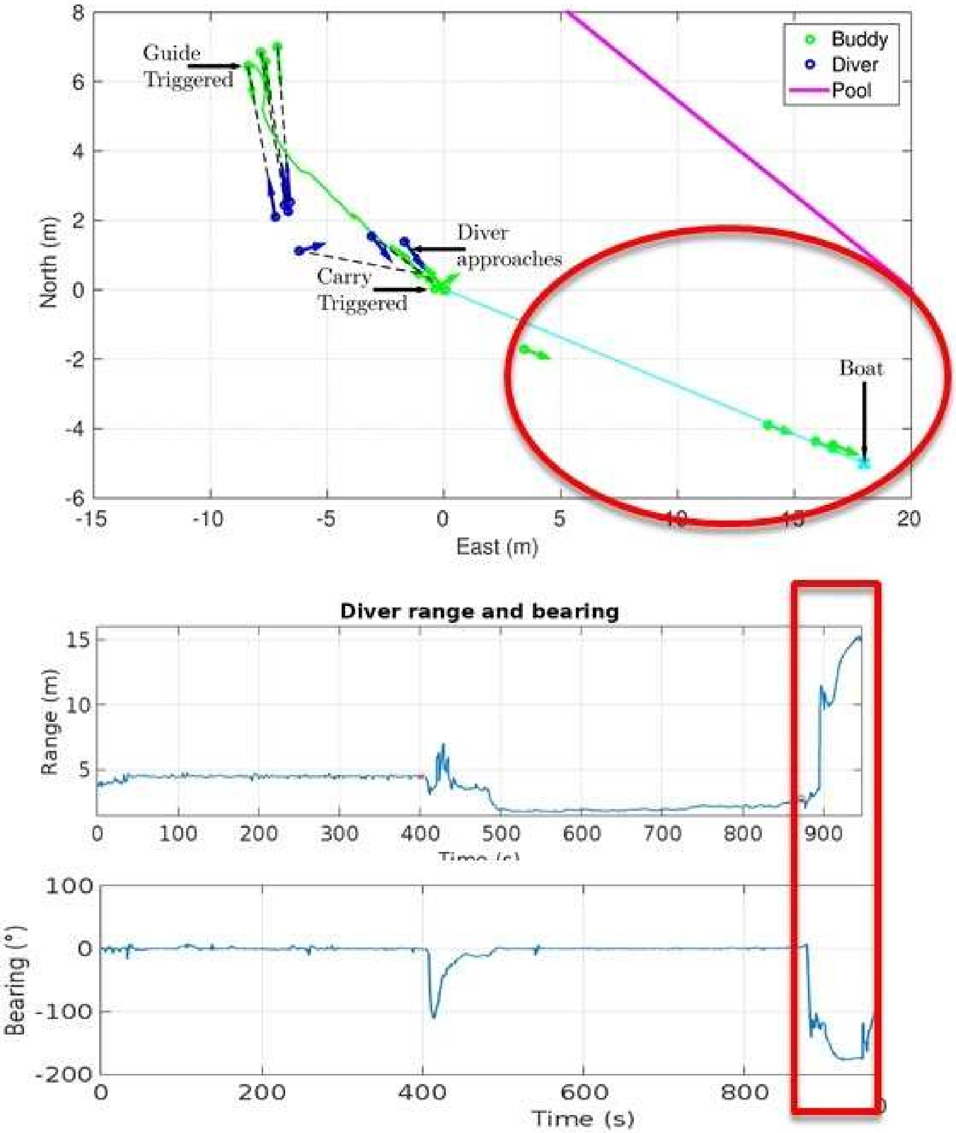

Fig.17: AUV motion during "carry" operation. Top image shows the horizontal motion, bottom image depicts the range and bearing changes when the robot gets far from the diver.

The collected set of results was sufficient to evaluate and validate work done in the scope of the CADDY project. The summary of the most important conclusions is:

- The validation was successfully accomplished and CADDY complied with most of the indicators. Parts in which full compliance were not reached were: diver guidance using envisioned pointer algorithm mainly due to not sufficiently accurate and frequent diver orientation feedback and gesture recognition in challenging environmental conditions;
- Divers felt safe and comfortable working with the robotic system, they recognized potential and possible benefit of using CADDY system, but divers also expected system performance related to communication and guidance, to be comparable to the performance of the human buddy. CADDY did not introduce extra mental or physical demand on divers;
- The technology is validated in relevant environment and the overall system reached TRL5 by the end of the project based on key performance indicators. The prototype is not very far from TRL7. Robustness and immunity to external conditions should be further investigated.

7. Future steps

This cutting-edge project has sparked new ideas for project follow-ups in the direction of industrial and societal exploitation, as well as new scientific and technological. Proposals for project follow-up in the direction of industrial and societal exploitation are currently under consideration. Scientific challenges and industrial objectives are heading towards robust cognitive systems that can safely interact with several human agents, sharing the same operational environments, interacting in the most natural way, Fig.18. If nowadays underwater technological level is limited by different physical factors, new methodological approaches can overcome these obstacles leading to the development of efficient, highly performing and safe robotic tools to help human operators.

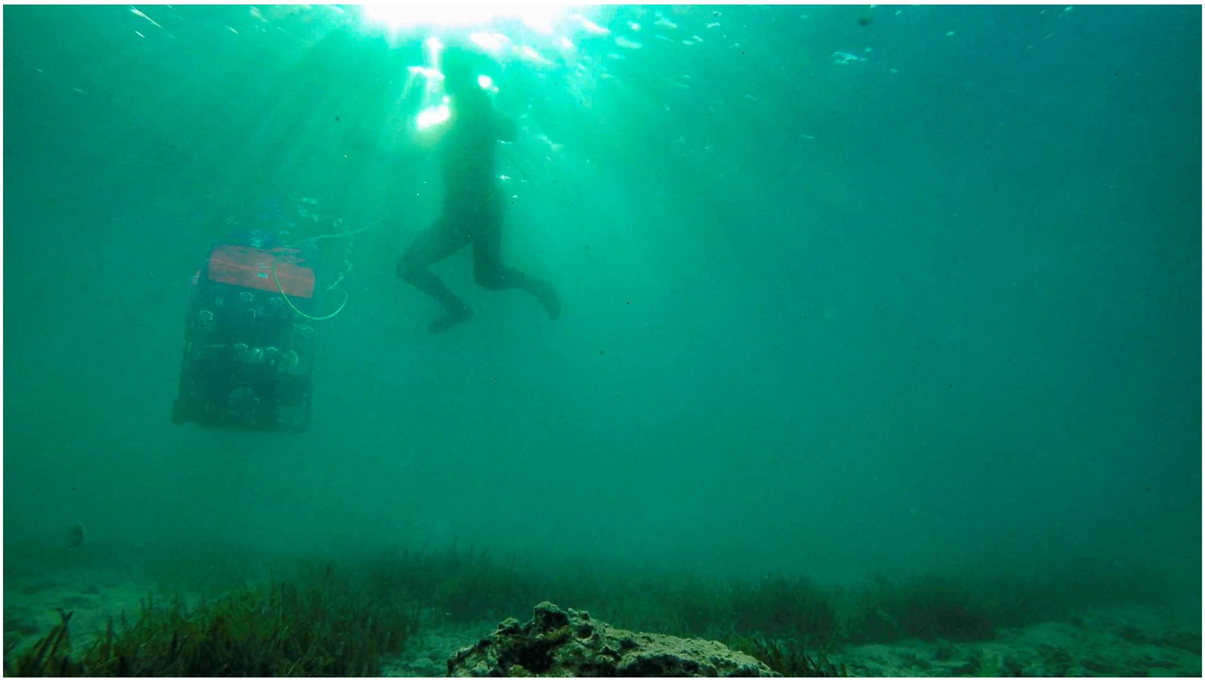

Fig.18: Future underwater robot-human cooperative scenarios where human can naturally interact with robotic platforms

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Virtual and Augmented Reality Solutions to Industrial Applications

Leo Sakari, Seppo Helle, Sirpa Korhonen, Tero Säntti, Olli Heimo, Mikko Forsman, Mika Taskinen, Teijo Lehtonen, University of Turku, Turku/Finland,
{leersa | seilhe | sikrko | teansa | olheimo | miolfo | mhjtas | tetale}@utu.fi

Abstract

This paper introduces a variety of virtual and augmented reality solutions for industrial applications. In addition the technologies and techniques required for producing these kind of solutions are presented. The issues studied in research projects referred here include data connectivity, processing and 3D visualization of construction models, positioning and tracking solutions and user experience design. An open database containing evaluations about available virtual and augmented reality platforms is also presented.

1. Introduction

During the last few years, virtual reality and augmented reality have both been hot topics in the entertainment industry, but still the implementation of these technologies in industrial context has been lacking. While in industry various technological solutions are widely used with efficient results it is still usual to use tools that have been in use for over a decade. However there seems to be much to utilise in augmented reality (AR) and virtual reality (VR) technologies if one wishes to promote the information flow from the design bench to the construction process by enhancing the aforementioned processes with visual aids. Due to the requirements of the work processes, these solutions must be meticulously designed and have higher standards for current and correct information and thus they differ quite a lot from their entertainment counterparts.

Virtual reality refers to technologies that are used to generate virtual images and sounds to simulate physical presence in another environment. In VR the content can be linked to the real world, but it does not have to be. The physical location of the user is irrelevant to the content per se, but in a large system the movements of the user can be tracked and reflected into the VR world. Some of the content can be real time sensory data, for instance the user can navigate a virtual model of a building on the other side of the Earth, and see the air flow in a given ventilation duct. This allows remote monitoring, without physical presence. In training and education VR provides a low-cost alternative to sending the learners on site. Additionally, VR allows simulated situations that would be hazardous to the user and costly to perform, like how to react in case a fire starts.

Augmented reality involves superimposing virtual content on the user's view of the real world. In AR, views from real-world environments are augmented with digital 3D-objects and/or other data in real time. The content can include real time data, e.g. the status of a given item, such as the temperature of a water pipe, or static data, like the material used for a given item. In the AR-case, the content is linked to the physical location of the user. Additionally, the user can be provided with access to further data, such as manuals or instruction for maintenance operations, based on the item(s) seen in the AR-view.

Mixed reality (MR), https://developer.microsoft.com/en-us/windows/mixed-reality, can be imposed by changing incoming information from all senses. Usually MR uses at least visual and aural methods but also olfactory, gustatory, and haptic can be used, e.g. *Ranasinghe et al. (2011), Colwell et al. (1998), Ischer et al. (1998).* Visual effects can be e.g. computer-generated 2D and 3D images or information superimposed on the real-world view captured from the camera of a smartphone, computer or other device, *Bujak et al. (2013), Heimo et al. (2017).* Mixed image appears to its users as virtual and real objects coexisting simultaneously in the same space, *Di Serio et al. (2013), Seppälä et al. (2016), Heimo et al. (2017).*

MR consists of various setups and combinations of levels of reality and digitally generated material. As virtual reality experiences attempt to recreate all these signals, AR only attempts to enhance the natural elements with some artificial information. Therefore, MR covers the whole area between the physical reality and completely simulated virtual reality, illustrated in the famous Virtual Reality Continuum in Fig.1, *Milgram et al. (1994)*.

Fig.1: Levels of mixed reality

In our project, we studied industrial applications of both virtual reality and augmented reality. Several demonstrative applications have been built to study potential MR-assisted functions in construction and shipbuilding industries. In this paper, we describe those demo applications and what has been learned through them.

The applications demonstrate certain solutions that are essential in many kinds of industrial applications. One such issue is connectivity to relevant databases where 3D CAD-models and related metadata are available. It enables the application to use real time data so that, e.g. the displayed model is always up to date, and it is possible to show actual, real time data from dynamic systems like air conditioning or water piping. Another common issue is indoor localization - how to define the user's location.

We have interviewed several potential users of VR/AR solutions among different industries. Demo applications have also been presented to people not familiar with the technologies, and their initial reactions and possible changes in opinions after that have been observed. The study gives light to questions like what people typically know about VR and AR in advance, and what kind of potential is seen in these technologies for usage in various functions.

We outline the current state of technology, regarding for example VR and AR glasses (HTC Vive, Oculus Rift, Microsoft HoloLens etc.), and what is still needed for a real breakthrough. We discuss the findings from the user interviews, and we give an estimate how quickly such solutions can be taken into use in industrial processes.

The MARIN2 research project led by the University of Turku was focused on industrial uses of augmented and virtual reality technologies. The project ran from January 2015 to March 2017 and continued the work started in the earlier MARIN project (2012-2014). The project had several industrial partners including infrastructure, construction and shipbuilding companies.

The research topics in the project had emphasis on data handling. Connectivity to databases containing plans, models and metadata is essential for many industrial applications. Data format conversions are often needed, and so is filtering and simplification of the models, especially when they need to be rendered on consumer level mobile equipment. Tracking algorithms and localization technologies were studied and developed. The project also did technology follow-up, testing and evaluating new commercial products. The project delivered demonstrative applications of AR and VR technologies and several publications about those. A web site collecting and delivering information about MR headsets and software development solutions was also built and is being maintained at ar.utu.fi/mrdb.

2. Background / Related work

Airbus uses the Smart Augmented Reality Tool (SART), designed and developed by the Airbus subsidiary Testia, http://www.testia.com/. SART is an inspection tool at the aircraft fuselage assembly lines, as described in *Guillot (2016)*.

SART is being used for inspection of mounting brackets in the aircraft fuselage. There are thousands of brackets in an airliner, and correct installation of each one must be inspected. An AR solution for this specific task was designed and implemented initially in 2010, and it has been in routine use since 2011, with further refinements and updates during the operational period. The application includes a reporting tool, integrating the inspection task into one device. With the AR application Airbus claims to have reduced the inspection time to one fifth of what is needed using the traditional method involving paper or laptop based inspection sheets and Excel/Word applications for reporting. Also quality improvements (decrease of non-conformities) are reported, http://www.manufacturing-summit.com/wp-content/uploads/2016/10/Aurelien-Cottet-Airbus.compressed.pdf.

The SART process includes data processing where 3D-models and parts data are prepared to be run on a mobile device. This phase is done in the office before the actual inspection task. The inspection requires human approval for everything – according to aircraft industry regulations – as an automatic system can't approve the inspection results. Thus SART is designed as an assistant for human operators, not as a fully automated system capable of unsupervised work.

The actual SART tool runs on a tablet computer, with a specific camera module attached to it. In the inspection work, it uses a marker-based, in-house developed tracking method with millimetre scale accuracy. A markerless solution exists too, having lower accuracy, but being useful in some applications. The markers are set to place by the operator during the work task. Typically one marker every 3-5 m suffices, but it depends on individual working styles. The marker-based solution ensures good localization, although it also requires some effort from the operator. For example, an aircraft fuselage has a lot of repetitive elements, making correct localization by an automatic, markerless system very difficult.

The tablet device is used with a light neck strap or harness, which makes carrying it relatively easy. The currently available AR glasses would be impractical and inconvenient for continued use. The tablet can be used continuously for half a workday, and its battery is changed or charged during the lunchbreak.

Another example of the recent development would be the EdcAR system, developed for the European Space Agency (ESA) by Technical Research Centre of Finland (VTT), Thales Alenia Space, and Institute of Communications and Computer Systems, Greece. *Helin (2016)* presents the system, as well as two use-cases: (1) AR supported telecom payload coax cables assembly; (2) AR based on-board training and remote support for centralized cabin filter replacement in ISS. The EdcAR AR-system was designed to give a simple solution based on standards for portability and expandability. With this in mind, modularity and reusability were highlighted in the development. These were achieved by using the ALVAR 2D/3D tracking system, http://virtual.vtt.fi/virtual/proj2/multimedia/alvar/index.html, on top of the Unity engine with ROS (an open-source Robot Operating System) providing the platform support. The team reported the following lessons learnt:

- Point cloud tracking works well, but needs expertise in set-up
- Main show-stopper is usability and processing power of AR-goggles
- EdcAR system works with smart phones and tablets
- A lot of resources was spent to the backend system and loading content in real time
- A fully Unity-based system could show much better features of AR and would also enhance performance

Within the MARIN2 project several systematic literature reviews were conducted about subjects related to the industrial use of augmented and virtual reality solutions. One review collects information about use of depth sensors in augmented reality applications *Taskinen et al. (2015)*. Usage of inertial sensors for movement tracking on a map is the theme in *Kaustinen et al. (2015)*. Advances in monocular model-based tracking are analysed in *Lahdenoja et al. (2015)*, while articles about hardware accelerated visual tracking algorithms are collected in *Korhonen et al. (2015)*. Developments of user interaction technologies in mobile AR are presented in *Härkänen et al. (2015)*. All these literature reviews are available in the Technical reports series of the University of Turku, which also provides other reports from the research areas.

3. Technology review

This section presents a summary of findings about devices and technology platforms that were studied during the MARIN2 project.

3.1. Display devices

Head-mounted VR glasses are being developed by several companies, and new models are released frequently. In March 2017, the two best-known VR glasses were Oculus Rift, www.oculus.com/rift/, and HTC Vive, www.vive.com/. The operation and display specifications for the current generation models are fairly identical for the two products. Both have a 2160 x 1200 pixel resolution display (1080 x 1200 per eye) and 110° field of view. Positional tracking is done using sensors located in front of or around the user, giving a few square metres of floor area (tracking volume) for the user to move around in. Both support specific, tracked hand motion controllers with several interaction buttons, although with Vive these are included in the basic system, while for Rift they must be purchased as an extra. Currently, Vive can do positional tracking within a slightly larger area than Rift. On the other hand, Rift seems to be a more polished product from the consumer point of view, with a simpler setup and built-in headphones. But both products are expected to get updates in the future, and the "leading position" may well change. As these are just display devices, the performance of both systems depends mostly on the computer being used, which is not sold as part of the system. In fact, a high-performance computer for these displays will cost more than the VR glasses.

Compared to the experiences with earlier versions of e.g. Oculus Rift systems, dizziness or motion sickness seem not to be a major issue any more, *Heimo et al. (2017)*. This is due to the improvements in both computer performance and in the actual display hardware. The current Oculus Rift and HTC Vive VR glasses can be successfully used in visualization of complex industrial and architectural models: the image quality is high enough, even though it cannot yet match human acuity. New interaction solutions taking advantage of e.g. hand motion controllers have emerged with these displays, and widely accepted conventions seem to be forming, as summarized by *Hayden (2016)*. One such popular concept is moving by teleportation: the user points with a hand controller to a point in the virtual ground, and when pressing a button, jumps instantly to that point. This method helps avoiding the motion sickness that can often be experienced when moving continuously in the virtual environment. With continuous movement in the virtual environment, the sensations from the visual system and inertial sensing organs are in conflict, whereas with the instant location change the senses remain in harmony.

Solutions based on Google Cardboard, vr.google.com/cardboard/, and Samsung GearVR, www.samsung.com/global/galaxy/gear-vr/, were also studied. These are low-cost systems that utilise a mobile phone that is attached to a head-mounted mask. Development efforts were focused on desktop-based glasses, due to the performance requirements imposed by highly complex CAD models.

Augmented reality glasses with see-through optics have been commercially available for several years, but the speed of technical progress with them has not been very fast. www.vuzix.com/, epson.com/moverio-augmented-reality and www.brother-usa.com/AiRScouter/ are some of the companies that offer wearable AR glasses. However, so far there has not been a great hit among such products, and new model releases occur rather rarely. The products still seem like curiosities aimed at research and development use rather than complete packages that would offer a commercially attractive solution. Technologically the products suffer from a limited field of view, they are typically rather heavy to be worn for long time, robust tracking systems are missing and the availability of software content is very limited.

Google Glass, https://en.wikipedia.org/wiki/Google_Glass, was a much-hyped augmented reality product a couple of years ago, but the first generation was a commercial failure. Google aimed to create an unnoticeable wearable device, one that could be used as easily as ordinary spectacles. That led to a design with a very small, off-centered display and nearly no capabilities for tracking. In the end, most researchers, e.g. *Zerkin (2013)*, do not consider it an actual AR device. However, Google has since then launched the Glass at Work program, https://developers.google.com/glass/distribute/glass-at-work, for certified partners to deliver enterprise solutions for Google Glass. One such application is used by Boeing in aircraft production as explained in *Wheeler (2016)*. Google is reportedly working on a new generation of devices with a similar concept but improved specifications.

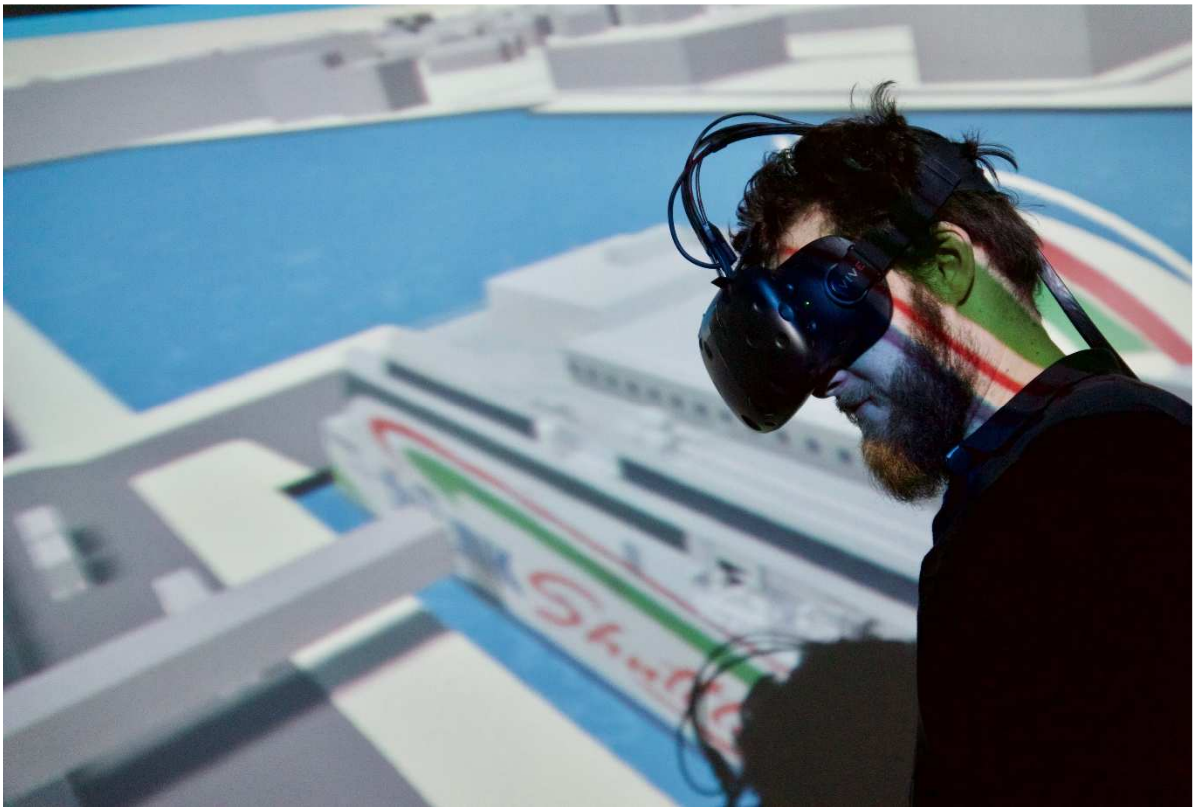


Fig.2: ShipVR

Microsoft's HoloLens, https://www.microsoft.com/microsoft-hololens/en-us, has set a new standard on AR glasses. It has a few strong and unique features that give it an advantage over its competition:

- It has a very robust tracking that does not need markers, and adapts to the environment: it recognizes walls and other shapes of the room and can estimate its own location very accurately.
- The devices is fully untethered and autonomous. Computing occurs in the device itself, so it needs no wires or connected backpacks for the equipment to function.
- The device can interpret user's hand movements and use them as input. This can be very handy, although long interactive sessions can also be tiresome. A lightweight controller device is also supported, to help avoid the arm fatigue problem commonly known as the gorilla arm syndrome, http://www.catb.org/jargon/html/G/gorilla-arm.html.

The field of view in HoloLens in one of its less impressive features: it is only about 30 x 17 degrees, which means you often lose sight to some content. It is, however, good enough to give a fairly good view of the virtual content around you. The glasses need to be tightened around the wearer's head, which means long sessions might get tiring. The device itself is not very heavy but battery capacity imposes a practical time limit on usage.

Instead of glasses it is also possible to use smartphones and tablets for AR applications. Then the augmented content is put on the online video on tablet's display or even on laptop display (see SART in the previous chapter). This solution works quite well in cases when there is no need to move around but instead take a snapshot of some view and inspect that view in detail.

Tablets have a few advantages over AR glasses:

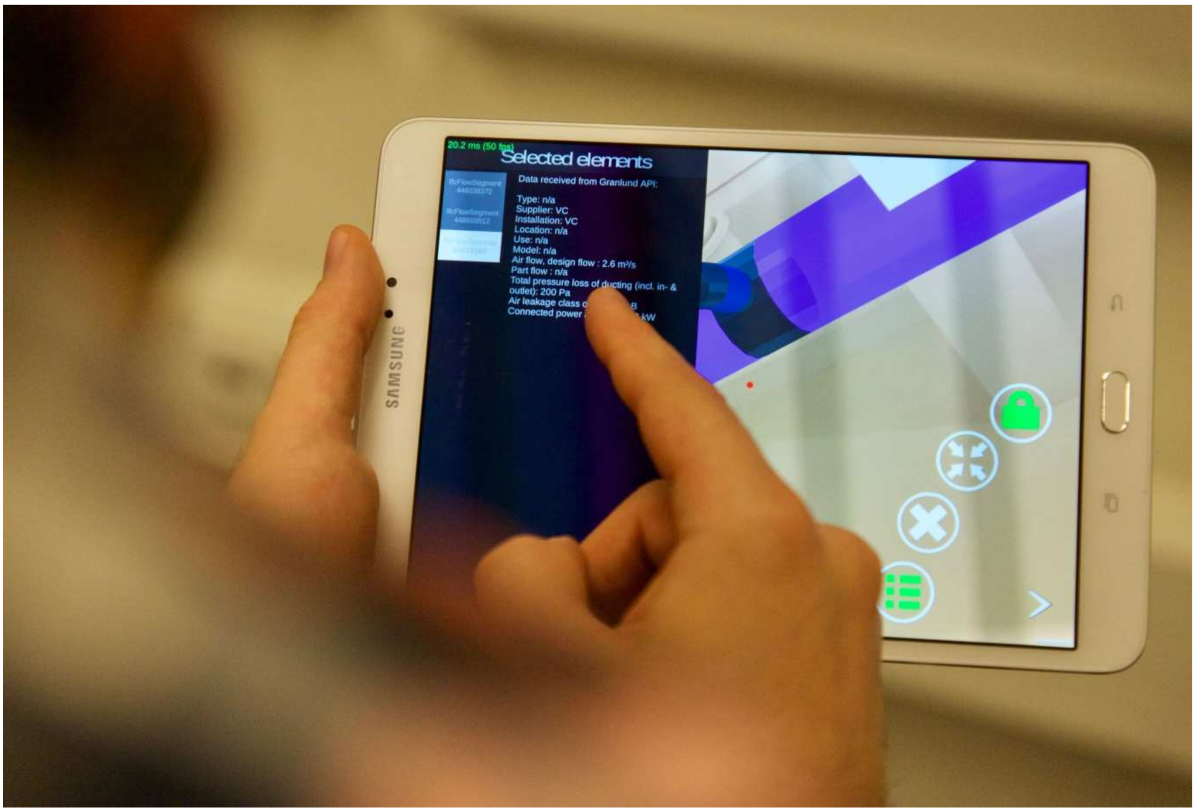
- The user can instantly switch between the AR view and reality view.
- The weight of the device is not carried by the head.
- Tablets are often already standard equipment in industrial environments, so new equipment investments are minimal.

However, the computing performance in tablets may not be sufficient for some applications. Typically this may be the case when the models to be displayed are very complex. Then a desktop computer is needed, or the software and displayed content must be optimized for mobile devices. Another drawback is that the user's hands are occupied when carrying a tablet, unless it is worn in a harness or strap. Stereoscopic perception is also missing from the tablet display, which may be a significant factor for some applications.

Tablet, when held in front of the user's face, may also block the view, causing hazards in the workplace. This can be at least partly avoided with a dedicated tracking camera that can be aimed to other directions than the tablet display. It allows keeping the tablet in a working pose, as in the SART solution, see Section 2.

3.2. Software tools

In AR applications, a key element is the tracking method, i.e. how accurately and robustly the augmented data can be placed over the surroundings. There are many commercially available platforms (for example www.wikitude.com, http://sightspace.pro) that offer coarse tracking based on geolocation, or GPS, magnetic compass and gravity sensors. This is sufficient for e.g. some travel applications but not for highly accurate localization.



Data received from Granlund API:

Type: n/a
Supplier: VC
Installation: VC
Location: n/a
Use: n/a
Model: n/a
Air flow, design flow : 2.6 m³/s
Part flow : n/a
Total pressure loss of ducting (incl. in- & outlet): 200 Pa
Air leakage class o[illegible] B
Connected power [illegible] kW

Fig.3: Indoor AR

Marker-based tracking solutions are also supported on several platforms, for example www.layar.com, www.wikitude.com and www.vuforia.com. These are based on recognizing a simple, typically black-and-white 2D rectangular object with some internal pattern, and calculating the device location from the marker image. Such systems can achieve good accuracy (within a few millimetres or better) in the area where markers are distributed. For many industrial applications, such accuracy is needed, and markers are not necessarily a major problem in these environments, so a marker-based system can be a feasible solution. However, if the system can only recognize the markers and not the actual objects of the working environment, any dynamic changes in the environment are not considered, which may limit the potential applications.

Markerless tracking means a system where the device localization is not based on dedicated graphical markers in the environment. The general idea of markerless tracking is using the camera signal for recognition of 3D features in the environment and comparing them to a 3D-model made in advance, or to create a model of the current environment on the fly and then continuously tracking the device's location in that model. Some industrial localization systems exist that are based on beacons – transmitting optical, radio or audio signals – that are in fixed locations in the working space, and the location of devices is calculated from the timings or travel times of the beacon signals.

Some small companies in the tracking business (most notably Metaio) have been acquired by other companies, and in some cases this has meant that the solution disappeared, at least temporarily, from the market.

A significant number of augmented reality software development solutions, such as libraries and software development kits (SDKs), were reviewed during the project. The results of these reviews were organized into MRDB, https://mrdb.utu.fi. MRDB currently contains information on a total of 89 unique augmented reality solutions ranging from computer vision libraries to software companies. The database is maintained and kept up to date by University of Turku.

In MARIN2 a panorama tracking implementation, described in detail in *Forsman (2016)*, was developed for outdoor purposes. Panorama tracker is a visual tracking method for monocular cameras. The basic idea of the tracker is to create a panorama map of the area parallel to the tracking. The tracking is based on natural features that are tracked using template matching with the OpenCV library. The tracker works only in 3 degrees of freedom, which means that it tracks rotation only, but not translation. The advantage of the tracker compared to e.g. simultaneous localization and mapping (SLAM), is that the implementation is quite simple, and since the tracker only tracks rotational movement, it is not required to estimate the depth of the tracked features. The tracker is usable on high-end consumer tablets. The largest restrictions are that the tracker must be reinitialized every time that the user moves to a different location, or whenever the tracked scene has changed too much for the tracker to function.

3.3 Interfaces to databases

An essential part in both AR and VR applications is the connection to databases where the models and related metadata reside. For this purpose, the BIMconnect solution was developed, described in detail in *Riikonen et al. (2017)*. It is an open source asset for transferring data from BIMServer to Unity based applications. It enables importing IFC models that exist on BIMServer directly to Unity applications, as well as examining related metadata.

The 3D CAD-models of a bridge, ship or buildings are typically very large in terms of amount of data. For being able to visualize then fluently in AR/VR applications where computing capacity is limited, techniques for simplifying the models have been studied. The results of studies are in *Arvo et al. (2015)*.

3.4 Positioning

Typically, MR systems require the location of the user to be known. In case of an outdoor application, Global Positioning System (GPS) can be used. GPS systems in modern phones and tablets provide reasonable accuracies, and if that is not sufficient, Real Time Kinematic (RTK) extensions can be adapted, *Sakari et al. (2016)*. However, GPS cannot be reliably used indoors. Acquiring the user position with non-visual methods is required, since a building can have several rooms which appear identical. These cannot be identified simply based on the images from the camera. Several solutions for this problem exist, and the selection of the most suitable technique is case dependent. The location can be detected by visual markers, which must be placed in each room, and linked to the 3D-model. This method is very straight forward, but laborious. Also, the markers can be less than attractive. Some buildings can already have RFID devices used for access control. These can be used to notify the system of the current location.

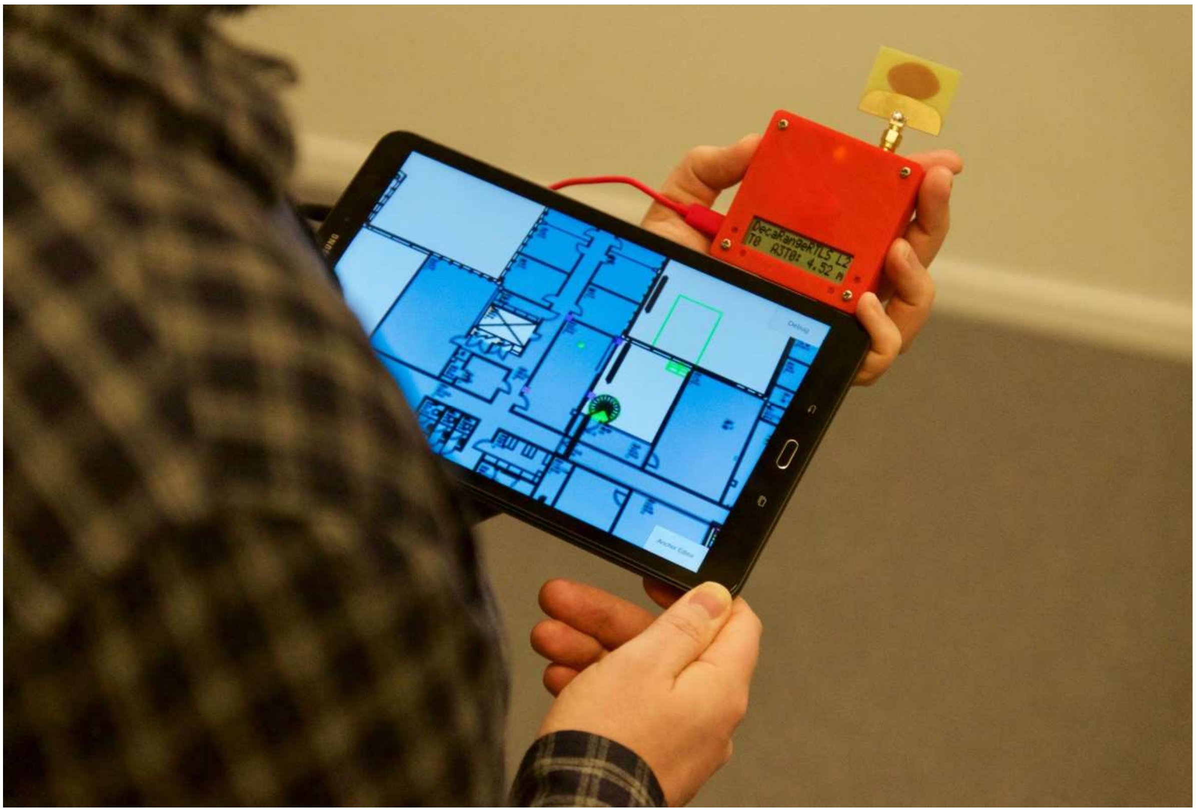


Fig.4: Indoor Tracking

In some cases, the WiFi networks in a building have been used to create a map of the network names and strengths, but this solution is volatile to changes. Especially if the building is shared between different parties, each controlling their own networks. The solution that was found to be the most robust and accurate, with limited set up required, is based on ultra-wideband (UWB) radio technology. It requires a few anchors to be placed in known locations, and the system can calculate the user's position based on those. The system tolerates walls and other obstacles rather well, since all of the frequencies are not required for detection. The number of the anchors depends on the size of the building, and to some degree on the required accuracy. Typical ranges for UWB systems are in the order of tens to hundreds of metres, depending on the materials, and the system requires contact to 3 or 4 anchors. 3 anchors provide localization in 2D environment, and with 4 anchors the user can visit different floors as well, since the system provides a 3D location. The accuracy is in the order of few centimetres, which is more than sufficient for most purposes.

4. Demonstrators

In total nine demonstrators have been created for being able to cover different kind of environments (indoor/outdoor), different kind of users and use cases (e.g. visualization, reviewing/inspection, user instructions) and for testing some technological aspects. All the demonstrators have been implemented using the Unity game engine, https://unity3d.com/, https://www.unrealengine.com/. Unity offers an application development environment and tools for presentation of virtual 3D content and user interaction, but it is not an AR environment in itself. Thus, to make AR applications, an AR library or development kit is also needed.

4.1. VR Demonstrators

ShipVR is a virtual reality application built for HTC Vive. The main purpose of the application was to create an immersive visualization of the Tallink Megastar vessel before its construction work was finished. The vessel can be observed from the outside in a simplified dock-environment and from the inside in the duty-free shop of the vessel. A miniature "doll-house" version of the duty-free shop is also presented. The 3D-models of the ship and its duty-free shop were supplied by Meyer Turku.

Movement inside the virtual environments has been implemented by teleporting. When holding the teleport button the application projects a teleportation curve from the tip of the Vive motion controller. The user can then designate a suitable teleportation destination, and after releasing the teleport button, the user is relocated to the new position. The transition is smoothed by using an animation that simulates blinking eyes. As in all Vive applications, it is also possible to move by physically walking inside the tracking volume.

BridgeVR is a virtual reality application built for Oculus Rift. The object is a road bridge. The application allows for dynamically loading IFC-models from an online server into a virtual environment. Several movement options are presented for the user to allow easy and quick navigation in the possibly large-scale environments. Visibility of parts of the models can be toggled on and off, and metadata contained in the IFC-model can be inspected inside the scene. The user experience can also be customized by letting the user select between different object highlighting and movement options.

Fig.5: Bridge VR

The application is controlled with an Xbox 360 or Xbox One controller. Movement inside the virtual environment has been implemented by using joysticks and gaze teleporting, while user interface elements and model objects can be selected with gaze. BIMServer and BIMconnect were used in conjunction to make dynamic loading of CAD-models possible. IFC-model data is streamed directly from BIMServer and the models are constructed one-by-one into Unity.

BuildingVR is a virtual reality application that is based on BridgeVR. The main difference between BridgeVR and this is that as well as displaying static metadata contained in the loaded IFC-models, BuildingVR contains components that allow gathering data from the design databases. In this demo was used as an example Granlund Designer, a building information application by Granlund. The integration with Granlund Designer allows for combining the models of the buildings/spaces in the application with real-time sensor data contained in Granlund Designer. This means that inspecting e.g. the models of air conditioning systems gives the user real-time data about the state of the selected air conditioning components.

4.2. AR Demonstrators

OutdoorAR is an augmented reality application built for high-end customer-grade tablets. The application can be used to augment a 3D-model in an outdoor scenario. The initial placement of the model can be done either manually, or by using a GPS based system that uses 2 distinct GPS locations. The tracking in the system is based on the panorama tracker, which is only capable to track the rotational movements of the device, so the tracker must be reset whenever the user moves to another location. Panorama tracker is a markerless tracker, so it doesn't require any markers or previous knowledge of the area, *Forsman et al. (2016).*

IndoorAR is an Android tablet application that combined results from several different research areas. The application guides its user to the maintenance target with a dynamically updating indoor map, downloads the CAD-model of the maintenance target from a server, and allows the inspection of the maintenance target via augmented reality. Several objects can be selected for inspection, and static metadata from the IFC-model as well as real-time data from Granlund Designer are displayed to the user. The functionality of the application is based on several subsystems.

Tracking is handled using the *Vuforia SDK*, https://mrdb.utu.fi, and the tablet's gyroscope as a backup. Vuforia's marker tracking and extended tracking are used to calculate the exact pose of the user, while the gyroscope of the tablet is used as a backup if the visual tracking system fails to determine the pose.

Indoor localization is handled with an UWB (ultra-wideband) system that uses UWB beacons by Decawave. The system calculates distances to UWB beacons that are situated close by and then uses triangulation to determine the exact position of the user.

Dynamic loading of CAD-models is made possible with a combination of a BIMServer and BIMconnect, in very much the same way it is done in BridgeVR and BuildingVR.

Displaying real-time data from the environment is made possible with a component that communicates with the Granlund Designer API (application programming interface). The system extracts component identifiers from the metadata contained in the IFC-model and then uses those identifiers to request for component specific real-time data.

4.3. Small Scale Demonstrators

HoloLensAR is a simple proof of concept created for Microsoft HoloLens. The application contains the 3D-model of the air conditioning system situated in the office building. The air conditioning system is positioned so that it is overlaid directly on top of the real-life system. After positioning the model, real-time data from the air conditioning system can be fetched from the relevant databases. In this case it was Granlund Designer.

PhoneAR is a proof of concept for using the commercial augmented reality SDK Vuforia in a device training/maintenance application for Android tablets. The application shows step-by-step visual instructions for the usage of a Cisco IP phone. The visual instructions are overlaid directly onto a live video feed. This is accomplished by recognizing the phone using the tracking functionality in the Vuforia SDK.

OfficeVR is a virtual reality application that is based on BridgeVR. Most of the more complex functions of BridgeVR have been removed, but the graphical fidelity has been improved. The main purpose of the demo is architectural visualization using CAD-models and virtual reality tools.

4.4. User experience

Three usability tests were carried out, all varying with different MR systems, different test subjects and different test settings. This was due the variance in the target groups, company aims and suitable times. The test settings include quantitative and qualitative testing as well as observing the use-situations. Preliminary results show positive feedback from most of the test subjects.

According to the test subjects the potential to use VR and AR in industry seems good. Users saw that the technology could improve their work processes and they were eager to implement the solutions to their use. The was an interesting notion that the VR and AR development should be focused on their specific field where it would be a big improvement (but not necessarily to others) thus giving a hint that if everyone feels this way, perhaps they are suitable for many of those fields.

While the larger analysis of the results is still on-going, we argue that these systems - when designed correctly - a) do not generate a large-scale user-resistance and b) will improve the work process of most of the stakeholders in the industrial field.

5. Conclusions

In this paper, the current state of commercially available display hardware and software tools supporting augmented and virtual reality were discussed. The current level of sensor and display technology, even in consumer-oriented devices, allows creation of viable augmented and virtual reality solutions for industrial use. In the software field, more robust positioning and tracking solutions are wanted – this is especially the case with markerless tracking, for which a commercially available, truly efficient and robust solution seems to be missing. For coarse positioning, UWB technology offers a working solution, at least in cases where using a beacon system is acceptable.

These AR and VR proof of concepts and prototypes implemented in the MARIN2 project covered several different areas. These solutions were rather easy to produce given the fact that no applications alike were produced before. During the 4-year research period the technology took huge leaps in both AR and VR of which the last leap – the Microsoft HoloLens – made the biggest impression. While before the tracking and other base-level programming took most work in the development of AR solutions, the new technology frees the resources for content creation. In addition, the VR technology has taken huge leaps in both quality and prize. Therefore, it seems likely that these solutions will get cheaper and thus more common in near future both in entertainment and industrial sectors.

AR and VR solutions were tested by potential users from the partner companies in the project. Feedback from them supports the view that such tools would be useful and potentially could be taken as part of their work. Thus it seems that from both the perspective of work and workforce, as well as from the economical point of view, developing and implementing AR and VR as a part of industrial work processes seems an idea worth considering.

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The Evolution of Virtual Reality in Shipbuilding

Denis Morais, SSI, Victoria/Canada, Denis.Morais@SSI-corporate.com
Mark Waldie, SSI, Victoria/Canada, Mark.Waldie@SSI-corporate.com
Darren Larkins, SSI, Victoria/Canada, Darren.Larkins@SSI-corporate.com

Abstract

Virtual Reality (VR) has gone from being science fiction, to being realized in the research lab, to being treated as a toy, to being used in practical applications, including shipbuilding. This paper examines the history of VR technology as well as its current state. It then predicts the future of VR by analysing the forces that have either hindered or promoted the implementation of Virtual Reality in the ship design and construction industry. Challenges are identified as well as possible solutions, in the context of technology, economics and organizational culture.

1. Introduction

The year is 1992. You are in a theatre to watch a science fiction/horror film starring Pierce Brosnan. The movie is Lawn Mower Man. It opens with a black screen showing some scary, yet exciting prophetic text:

"By the turn of the millennium, a technology known as VIRTUAL REALITY will be in widespread use. It will allow you to enter computer generated artificial worlds as unlimited as the imagination itself. Its creators foresee millions of positive uses- others fear it as a new form of mind control…"

Fig.1: Lawn Mower Man: Collector's Edition Promotional Poster Image

The movie then proceeds to show how Brosnan, the scientist, does experiments using virtual reality (VR) on a hapless simpleton who mows lawns for a living. The experiments involve head mounted displays (HMDs) and haptic bodysuits to provide touch sensations. VR is so perfect as a training medium that the lawn mower man becomes a genius; he even develops the ability of telepathy. VR was thought to be that powerful.

It is just a movie, and much of it may seem laughable, yet at the time, it was not considered all that unbelievable; VR was all the rage. In the early 1990s, there was a broad market for books, magazines and newsletters about the subject. There was Ben Delaney's 'CyberEdge Journal' which addressed the business aspects of virtual reality. MIT launched 'Presence' to cover virtual environment research. There was even a bimonthly magazine called 'PCVR' which was a how-to guide for building home VR systems. VR was everywhere, VR was the future, VR was going to transform industry, and VR was going to transform life.

Companies were formed. Academic institutes were established. It was on the news and then, by the late 1990s, as far as the general public was concerned, the technology was hardly noticed. A search of Google Trends, which goes back to 2004, shows a slow, but generally continuous decline in searches for the term “virtual reality” until the spring of 2014, when suddenly, interest starts curving upward. It’s difficult to establish exact numbers since the graph just shows a relative scale; however, it is clear that the popularity has grown so much that most recently, VR headsets were a hot tech gift during the last Christmas season (See the Dec. 2016 spike up in Fig. 2).

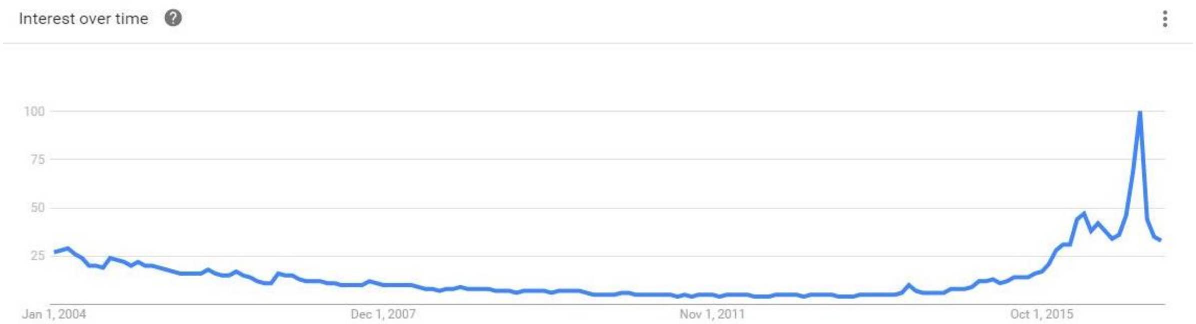


Fig.2: Google Trends: Search for Virtual Reality, January 2004 – March 2017

Virtual reality seems to be a good fit for what, in the tech world, is known as Amara’s Law. The law states, “We tend to overestimate the effect of a technology in the short run and underestimate the effect in the long run.”

This insight was first stated by Roy Amara, formerly President of the US-based Institute for the Future. His concept was further expanded by Gartner Inc. and popularized in a graph called the Hype Cycle. The Hype Cycle shows a new technology being greeted with massive hype and excitement. This continues until people reach a peak of inflated expectations which crashes down to a trough of disillusionment as they realize that they have overestimated the technology (at least in the short run). However, just as all hope is about to be abandoned, the technology advances, prices come down, better designs and applications are found, and slowly, people’s recognition and usage of the technology climbs a slope of enlightenment to the plateau of productivity. This is a familiar story that can be applied to many developments including VR. After the collapse in the late 1990s, VR is rising again.

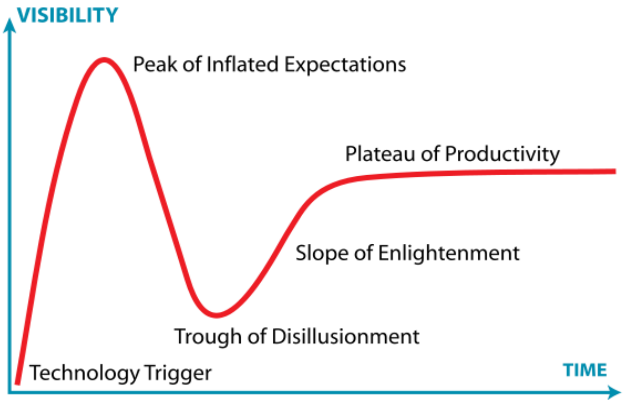


Fig.3: Gartner Hype Cycle

But how and why we got to this state of renewed interest and adoption is a fascinating story, as is the likely outlook for the technology’s future. By looking at the forces affecting the adoption of virtual reality, particularly in regards to ship design and shipbuilding, we will show where we think the adoption of this technology is headed.

2. What we mean by Virtual Reality

First, we should clarify what we are talking about. As was pointed out in a paper at the very first COMPIT in 2000, sometimes in the shipbuilding industry, people have used the term “virtual reality” to mean things that are not really immersive; just mouse-controlled navigation through a non-stereoscopic three-dimensional graphical representation on a monitor, *Bertram (2000)*. That ability alone has provided significant advantages and is quite an achievement. However, for the purposes of this paper, we mean something more. The characteristics of immersive virtual reality include the ability to seem like you are inside of a 3D scene, either by viewing through a head mounted display (HMD) or by using 3D glasses to look at a projection on one or more walls. The virtual objects are displayed in full scale so that it seems as if one is actually walking around or flying through a real world. Along the way, you can interact with objects you see.

In other words, with VR, there is an illusion that you are experiencing a different reality, created by a computer. This effect would be even stronger if it was enhanced by auditory, tactile and other non-visual technologies. However, for the purposes of this paper, that is generally more than what we mean. Still, anyone who has ridden a roller coaster using a modern VR headset knows that the effect seems very realistic.

3. History of Virtual Reality

Here’s how we got to the technology of today. We could trace VR’s roots back to experiments with stereoscopes such as the children’s View-Master toy. We could also talk about some simplistic head mounted displays created in the 1960s. But the name *Virtual Reality* was coined by Jaron Lanier of the Visual Programming Lab (VPL) in 1987. VPL then went on to develop a range of virtual reality gear that used hand and head tracking to immerse users in a computer simulation. Note the prices:

- Head mounted displays (HMD): Eyephone 1 HMD: $9400; EyePhone HRX: $49,000
- Dataglove: $9000.

In 1991, we started to see virtual reality arcade games from Virtuality Group. In 1993, at the Consumer Electronics Show, Sega displayed a VR headset for the Sega Genesis video game console. Not to be outdone, in 1994, Atari showed off its own VR prototype to go with its Jaguar console. In a similar vein, in 1995, Nintendo released Virtual Boy. Unfortunately, these VR related devices flopped when they hit the market and Sega Genesis VR never even made it out of the prototype stage. There were also VR failures from consumer electronics companies such as Tiger and Philips. By the late 1990s, most of the VR related companies, institutions and publications were dead or on life support.

Fig.4: Sega VR Prototype for Sega Genesis

But here’s where things get interesting. Outside of the public eye, industry continued researching applications of virtual reality using devices such as the CAVE wall projection based system from Fakespace Labs. This research and experimentation was noticeable in the marine industry and continues to this day. In fact, for years, some shipbuilders have been using VR as a regular part of business.

3.1 Virtual Reality in Shipbuilding Industry: COMPIT Papers

The marine industry's interest in VR was apparent at the first COMPIT held in 2000. Furthermore, a review of all the proceedings since then shows that with very few exceptions, almost every year the conference has featured several papers on virtual reality. Admittedly, sometimes the papers are about utilizing what one paper called "poor man's" virtual reality, just 3D navigation on a monitor, *Bertram (2000)*. Still, it is interesting to review the history. Here is a sample of papers presented:

In 2000, there was discussion of using VR for CFD post-processing, *Bertram (2000)* and discussions of how the Canadian Navy was using a virtual reality simulator for training on deep water manoeuvring, *Frutuoso and Soares* (2000). In 2003, there was a paper on the advantages of using VR for engine room design, *Baier (2003)*. In 2005, a paper talked about using VR to enhance clarity in the design of ship outfitting, *Nedeß et al. (2005)*.

The focus between 2000 and 2005 seems generally to have been on simulation and design review for manufacturing. Then, in 2006 and 2007, papers start talking about using VR more for sales and marketing and training. In 2008, there is a paper on how the Brazilian Navy was using animations of assembly sequencing to visualize possible problems in production, *Santos (2008)*. In 2013 there is talk about shop-floor 3D, supply chain collaboration, and integration with other software, *Larkins et al. (2013)*. More recent papers have been talking about VR's close cousin, Augmented Reality (AR).

3.2 Current VR Usage in shipbuilding

That brings us to today. Currently, if one surveys the actual usage of immersive virtual reality in our industry, two major players are Virtalis and Techviz. According to their websites, they have the following major shipbuilding clients:

Technviz Clients:
- DSNS (French Navy projects)
- Keppel FELS (Offshore builder)
- Hyundai Mipo Dockyard (one of the world's largest shipbuilders)

Virtalis Clients: (Software: Visionary Render & VR for CAD)
- BAE (British Navy projects)
- Dalian (Big Chinese shipbuilder)
- Irving and Fleetway (Canadian Navy Project)

Companies use VR for design review, shop floor 3D, sales, marketing and training.

In our survey of the market, something jumps out at us. The companies that use the big cave style immersive VR systems are typically involved in defence or in very large-scale shipbuilding. Companies building workboats, ferries and yachts are not typically using VR on this level. It's true, they do often use programs such as Autodesk Navisworks and other CAD software's associated viewing applications. However, head mounted displays and virtual reality viewing rooms are not typically used by anyone but large organizations, especially those involved with defence.

4. Back in Time: Consumer VR from 1990s until Oculus Rift

So why isn't immersive virtual reality used more often in our industry? Before answering that question, let us turn back to the consumer world because to understand what has happened in the last few years, you need to look at what happened from the 1990s until the development of the Oculus Rift.

Let us go back in time and look at why consumer grade VR died in the late 1990s. We'll get into more details later, but right now, it's simple enough to say this: Back then, VR was extensively promoted to the masses and there was a receptive audience. Unfortunately, the quality of what people experienced was disappointing, especially considering the high price and unique challenges of using VR systems. Furthermore, there were not enough games and other supporting technologies to make people see value. Virtual reality got a bad reputation, systems did not sell, there was less investment in the technology and things fed back on each other in a quick death spiral. People heard the hype and were interested; when they went to investigate further, they were let down by reality.

A business analyst might note that whenever a company is introducing a new product, that product must meet a certain minimum standard in order to be viable. Unfortunately with VR, the level of quality required to be an MVP (minimum viable product) is quite high. This is because so many other things must be in place at the same time for VR to work. All the hardware (headsets, controllers, sensors and computers) must be at a certain level and so does a range of supporting software. As far as consumers were concerned, in the 1990s, the supporting ecosystem to make VR viable was not in place.

4.1 Oculus Rift

And so, as far as the consumer world was concerned, VR languished. Then, in 2007, a 15-year old named Palmer Luckey took up an unusual hobby; he began collecting old VR headsets. He would go around buying unwanted HMDs that had originally been sold for $100,000. He acquired what would become the world’s largest private collection of VR head mounted displays. He studied them and decided to build ones of his own, but better.

Fig.5: Palmer Luckey, developer of Oculus Rift

In 2010 he designed an HMD that had a 90-degree field of vision, something previously unheard of in the consumer market. But he kept tinkering, kept improving. Then, by chance, in 2012, in an online forum, Luckey ended up chatting with famed video game programmer, John Carmack (lead programmer of Doom, Wolfenstein 3D and Quake). Carmack was interested in Luckey’s homemade headsets so Luckey gave him one. Carmack was so amazed by what he saw that he started promoting it in the industry.

In June of 2012, Luckey formed a company called Oculus and developed more headsets. The quality was so impressive that in March of 2014, Facebook bought his technology for $2 Billion. That is when the Google Search and news stories about VR began going up again.

Meanwhile, other companies started scrambling to get in on the buzz. Google Cardboard came out in 2014. It was a foldable cardboard viewer that fit around an Android phone; the price was as low as $5 and 5 million units were sold in the first 19 months. In 2015 a more traditional headset called Samsung Gear VR was released and in 2016, HTC released the HTC Vive.

5. Why the revival?

What is going on? One might be wondering what happened in the last few years to suddenly make VR more viable. The answer is, the underlying technology improved so that with the right design, the quality was able to go up and the price was able to go down.

Here is a good look at what happened. As Palmer Luckey was tinkering with parts from old HMDs, he realized that computer performance follows Moore's Law: the performance doubles every 18 months. Therefore, the power he had to play with was 10s of thousands of times greater than when Jaron Lanier had been working on a HMD back in 1987. Luckey saw the improvements in graphics cards and he saw the improvements in cell phone screens. In other words, if he could put some stereoscopic lenses on top of a new cell phone screen and hook it up to a powerful modern computer, he would have the beginnings of a better HMD. You can get a glimpse of how much improvement there has been in computers, phones and screens in recent years by looking at Figs.6 and 7.

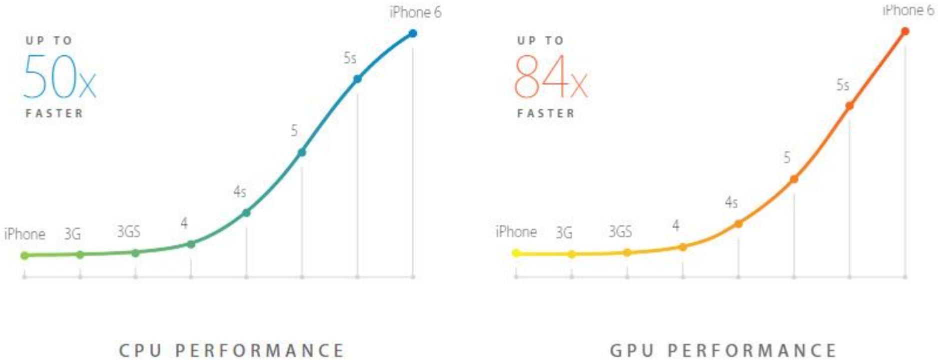
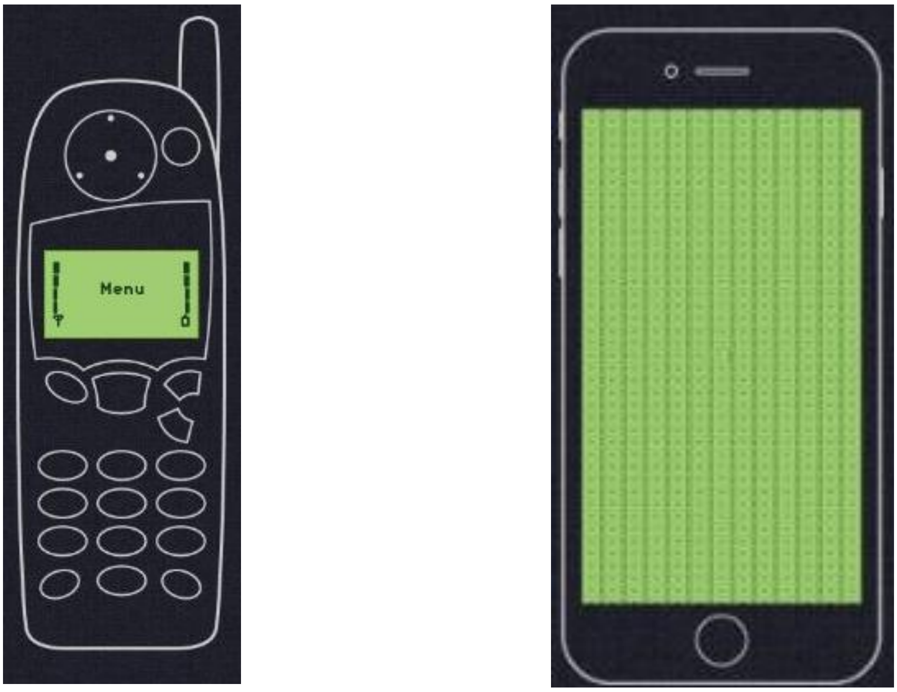


Fig.6: Performance: first iPhone (2007) until iPhone 6 (2014)



1998: Nokia 5110 - 84 x 68 pixels
65 pixels per square inch
Shows 90 characters

2015: iPhone 6s Plus - 1080 x 1920 pixels
401 pixels per square inch
<u>Shows 514 Nokia Screens!</u>

Fig.7: How many Nokia Screens could fit on an iPhone 6s?

There have been massive improvements. And as the quality was going up, the cost was going down. Consider how the price for consumer-level HMDs has dropped since the 1990s. As of March, 1 2017, the Oculus Rift Headset is $499 USD and the associated Touch Controller is $99. The price of Jaron Lanier's inferior technology in the 1990s was over $18,000!

6. Consumer VR still not ready

Unfortunately however, VR still does not appear to be ready for mass adoption by consumers. Even though in March 2014, Facebook's Mark Zuckerberg was willing to spend $2 Billion on virtual reality, in February of 2016 he said to 'Business Insider' that the technology remains a long way from reaching the mass market; in fact, he thought that it would take at least 10 years.

There are several logical reasons for Zuckerberg's caution. There are several challenges that still need to be better addressed. First of all, even with the massive price reductions, the cost of VR equipment is still higher than most consumers want to pay to play video games. Not only do you need a special headset and controller, VR requires a more expensive computer than most people have. Then, there are several other factors which you don't think about until you start getting serious about VR: the headsets are bulky and not comfortable for long periods of use; they mess up people's hair and even their makeup. Being tethered to a machine with cables is a tripping hazard and you must spend quite a bit of time creating a controlled environment in an open space without furniture in the way. There are also sensors to set up. People do not want to do all this work in their homes. All of this is a significant cost and hassle, and what do consumers get out of it?

If quality is acceptable, the price is high, but if the price is low, the quality is poor. A lot of people were excited to see that they could leverage their phones to get virtual reality cheaply via solutions such as Google Daydream View ($99) or Samsung Gear ($69.99). Unfortunately, these are mostly just a novelty; these products do not support scenes as complex as most people would like.

As for all consumer VR in general, the newness of the technology means there are few games or applications available. The fragmentation of the market further makes it harder for consumers to know which platform they should pick. All of this leads to a Catch-22: less games and applications are developed, the price stays too high, and there is less of a reason for average consumers to spend on VR. It is true that virtual reality games and devices experienced an exponential increase in sales in the 2016 Christmas season. However, that was still dwarfed by sales of other technology. Zuckerberg is probably right; even though there have been exponential improvements, as far as consumers are concerned, VR still has ways to go before it will become ubiquitous.

7. Industry will Drive Enhancements

On the other hand, the situation is totally different in the business world. In fact, we believe that industry will lead the charge in VR development from here. This is in contrast to what we have been used to seeing over the past decade where technology for the consumer market (e.g. cell phones and tablets) has been driving development and later spinning off into business uses. Remember, unlike with the total collapse in the consumer market in the late 1990s, industrial usage of virtual reality never went away. A lot of the challenges and hassles that plagued products for consumers were not present, or at least, not felt as strongly in the business world.

When a business uses VR, it is not doing it for casual entertainment; it is to solve real business challenges. In the COMPIT papers over the last 17 years, it has repeatedly been noted that VR increases quality and understanding during design reviews which prevents rework, increases efficiency in production, and reduces costly errors. Still more benefit can be derived for training and sales. Therefore, there is a potential for significant return on investment; buying a VR system for an industrial application is not just something one does for amusement. This seriousness means that people working on high value designs are a bit more willing to accept a certain amount of annoyance such as tethering, bulky headsets, and even more prosaic problems such as mussing up one's hair and makeup with an HMD. Of course, these types of things still are concerns; they just do not have quite as high a weight as when people are merely using VR for fun.

As for the issue of computing power, this is far less of a concern for industry. It may be true that only 1% of consumers have PCs that can support VR. However, if a company is doing engineering, this is not the case. If a company is using CAD programs, it probably already has powerful VR capable computers and is used to buying machines of that calibre. Admittedly, depending on the VR solution deployed, they will probably need a separate machine for each graphics display node; however, buying high powered computers is not a shock for engineers.

Another relative non-issue for industrial use-cases is the availability of applications. Programs such as Virtalis Visionary Render or the software from TechViz already address several industry desires and support input from a wide variety of CAD programs. It is nothing like the situation with consumer VR where consumers are unwilling to buy VR hardware until more games are developed.

8. Challenges

Nevertheless, the fact that VR has not already been more widely adopted for business uses demonstrates that there still are serious concerns, particularly in the shipbuilding industry.

8.1. Challenge: Lack of perceived benefit vs cost

First of all, there is the price or rather, the perceived benefit vs. the cost. It is hard to justify spending money on virtual reality if it is not thought to be worth it. Below are some numbers:

With the price cut at the beginning of March 2017, you can buy an Oculus Rift and an associated Touch motion controller for $598 USD. It is advertised as being plug and play but when engineering managers go to experiment with it, they are shocked to find out that they probably need software for $17,000 (on top of a $4000 computer). And that is just the beginning. If you start looking at wall systems, things start to really add up. On top of the price of the high-end computer (actually, multiple high-end computers, depending on the collaboration scenarios), there is the cost of the projector. A projector with the necessary lumens and a resolution of 4K could be $150,000! If you start adding displays on the floor and multiple walls, or if you want multiple HMDs, you need more computers, software and projectors. On top of that is the construction (and preparation and dedication) of a special VR room itself. Therefore, for many applications, the price of a virtual reality system can run well into the hundreds of thousands of dollars. That is an order of magnitude more than the type of price that people these days expect to pay for anything to do with computers and electronics so this can come as quite a shock.

You also must remember that the upfront dollars are just one “cost” of VR. Virtual reality always involves at least some form of additional overhead, e.g. the hassle of putting on headsets and meeting in a special room etc. Thus, in order to justify the usage of VR, there probably has to be significant additional benefit to using it over the status quo. Indeed, the bigger the net benefit, the better.

8.1.1 Solution 1: 10x better

A good way to think of this is to use the 10x concept promoted by venture capitalist and PayPal founder Peter Thiel. He only invests in companies that offer a solution that is ten times (10x) better than the current way of doing things. Applying this concept to VR, we can see that in many scenarios, even if utilizing VR was a natural extension of current processes, the advantages would likely be perceived as being too small to create widespread adoption. Using VR for routine clash detection of geometry would probably fall into this category so we would not expect shipbuilders to be sold on VR for that.

On the other hand, using VR for sales and marketing would provide a dramatically better experience than looking at plain pictures. That is because VR allows better communication, especially with non-technical people who, by using VR would have a way to navigate through a ship model naturally. Virtual reality would thus be more likely to be adopted here.

8.1.2 Solution 2: Ability to do new things

Other cases where we see increased likelihood of adoption involve situations where VR lets a company do things that it might not even be doing at all currently because the difficulty and cost are too great. With VR, it is much easier to do things such as examinations for physical usability. Is a space too tight? Is there enough clearance? How wheelchair-friendly is a design? Doing tests in virtual reality is the next best thing to trials with a physical mockup, but far easier. This would seem to be a clear win for virtual reality.

8. 1.3. Solution 3: Ease of Trialability

Yet all of the above cost/benefit analysis presupposes the ability for shipbuilders to easily try out VR. They need to easily perform trials so that they can get a better feel for where they might use it in their organization and better understand the effort involved. Trials allow them to find where the 10x benefits are and give managers ideas for new things their organization could do. Indeed, the ability to easily try out technology before one buys it ("trialability") is a well-known significant factor affecting the successful diffusion of innovations, *Rogers (1983)*.

Here is where the excitement in the consumer space over the last few years fits into the picture. Vendors of VR systems for industrial applications have noticed a scenario repeatedly occur; engineering managers have increasingly been buying the HTC Vive or Oculus Rift to experiment. The price is low enough that it seems relatively risk-free to "check out". It allows engineers to "get their feet wet" and play a bit with the technology so that they can more fully understand the potential benefits vs. the costs. Wise VR vendors have started to take advantage of this new receptivity and it seems that this could be the beginning of increased adoption in our industry.

8.2. Challenge: Need for an Up to Date Model

Unfortunately, in many use cases for VR in shipbuilding, e.g. design reviews, you need to have an up to date model; VR has to be in sync with CAD. This presents a problem because unlike with many other industries, in shipbuilding, there is constant change.

If you are just bringing over the geometry from CAD into VR, this is less of a problem. However, if you need the metadata for all the parts (and many scenarios do), this is usually a challenge. You typically need to go through a manual export and conversion process and make sure all the metadata is included. This procedure needs to be done every time there is a change which, as we have noted, happens constantly. Therefore, if you must do this every time you want to use VR it is a major amount of work.

Fig.8: Customizations in VR software can be used to add animations for training, e.g. valves turning

And the problem is compounded once you start dealing with VR customizations. What we mean by VR customizations is adding data in VR. For instance, to make a scene more realistic you might change material properties. This helps when showing an owner or sales prospect what their ship might look like. Similarly, to help with training or simulation, you might add animations to make a door open or a valve turn. You would not want to lose all those customizations every time you updated the CAD model because recreating these would take a lot of effort. Indeed, the inability for software solutions to handle change is so significant that it often relegates VR usage to scenarios that change less often.

8.2.1. Solution: VR Must be a Natural Extension of CAD and Current Workflows

The solution to the challenge of change (and other problems, for that matter) is to make VR a natural extension of CAD and current workflows. In other words, working in virtual reality should be a seamless process. VR should be a natural way of viewing and interacting with the CAD data (including all properties, not just geometry). It should always be accurate and up-to-date and should be able to handle change without costly overhead. No special VR experts should be required to convert data into the system and no special CAD expertise should be required for users of the VR program to easily find the data. The entire process should be intuitive.

A key to realizing this solution would be linkages between the parts in CAD and VR. While in VR, you would always be working on a current CAD model and you would be able to add animations and enhance the scene, yet these changes would persist, even when the CAD model changed.

The linkages would bi-directional. This would allow you to be able to make annotations in the VR program and these would not just be sent to a notepad file, they would actually feed back into the CAD system so modellers would know of any changes that needed to be made. Everything would be as clear as possible and as simple as possible. This would make VR a natural extension of current shipbuilding software and thus speed the adoption of virtual reality in our industry.

12. Conclusion

In summary, we have witnessed continual improvement in computer performance and screen resolution since VR’s short-lived consumer heyday in the 1990s. More recently, we have seen VR once again explode into the public consciousness, including in the consciousness of shipbuilders who previously considered virtual reality to be priced out of reach. From here, we see industry leading the charge in terms of development because hassles that would deter consumers are of relatively smaller weight in a business context.

The issue regarding perceived benefit vs. price can be addressed by finding scenarios where VR contributes ten times the net advantage of the status quo, or by scenarios involving capabilities that a shipyard never considered possible before. While performing this cost/ benefit analysis, the ability to easily try the technology (“trialability”) will be crucial.

Many scenarios in shipbuilding will present a special challenge because they require and up to date model and our industry involves constant changes to a design. Building a VR solution that is tightly integrated with CAD via linkages will be a way of creating a solution that is a natural extension of CAD and existing workflows. This will lead to increased adoption of virtual reality in our industry.

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A Packing Approach Model in Support of the Conceptual Design of Naval Submarines

Siebe Cieraad, Defence Materiel Organisation, The Hague/The Netherlands, js.cieraad@mindef.nl
Etienne Duchateau, Defence Materiel Organisation, eae.duchateau@mindef.nl
Ruben Zandstra, Defence Materiel Organisation, rj.zandstra@mindef.nl
Wendy van den Broek-de Bruijn, Defence Materiel Organisation, wh.vd.broek.d.bruijn@mindef.nl

Abstract

Concept exploration has proven to be useful in the early stage design of naval surface vessels, especially when new operational concepts or complex design solutions are required. This paper presents a design synthesis model for diesel-electric submarines, based on the 2.5D Packing-Approach, which can automatically generate varying yet balanced designs. To do so, several new developments have been implemented in the 2.5D Packing-Approach to facilitate the design and balancing of submarine arrangements. The synthesis model was verified and validated with two test-cases. It was first used to redesign the Walrus-class conventional submarine. Second, to assess the models' capabilities as a conceptual design aid, several variations of requirements were performed and analysed. The results of these test-cases confirm that the synthesis model can be a valuable resource in the conceptual design stage of submarines.

1. Introduction/background

The preliminary design stage of a vessel balances the ambitions and needs of the customer with the technical feasibility and available budget. This is often done by exploring a broad number of designs in which different levels of technical feasibility, budget, and customer ambitions are considered. A process referred to as requirements elucidation or concept exploration, *Andrews (2011; van Oers (2015)***.**

Generally, naval vessels are novel complex concepts that need to fulfil a specific purpose for which multiple alternatives can be used. These alternatives can differ in the used components/systems and the configuration of those components/systems. For example, a RHIB (rigid hull inflatable boat) can be deployed from a vessel with a crane, a davit, or using a slipway, or a combination of these systems to increase flexibility. Each alternative has its advantages and disadvantages and can be placed on different locations on board the vessel which will result in a different vessel concept. Furthermore, the characteristics of a design concept can only be properly predicted and compared with other design concepts when a certain level of detail in the design is reached. Achieving this level of detail for a complex vessel requires considerable design effort due to the complex relations intertwined in vessel design itself and the complex systems for which the vessel acts as a platform. This effort, multiplied with the large number of designs needed to conduct a thorough design exploration, together with the generally limited time available, makes the design exploration of naval vessels a challenging undertaking, *Pawling (2007), van Oers (2011).*

1.1. Conceptual submarine design

Concept exploration for a naval submarine requires even more effort. The relatively small size of a submarine and the large amount of constrained components keep the diversity in the configuration of a submarine relatively low when compared to surface vessels. However, in submarines even small variations in the configuration can have large impact on the hydrostatic balance of the vessel.

The hydrostatic balance is the balance between the buoyancy and mass of any floating object. For submarines the hydrostatic balance needs to be exactly right in order for the submarine to be neutrally buoyant. Also, to make sure the submarine has no trim or roll angles the points of application of both the buoyancy and mass need to be placed exactly above each other. Surface vessels also need to be hydrostatically balanced but when there is a slight mismatch the vessel will have a slightly higher or lower draft where as a submarine loses its function to dive or resurface. Summarizing, to minimize the risk that a submarine design cannot be hydrostatically balanced in a later design stage, a higher accuracy in the early stage configuration, and therefore design effort, is needed.

1.2. Conceptual design tools

Over the years, various computer aided design tools have been developed for both the conceptual design of (diesel-electric) submarines and surface vessels. Some notable examples are: the Design Building Block Approach *(Andrews, 1988; Pawling, 2007)*, the Packing-Approach *(van Oers, 2011)*, GCD^2 *(Takken, 2008)*, and SUBCEM *(van der Nat, 1999)*. These tools rely (partly) on computational power to ease the process of generating balanced design concepts, allowing designs to focus more on the task of concept exploration. At the Defence Materiel Organisation (DMO) both the Packing-Approach and GCD^2 are used for the conceptual design of surface vessels. The combination of these tools allows the DMO to apply the following work flow: first, diversity is created by generating many varying design concepts; second, a narrow selection is made of promising design candidates; and third, conceptual design effort is de-risked by designing 1 or 2 promising concepts in more detail. This process roughly follows the proposed phases for concept exploration as named by *Andrews (2011)*.

The DMO needs to use the same steps in the concept design stage of the replacement program of the Walrus class submarine. However, GCD^2 does not possess the desired capabilities to design a balanced submarine. For this reason, a new tool SUPREME is currently under development in close cooperation with MARIN to enable the detail design of a promising concept, more in-depth information about SUPREME can be found in *van den Broek-de Bruijn (2016)*. Because SUPREME focusses on the more detailed evaluation of a single concept design, there is still a gap in the ability to perform broader concept exploration studies. Hence, this paper focuses on creating a diverse exploration by generating a submarine design space suitable for concept exploration.

1.3. Choosing a starting point

The following characteristics are used in Table I to compare several existing submarine design tools: architecture, concept variation, calculation speed, level of detail, number of solutions, and how the hydrostatic balance is found. The description of the configuration, called architecture, provides geometric information to verify if equipment and spaces actually fit. The concept variation shows if the concept configuration must be done manually, or that this process is automated. The level of detail indicates the accuracy with which the concepts are made. The calculation speed indicates how long it takes to generate a design space. The number of solutions indicates the size of the generated design space. The final characteristic, the hydrostatic balance, indicates if the tool is capable of automatically balancing design solutions, or if manual user input is required. Currently several submarine concept design tools exist. The Submarine Concept Exploration Model or SUBCEM, *van der Nat (1999*), Simulation Based Design or SubParm and Submarine Design or SubDes, *Nordin (2014)* are recent submarine specific design tools. The Packing Approach is also added to this table due to the expectation that it can be developed into a tool that can generate a submarine space, the positive experience with surface vessels at DMO, and the fact that it is readily available and used at DMO.

Table I: Comparison of submarine design tools and their capabilities

	SUBCEM	*SubParm*	*SubDes*	*Packing*
Architecture description	3D	Parametric/2.5D	3D	2.5/3D
Concept variation	Manual	Automated	Manual	Automated
Calc. speed	Hours	Seconds	Days	Hours
Level of detail	Medium	Low	High	Low
Num. of solutions	Ten	One	One	Thousands
Hydrostatic balance	Manual	Automated	Manual	n.a.

Table I, shows that the existing submarine tools all have at least one characteristic which is not at the desired level for a tool that generates a design space. Even though the Packing-Approach has up to this point never been used to generate submarines it has all the desirable characteristics. The choice is therefore made to develop a submarine synthesis model for the Packing-Approach.

This paper shortly introduces the Packing-Approach, before elaborating on the developments made to the synthesis model of the Packing-Approach, the performance predictors, and the steering of the incorporated genetic search algorithm. After the developments are discussed, the paper will elaborate on the model verification and the tool validation followed by the conclusions and potential future developments.

This paper represents the results of a master thesis performed in parallel to the early stages of the design exploration for the replacement program of the current Walrus class submarines active in the Royal Netherlands Navy (Cieraad, 2016). However, it is important to state that any potential solution preferences derived from this paper, the created model, variations and/or results from the performed test cases only act as an illustration of the tools capability and do not have any relation to the ongoing submarine replacement program at the Defence Materiel Organisation.

2. 2.5D Packing Approach

The 2.5D Packing-Approach is the most recent version of a tool originally developed for the preliminary design stage of (naval) surface vessels, *van Oers (2011), Zandstra (2014), Duchateau (2016)*. The term 2.5D refers to the three placement options in the transversal direction and a high placement resolution in the longitudinal and vertical direction, *van Oers et al. (2012)*. The tool is therefore not just 2D but also not fully 3D. This difference in resolution in the different placement directions reduces the amount of placement options, and therefore the computational effort required to determine feasible objects locations.

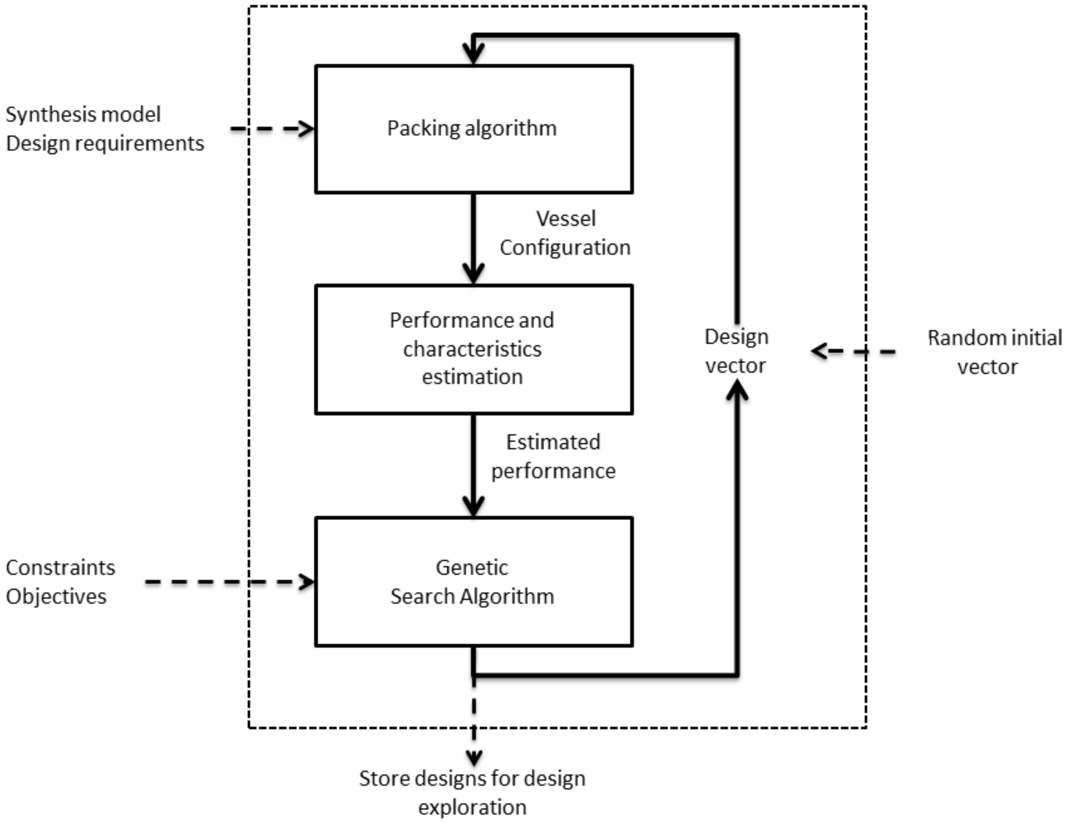


Fig.1: The 2.5D Packing-Approach process with required inputs

Fig.1 shows the process outlined of the 2.5D Packing-Approach. The 2.5D Packing-Approach consists of three main parts: the packing algorithm, the performance prediction, and a genetic search algorithm NSGA-II, *Deb et al. (2002)*, which work together to generate design concepts. The packing algorithm, or space allocation routine, is the unique feature of the 2.5D Packing-Approach. The packing algorithm uses information from the so-called design vector to place building blocks in the placement envelope in a 3D configuration. The size of the placement envelope is also determined by the design vector. The size of the building blocks is determined by the requirements. For instance, the size of the accommodation blocks is determined by the requirement for the size of the crew. The model uses six building block types and one placement envelope type to model the different objects and systems in the design, *van Oers (2011)*.

The design vector can be seen as the DNA of a design, it consist of a vector of numbers, and contains all the numeric configuration information of that specific design. The NSGA-II mimics the evolution of a population in nature by mixing and adjusting individual designs through multiple design generation steps, evolving a concept in the desired direction. Each design generation consist of a certain amount of individual designs with accompanying design vectors. The NSGA-II modifies the design vectors depending on the estimated performances of the generated design configurations and the objective of the design study. The new design vectors are then used by the Packing Algorithm to generate the configurations of the next generation of designs. Before this loop between the packing algorithm and the NSGA-II can start, the naval architect needs to provide the tool with: the requirements for the design, a synthesis model for the packing algorithm to configure, the desired performance predictors, and the constrains and objectives for the NSGA-II algorithm.

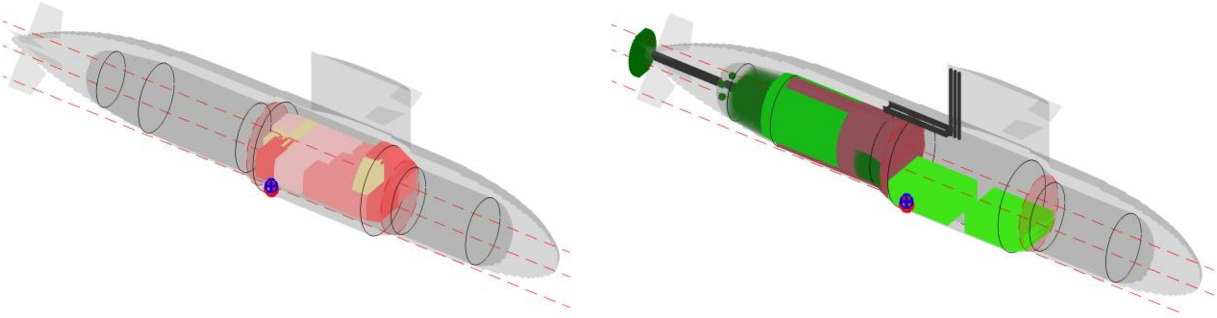


Fig.2: The accommodation (left) and propulsion blocks (right) in a submarine design that visualises the concept of building blocks placed inside a placement envelope

The packing algorithm and the NSGA-II are generically implemented for all models and therefore do not need to be modified to enable the generation of submarines. These parts of the tool will not be further discussed in this paper. The Packing Approach generates the design space in which the design exploration takes place. The exploration of the design space is done with the method developed in the PhD thesis of Duchateau**.** This exploration method is also generic and not altered for submarines. More in depth information about these algorithms, the design space exploration method, and a mine countermeasures vessel (MCMV) synthesis model can be found in *van Oers (2011), Zandstra (2014), Zandstra et al. (2015), Duchateau (2016)*.

3. Method/approach

3.1. Objectives and constraints submarine model

The NSGA-II requires objectives and constraints to direct the generation of new designs. *Van Oers (2011)* and *Duchateau (2016)* showed that constraints within the NSGA-II process limit the NSGA-II in both diversity and calculation time to create a set of designs. Therefore no design constraints are used in the NSGA-II during the generation of the design space. Design constraints such as non-negotiable stability requirements are applied in the post-processing of the design space.

The objectives used in the NSGA-II are implemented as characteristics that need to be minimized. For submarines three objectives are used:

1. Minimize the envelope volume
2. Minimize the delta between buoyancy and mass
3. Minimize the trim moment

The first objective is needed because submarines are generally volume critical, that is, additional weight (often in the form of lead) is required to compensate for the abundance of volume in the design. Therefore, when the same systems are included in a smaller volume the density will increase and thus less additional weight is necessary. In addition, the assumption is made that the smaller a submarine is cheaper to build. The first objective is therefore to have an as small as possible submarine which includes the desired capabilities. The second and third objective are used to search for a hydrostatically balanced design.

3.2. Adjustments to the modelling core

To enable the generation of submarine designs, a packing model with roughly 80 building blocks has been modelled. Fig.2 shows several the building blocks. The modelled building blocks cover all on board systems ranging from auxiliary space, sensors, weapons, communication systems, external and internal tanks to accommodation and workspaces. The modelling of the building blocks is similar to the modelling of building blocks for surface vessels and discussed by *van Oers (2011)* and *Zandstra (2014)*. Therefore, this aspect of the submarine model is not further discussed in this paper; instead this paper will focus on the developments that were added to the modelling core to enable the packing algorithm to work with submarine designs.

3.2.1. Resolution

The higher the accuracy in the object sizing and placement, the better the prediction of the performances, and especially the hydrostatic balance, of a submarine concept. Each packing building block is built-up of volume pixels called “voxels”. A voxel has a predetermined size in both the longitudinal (x) and vertical (z) direction while in the 2.5D Packing-Approach it has a continuous size in the transverse (y) direction. This difference in dimensioning is implemented due to the placement administration. For more detail on the placement algorithm refer to *van Oers et al. (2012)*. The level of accuracy in the packing model, in both sizing and placement of the building blocks, is determined by the predetermined size of the voxels. Increasing the level of detail (i.e., the resolutions) by decreasing the voxel size allows a more accurate placement of objects, and a better estimate of object dimensions (e.g., its volume, area, and centroid) especially when considering the more confined and rounded submarine hull. However, a higher resolution also causes an increase in computational effort required for the packing-algorithm to check all available voxel positions (e.g., this is comparable to the computational effects of increasing the grid detail in CFD or FEM calculations). For the submarine packing model a smaller voxel size (0.25x0.20m), and thus higher resolution, is used compared to the surface vessel models (0.50x0.50m). *Zandstra (2014)* recommends that the resolution of a packing model should be kept adjustable as adjusting it manually later on requires considerable effort. Hence, for the submarine packing-model the resolution is kept adjustable. This allows the designer to adapt the resolution of the model, should a higher level of detail be required. Several tests with varying voxel sizes were performed to determine the right balance of model accuracy, calculation speed, and overall level of detail.

3.2.2. Placement envelope

The placement envelope is the envelope in which the building blocks are placed and determines the shape and size of the vessel (i.e., usually the hull envelope and superstructure). For the submarine model the placement envelope is relatively simple. Submarines commonly have an axisymmetric hull shape while surface vessels have a complex hull shape as well as a superstructure which is wrapped around the objects that are placed on top of the hull.

An existing parametric description for submarine hull shapes was adapted to create the packing envelope for submarine synthesis model, *Jackson (1992); van der Nat (1999)*. The parametric description is capable of generating the three structure types currently used in conventional naval submarines. The single, double, and semi double-hull type differ in the way the (structural) pressure hull and (streamlined) outer hull are combined and utilised, *Renilson (2015)*. Fig.3 shows the parametric description of a semi-double hull and a single hull type, the full double hull type is similar to the semi-double hull with the exception of the mid ship section where a gap between the pressure hull and outer hull exists over the full length. The parametric hull description provides the translation between the design vector and the (volumetric) placement envelope.

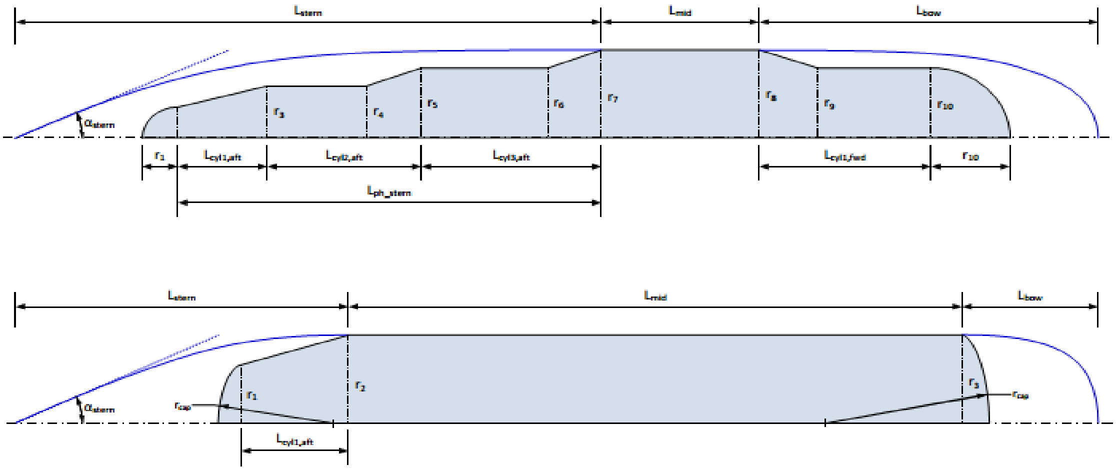


Fig.3: Parametric description semi (top) and single hull (bottom) types

The space between the pressure hull and the streamlined hull is generally used for the placement of tanks and equipment that can withstand the sea environment and diving depth pressure (e.g., the main ballast tanks, high pressure air bottles, and sensor equipment). See Figs.4 and 5 for clarification. Packing originally only supports a single placement envelope (i.e., the hull): a submarine design with both an inner pressure hull and outer streamlined hull cannot be modelled with this approach. Hence an extra placement envelope was added to the packing-model describing the outer hull shape. The space in between the pressure and streamlined hull can then be described as the difference of the outer and inner (pressure) hull.

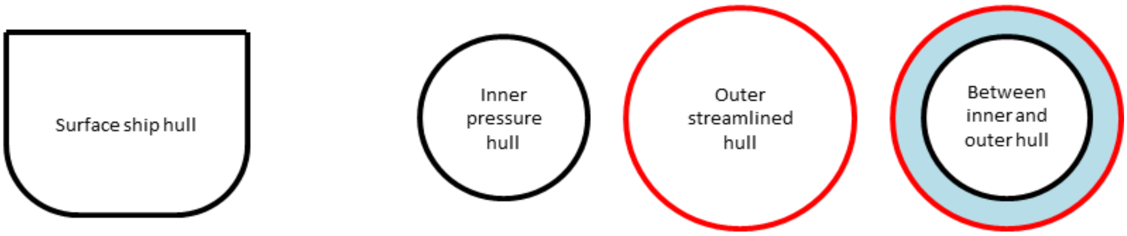


Fig.4: Cross section view of a surface ship placement envelope (left) and multiple submarine placement envelopes (right)

Due to the way the packing algorithm is currently set up, it is only possible to place symmetric tanks and objects in between the pressure hull and the streamlined hull. This is caused by the fact that the placement administration only keeps track of the available width and not where that width in the transverse dimension is available. Hence it is not possible for the packing algorithm to detect where the ‘hole’ is that represents the pressure hull in the available width administration of the “in between the pressure and streamlined hull” placement envelope. This inconvenience is accepted because there is currently no need for asymmetric modelling at this level of detail in the design.

With the extra placement envelope, objects can be placed according to 4 options, Fig.5:

1. Water (outside the outer hull),
2. Inside inner hull
3. In-between the pressure and streamlined hull
4. Inside the streamlined outer hull

The last placement option is used to model objects such as torpedo tubes and hatches which protrude through the pressure hull and are therefore present in 2 placement envelopes.

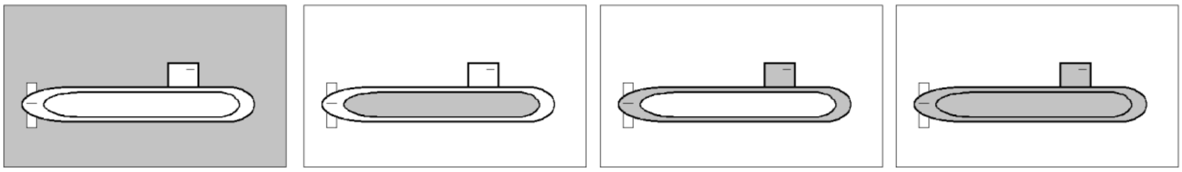


Fig.5: Four main placement options

3.2.3. Hydrodynamic hull considerations

During the design of a submarine several hydrodynamic considerations must be evaluated. At the early stage the main dimensions, the length over diameter ratio, and tail cone angle of the hull are important factors to determine as these aspects directly impact resistance and propulsion characteristics, *Renilson (2015)*. For the packing model a basic initial configuration of the control surfaces is determined to incorporate the placement of the control equipment and to accommodate for the added resistance induced by these control surfaces. The actual size and final configuration of the control surfaces can be adjusted later on.

3.2.4. Two vertical placement grids (decks)

Unlike many surface vessels, submarines do not have a structured deck plan. First, decks on a submarine have no global structural contribution. The decks are placed based on the local structural needs such as the placement of equipment or to enable people to reach certain areas of the submarine. Second, equipment and objects are placed according to their volume, weight, and possible required adjacencies with other systems with regard to the stability of the submarine and to increase the density as much as possible. The unstructured deck plan of a submarine causes a problem as packing currently only supports one vertical placement grid in the form of a tank top and several decks with a certain height (which arose from the general arrangement of surface vessels). Hence, an adjustment must be made to accommodate the placement of objects on varying levels.

The solution is to use two vertical placement grids, the first using the traditional deck levels, and the second where objects can be placed at any z-voxel position. The second vertical placement grid is therefore set at the same height as the voxels heights. The first vertical placement grid makes sure that the accommodation and workspaces, such as the command centre, have a relatively flat floor space. This grid consists of a tank top and several accommodation decks (similar to surface ships). The height of the tank top is variable between a set minimum and maximum. The height of the accommodation decks depends on the pressure hull diameter and the number of decks, with a minimum height, that fit between the tank top and the top of the pressure hull. This makes sure that the accommodation decks are always equal to the minimum deck height or higher and the space between the tank top and top of the pressure hull is fully utilised. Both the height of the tank top and the accommodation decks use the voxel height as discrete steps to make sure these decks concur with the vertical placement grid of the other objects.

The use of two vertical placement grids ensures that the packing algorithm can produce a vessel with a high packing density (i.e., the ratio of the occupied and total available volume within a packing placement envelope) while maintaining a workable environment for the crew on board.

3.2.5. Building blocks and hull roundness

Objects such as cabins and the command centre are modelled by the soft building block type. This building block type is used for objects that fulfil certain functionality independent of their shape, *van Oers (2011)*. Hence, a cabin or workspace is defined as a space with a required amount of usable floor area. A surface vessel generally has fixed deck heights and relatively straight walls and ceilings. Such an orthogonal reference makes it relatively easy to let the packing algorithm place a soft object with a certain length, width, and aspect ratio to form a rectangle to match the space's required area. If extruded upwards along this rectangle forms a box that models a certain space (e.g., the cabin or command centre). The placement administration then deduces the width of the area from the available width over the longitudinal and vertical points the entire box covers.

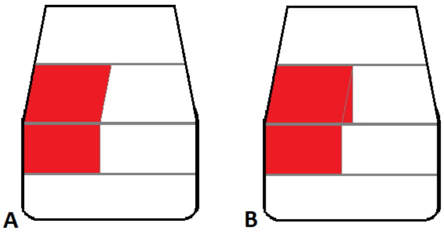


Fig.6: Cross-sectional views of a surface vessel placement envelope. Uncorrected soft objects (A) and corrected (B).

Fig.6A shows, on the lower deck, that this method works well when the envelope has straight lines but when the walls have an angle the soft objects can receive the same angle as the wall, as shown a deck higher in Fig.6A. This can lead to strange object shapes that cannot fulfil the purpose of the modelled room. In the surface vessel model this is solved by making the angled side vertical from the widest point as shown in Fig.6B. This ensures that the tool models an object that always has sufficient usable floor area. However, in the confined cylindrical shape of a submarine the described problem becomes worse, as is shown in Fig.7A. The resulting object has a geometry that does not model a useable room. Although the area at floor level complies with the required area of the object, the strange shape clearly causes problems at higher levels (e.g., the standing height for instance). In addition, the strange shape also troubles the placement of objects at the opposite side of the hull.

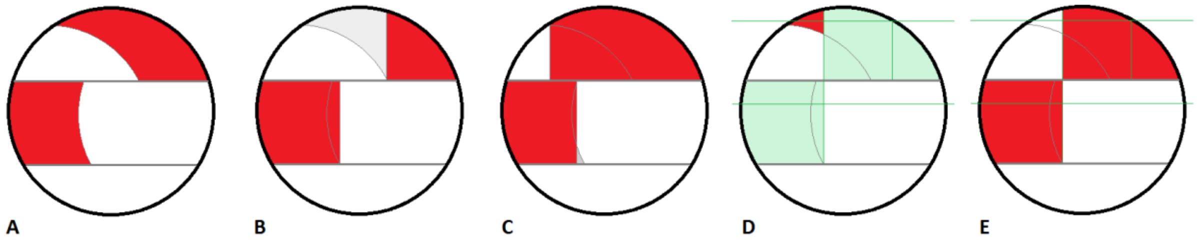


Fig.7: Cross sectional views of a submarine placement envelope and the integration methods of "soft-objects". The different correction methods are: no correction (A); correction from smallest width (B); correction from largest width (C); correction based on required width at standing height (D); the final integrated soft object width corrected shape (E).

Fig.7 shows that there are several of ways to solve this geometry problem with soft objects. Solution B, as shown in Fig.7B, is to cut the object at the width of the floor area. This ensures that the remaining space has a geometry in which it is easier to place other objects. But the geometry problem for the object itself is not solved. Depending on the radius of the cylinder, the available height restricts the actual use of the floor area and therefore the usability of the room the object represents. Solution C extends the width of the floor area to the maximum width of the created objects. This solution is now used on surface vessels. Again, this ensures a straight edge of the object to ease the placement of other objects; however the object claims a lot more space than needed, especially when the deck height is higher than the needed standing height. The chosen solution, shown in Fig.7D and E, is to add a minimum required standing height to the objects characteristics. The standing height is shown as a line in Fig.7D and E. This ensures that the generated object contains a box with at least the required floor area and minimum standing height while still keeping the flexible characteristics of a soft object. The spaces above and besides the box are kept appointed to that object so this surplus in the objects volume can be used to ensure that there is enough space in later design stages to include storage space, cables, piping, and ventilation ducts within the design.

3.2.6. Compartmentalisation

The arrangement of surface vessels is, to a large extent, governed by the placement of the watertight bulkheads. These are placed while considering the floodable length curve and divide the hull into multiple compartments to ensure that there is enough reserve buoyancy in the case of damage. A submarine needs to be exactly hydrostatically balanced; it therefore cannot have any surplus or reserve buoyancy. The compartments on a submarine only act as a safe zone from which the submariners can escape or be rescued in the case of an emergency. The number of bulkheads on a submarine depends on the adopted safety design philosophy and corresponding number of water and pressure tight compartments the naval architect has to implement. As there is no floodable length curve to dictate the placement of the bulkheads, they are now placed by the NSGA-II within the ranges that are determined by the adopted design safety philosophy.

3.2.7. Order of placement

The order of placement has influence on the “packability” and eventual design due to the fact that two physical objects cannot be placed at the same location. The rules of thumb for creating a packing placement order are, *Zandstra (2014)*:

- Heavily constrained objects before unconstrained objects (e.g., the main electric motor is placed early as its position is heavily constrained at the aft end of the pressure hull);
- Large objects before small objects (e.g., large fluid tanks are placed before smaller fluid tanks as the latter are more easily placed in small gaps);
- Hard objects before soft objects (e.g., the “hard” diesel engines are placed before the “soft” fuel tanks, as soft objects can change their shape to wrap around other objects).

In the synthesis model for surface vessels the placement of bulkheads is done before any other objects are placed due to their fixed place according the floodable length curve. In the synthesis model for submarines the bulkheads do not have this constraint while other objects do. The placement of bulkheads is therefore performed after the placement of the torpedo tubes and adjacent to the torpedo storage (located at the front end of the pressure hull). The adopted packing order used in the submarine model is: envelope, decks, torpedo tubes and torpedo storage, bulkheads, propulsion objects, trim and compensation tanks, sail equipment, accommodation and workspace spaces, auxiliary spaces, internal tanks, external systems, and external tanks.

3.3 Adjusted performance predictors

Most of the needed performance predictions are the same for submarines as used for the surface vessels. Those that required adjustments, or were added to correctly predict the performances of submarines are discussed in the following sections.

3.3.1. Resistance

The resistance is, unlike the other performance predictors, estimated directly after the placement envelope is generated and the geometry of the hull is known. With the resistance curve and requirements, such as ranges, speeds, and endurance, it is possible to calculate the input parameters for the sizing of objects such as: the fuel tanks, the batteries, the main electric motor and the diesel generators. A submarine operates both at the surface and submerged, therefore resistance curves is are needed for both conditions. The submerged resistance curve is predicted with the method described in *Jackson (1992)*. The surface resistance estimation method for surface vessels is unusable as the submarine's hull is optimized for submerged conditions and therefore has a completely different shape. This mainly results in a lack of a fast and good prediction for the resulting wave making resistance. This makes the prediction of the resistance of submarines at the surface very difficult. During concept design, a first very rough estimate, at lower speeds, can be made by doubling the submerged resistance at lower speeds.

3.3.2. Stability

As with the resistance, the stability of a submarine needs to be predicted for both submerged and surfaced conditions. In surfaced conditions the stability prediction is roughly the same as for surface vessels while submerged the contribution of the waterline area disappears as the entire vessel is submerged. The submerged stability is therefore completely dependent on the vertical separation of the buoyancy point (KB) and the centre of gravity (KG). This distance should lie between predefined upper and lower stability limits.

The stability of the submarine when transitioning between the surface and submerged conditions is extremely dynamic, non-linear, and depends on which way the transition takes place. Hence, the final prediction of the stability conditions during the transition is therefore not done at this stage of the design and the assumption is made that when the stability in the surfaced and submerged conditions is sufficient, the stability during the transitions will also be sufficient, *Renilson (2015)*.

3.4. Balancing the submarine

A submarine needs to be hydrostatically balanced in order for it to sail neutrally buoyant underwater. This hydrostatic balance has a fixed part and a variable part. The fixed part is induced by the fixed objects such as the submarines hull and the on-board equipment. The variable part is caused by operational activities of the submarine. Due to the importance of the hydrostatic balance both these parts must be considered accurately in the conceptual design stage.

3.4.1. Fixed part of the hydrostatic balance

For most submarine designs it is not possible to achieve an exact hydrostatic balance with only the needed equipment and objects. A submarine design can have a surplus in volume, a surplus in mass, and a resulting trim moment that needs to be compensated to achieve a hydrostatically balance design. In the case the submarine has a surplus in mass, extra volume must be added. This generally means an increase in size and a redesign of the vessel's hull which, especially when the surplus in mass is noted in a later design stages or even during construction, is a very expensive and time consuming exercise. On the other hand, when there is a surplus in volume, extra mass must be added. This can relatively easily be achieved by adding ballast in the form of lead. It is therefore important to make sure that the submarine has a surplus in volume at the early stages of the design to act as buffer for potential weight growth in the later design stages. This surplus in volume also enables the use of lead to correct the trim moment.

3.4.2. Variable part of the hydrostatic balance

The hydrostatic balance of a submarine can change due to operational activities. Obvious aspects such as firing a torpedo but also the consumption of fuel and stores, internal movement of weight, or a different sea water density influence the hydrostatic balance and trim condition. These variations must be compensated to ensure the submarine remains hydrostatically balanced and trimmed throughout a voyage. This is done by the so called trim and compensation system. The trim polygon is used to compare and check the capabilities of the trim and compensation system with the load variation due to operational activities.

The size of the trim and compensation systems (i.e., the size of the trim and compensation tanks) is determined by an estimation method shown in equation 1 *(Burcher and Rydill, 1994)*. This volume estimation is used to set the upper and lower boundaries for the NSGA-II to choose a volume. The upper and lower boundaries are set at 0% and 20% above the initial estimated volume. The volume and placement of the involved tanks indicate which loads can be compensated. The extremes are displayed as a polygon.

$$VOL_{trim\,sytem} = \left(\rho_{sw}^{max} - \rho_{sw}^{min}\right) \nabla_{submerged} + \frac{\Delta m_{stores}}{\rho_w} \tag{1}$$

The variable loads are modelled in two different ways. First, for packing objects that are labelled as a storage space or tank, the variation in density is prescribed. For instance, if a soft object is labelled as a fresh water tank the tool appoints the right densities and tank filling levels for each loading condition. This, in combination with the volume and location of the tank object, allows the tool to determine the contribution of the mass of the fluids to the different load cases. Second, the load case contribution of objects that have discrete weight changes, such as the torpedo storage rack, are predetermined during the object modelling due to the unique discrete steps in mass of these objects. With these contributions to the different predetermined load cases, all the extremes are calculated and displayed as a polygon. If all the load cases can be covered by the trim and compensation system, the load case polygon should be completely overlapped by the trim and compensation polygon.

4. Model verification and validation

The developed packing submarine model was verified and validated to check whether the tool is: (i) able to reproduce an existing submarine design using basic input requirement, and (ii) able to aid designers with submarine concepts exploration by generating concepts for varying requirements. Both aspects are dealt with below, however, due to the confidential nature of the results only limited (relative) figures can be published.

4.1. Model verification

The Walrus class submarine of the Royal Netherlands Navy is used to verify the created model. The requirements of the Walrus are used as input to generate a design space using the Packing-Approach and the developed packing mode. A selected design form the generated design space is then compared to the actual vessel. The smallest balanced concept design which complies with the requirements is chosen.

Calculation time is an important aspect of the developed tool. The calculation time depends, amongst other aspects, on the NSGA-II optimization settings (e.g. population size, and number of generations). All runs for this paper have been performed on the same PC with a population size of 200 designs which are optimized by the NSGA-II over 800 generations. The resulting 160200 designs (including the initial population of 200), are evaluated within a time span of 8-11 h. This allows a naval architect to generate a full design space overnight. Of these 160200 designs, a total of 6907 are fully packed and meet the requirements for the hydrostatic balance and stability, giving a successful yield of 4.3%.

Due to the confidentiality of the associated parameters the actual results cannot be discussed in detail. However, it is possible to show the validity of the model with a relative comparison of selected parameters, Table II.

The total submerged volume of the packing model is 4% higher, however its weight without margin ballast is within 1% of the actual vessel. This difference in volume and weight is compensated in the packing model with extra lead ballast, hence the higher ballast weight group. Due to the relative comparison and the fact that the actual margin and ballast weight is quite small the relative difference between the model and the existing vessel for this weight group is large.

Table II: Relative comparison of selected parameters from the actual submarine and concept designed with the packing model.

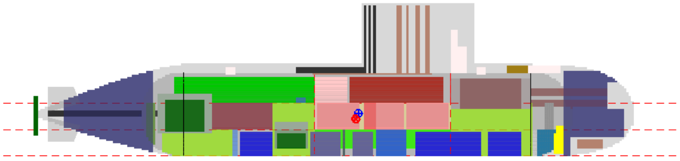
Parameter	%
Length (over all)	-1
Diameter outer hull	0
Diameter pressure hull	0
Accommodation area	0
Fuel tanks volume	7
Main ballast tank volume	4
Trim and comp. tank volume	8
Pressure hull volume	4
Total submerged volume	4

Parameter	%
Structure weight	-2
Propulsion systems weight	-1
Electrical systems weight	-2
Control and Communication weight	1
Auxiliary systems weight	1
Outfitting & furnishing weight	6
Armament weight	4
Total weight excl. ballast	0
Margin & ballast weight	119
Total weight	8

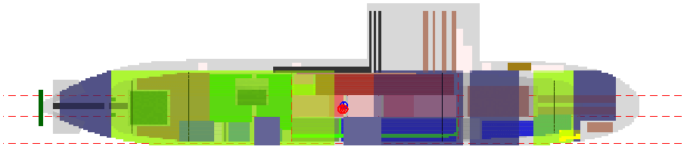
Whether the generated concept indeed has the required modelling accuracy can only be determined when one of the designs is manually re-design in more detail. However, the current comparison with the Walrus class submarine indicates promising results.

4.2. Short validity demonstration

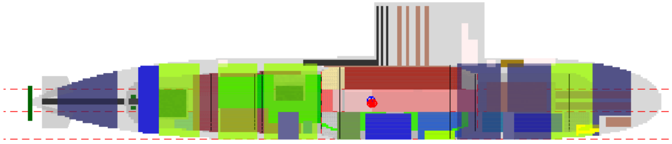
Reproducing a single design is one thing but generating a design space that can be used to provide a typical design consideration with the needed information is another. In order to test whether the tool is capable of aiding the designer with such design considerations, the tool was used to perform a number of requirement variations. This paper presents one such variation: the used hull type (see Section 3.2.2)



(a) Single hull



(b) Double hull



(c) Semi hull

Figure 9. Three designs with the equal requirements but different hull types

For this variation a single set of requirements has been used in which only the required hull type is varied (i.e., semi, single or double hull). Hence, requirements such as: diving depth, speed, range, and crew complement, are equal for all three hull variants that where generated. The NSGA-II optimisation settings were kept equal to the settings applied in the model verification section (see Section 4.1). From each generated set of designs the smallest (e.g., in submerged displacement) was chosen. The three resulting designs with varying hull types are shown in Fig.9. The accompanying relative comparison of select parameters is shown is Table III.

The relative comparison shows that, although the double hull is shorter compared to the semi hull, the total submerged volume for both these hull types is equal. The side view in Fig.9 shows that the double hull has fuller stern section compared the semi hull. The single hull is 18% larger than the other two hull types. This makes this hull structure type, based on submerged volume, not an optimal choice for this set of requirements. To make a choice between the semi hull and the double hull a number of parameters can be used. For instance, the hydrodynamic characteristics are determined by the length of diameter ratio. The semi-double hull has a higher length of diameter ratio than the double hull and will therefore probably be less agile. Even though this demonstration only shows a small amount of the data generated by the tool, it does indicate that the tool is capable of aiding in generating information for early design considerations and concept exploration studies.

Other variations which can be performed using the developed tool are, for example, variations in: speed and endurance (both above and underwater), crew size and complement, adopted system solutions (e.g., battery type or sonar systems), accommodation standards. Ultimately such variations can help aid in identifying the existence of trade-offs between requirements, providing valuable insight for decision makers.

Table III: Relative comparison of selected parameters for different hull types.

Parameter	*Semi*	*Double*	*Single*
Fuel tanks volume	1	1.06	1.20
Main ballast tank volume	1	1.02	1.19
Total trim and comp. tank volume	1	0.97	1.36
Pressure hull volume	1	1.01	1.49
Total submerged volume	1	1.00	1.18
Length over all	1	0.93	0.93
Diameter outer hull	1	1.00	1.10
Diameter pressure hull	1	0.90	1.10
Tank top height	1	0.93	0.93
Accommodation deck height	1	0.92	1.17

5. Conclusions

The conceptual design stage of submarines requires considerable effort. In part, due to the complexity introduced by the submarine design problem itself, but also through the need for thorough concept exploration efforts to support the naval procurement and requirements elucidation dialogue. Hence, the identified need for better tools and methods in support of the early design stage.

This paper presents an overview of the developments made to the 2.5D Packing-Approach in order to allow the modelling of conventional diesel-electric naval submarines. These developments should enable the Packing-Approach to be used in support of concept exploration studies for conventional diesel-electric (naval) submarines.

The main developments to the 2.5D Packing-Approach presented in this paper are:

1. Adaptable resolution: Contrary to earlier Packing-Approach design models an adaptable resolution was imbedded within the model to enable the search for the right balance between calculation speed and a higher level of detail. In addition, a higher resolution was adapted for modelling the submarine in order to overcome accuracy issues.
2. Hull modelling: A second placement envelope was added to model objects in between the pressure hull and hydrodynamic hull. This development not only allows the Packing-Approach to now model the three most common submarine hull types (i.e., semi, single and double hull) currently adopted in submarines, it also opens up possibilities for surface ship types which have more complex double hull constructions (e.g., double hull auxiliary tankers,

floating production storage and offloading units). Moreover, with additional modifications the multiple placement envelope method could also be used to model multi-hull vessels.

3. Deck layout: To cope with the disjoint deck-layouts of submarines, two separate vertical placement grids are implemented. This was done to enable a high system density inside the submarine hull, while still making sure the crew spaces can be placed on logical deck levels.
4. Hull roundness: A minimum required standing height was introduced for soft objects. For complex hull shapes, such as the round submarine pressure hull, this ensures that modelled accommodation and workspace blocks have sufficient usable floor space including the minimum standing height.
5. Adjusted performance predictors: A number of performance predictors were adjusted for submarine design, such as resistance and stability calculations.

The above modifications enable the modelling of conventional diesel-electric submarines in the 2.5D Packing-Approach tool.

To verify if the tool is indeed capable of producing designs with the required level of detail suitable and necessary for the early design stages, several test-cases were performed. This paper presented results of two of these test-cases:

1. The submarine packing model was verified by using it to redesign a Walrus class submarine based on the actual design requirements (i.e., the original design requirements were used as a basis to redesign the vessel with the new tool). Results of this verification study show that the design tool can remodel the Walrus class design well with 10% of the actual values. Much needed verification of the tool with other existing submarines is part of future work.
2. To demonstrate that the Packing-Approach with the new submarine model can be used in the same fashion as the surface vessel model in support of early stage design, a typical design requirement variation was also performed. Three submarines with equal requirements but varying hull structure types were generated and assessed. Results of this test case show that the tool is capable of aiding designers with typical early stage design considerations and variations.

To summarize, the application of the 2.5D Packing-Approach to submarines shows that, with the necessary modifications, the packing-based design approach can still successfully and time efficiently balance requirements for space, arrangement, weight, and centre of gravity. This again proves the Packing-Approach to be a versatile and generic tool during the conceptual design stages. In addition, the tool now enables designers to evaluate a wide range of requirements and their accompanying balanced submarine design alternatives in a short time-frame, supporting the requirements elucidation dialogue between the Dutch Defence Staff and the Defence Materiel Organisation. Moreover, the tool can also quickly provide solid starting points for more detailed designs and analysis using alternate, more user-centric, design tools. Hence, the developed design tool greatly eases the conceptual design process of diesel-electric naval submarines.

6. Future improvements

The model verification and validation results show that the submarine model is capable of achieving the level of detail needed in conceptual submarine design. However, several improvements to the existing model are envisioned:

- As presented in this paper, the model is verified with only one existing submarine. By verifying the tool with more vessels, with varying requirements and sizes, the model can be fine-tuned further.
- The parametric weight estimation for the non-discrete objects such as accommodation spaces and the pressure hull structure are based on a limited amount of reference submarine designs. Due to the confidential nature of submarines these figures are not publicly available and easily obtained.

The used reference submarines currently provide enough data, but increasing this number will further improve the parametric weight estimation.
- The estimation used for the required auxiliary and switchboard space is performed based on the previously mentioned example reference submarines, most of which were built and/or designed several decades ago. Although advances in power electronics have made various items smaller (e.g., from rotary to static converters), the assumption is made that the overall size of such machinery spaces is still a valid reference. The validity of this assumption must be investigated if the tool is to be used.
- Currently no cost estimation is incorporated within the performance predictors. This would make it possible to provide additional information on the impact of potential requirement changes.

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4GD Framework in Ship Design

Greta Levišauskaitė, Ulstein Design & Solutions, Ulsteinvik/Norway, greta.levisauskaite@gmail.com
Henrique Murilo Gaspar, NTNU, Ålesund/Norway, henrique.gaspar@ntnu.no
Bernt-Aage Ulstein, Ulstein Design & Solutions, Ulsteinvik/Norway, bernt-aage.ulstein@ulstein.com

Abstract

Shipbuilding companies are seeking innovation and production cost reduction by exploring the opportunities and capabilities of data management and modelling software. However, they yet struggle with the combination of efficient 3D modelling tools and keeping high control on the product's lifecycle. Therefore, it is a significant matter for the maritime companies to have well-develop tools and approaches to efficiently manage vessel's lifecycle and boost innovation. There are several commercial software and approaches on how to manage vast amount of data during ship design, of which one of the most current one is 4th Generation Design (4GD), that manages the design and product data in one environment. In this context, this work intends to apply and investigate the 4GD approach in ship design and evaluate if this is a beneficial approach in comparison with the traditional hierarchical approach. Due to the wide range the maritime scope, our case is limited to the investigation of a simplified Platform Supply Vessel (PSV) during basic design, specially for the exchange, improvement and 3D reuse facilitation from the 3D designer point of view. The evaluation method is uniformly applied to the 4GD and traditional assembly approach to perform a comparative analysis. The main case study of the research comprises from the modelling and change processes of a PSV based on the challenges commonly met in the industry. The results of the case study are summarizing the user's experience working with 4GD and traditional assembly approach. A comparative analysis is performed on the two methods to emphasize the advantages and disadvantages one against each other. Finally, the concluding remarks suggests that 4GD has potential for innovation in ship design and is potentially beneficial for the shipbuilding companies.

1. Introduction

Ship production processes, Fig.1, are highly collaborative, with the project planning coordinating concurrently ship engineering, construction and maintenance from project development to outfitting, *Cang et al. (2013)*. Therefore, the challenge to combine rich product lifecycle management (PLM) systems and efficient developed designing tools, as well as to perform 3D modelling of a ship with thousands of units and parts arises. Currently, the maritime companies are struggling with one of the two cases, and to manage both adequately an available solution is the implementation of a well-developed PLM approach/software, configured to fit and manage the vessel's lifecycle efficiently, *NN (2013)*..

As an integral part of PLM, product data management (PDM) allows to manage product data and process-related information as one system by use of software, *Kramer and Filius (2014)*, thus providing easy accessibility for multiple teams across the company, such as CAD models, documents, standards, manufacturing instructions, requirements and bill of materials. PDM allows each team working with the project or assignment to access the data related to their needs in the appropriated context. PDM allows the maritime companies to optimize operational resources, finding necessary data quickly, reducing development cycle time, errors and costs. However, even if the usage of PDM in maritime industry exposes great advantages, the implementation of the system evokes difficulties due to the necessity of well-established requirements, compatibility and expectations from the PLM/PDM system from the ship design company as well as the shipyard.

To improve the ship design process, the virtual design environment (CAD representation) is paramount. Specifically, in conceptual design phase it allows having a first look at the concept of a ship which gives opportunity for the customer to view visualized product and improves sales argumentation, *Andrade et al. (2015)*. Likewise, accurate visualization in the detailed design phase is extremely important to evaluate interfaces, perform volume, motion or any other analyses on a product. 3D modelling ensures functionality comprehension but requires knowledgeable people to comprehend the complex interface and manage loads of data under many layers.

Fig.1: Project coordination in ship production process, *Cang et al. (2013)*

The most common method used in 3D modelling is the conventional assembly approach, which deals with connection features between pre-defined geometric entities defining the geometric positions, orientations, mating conditions, and parent-child relations, *Ma et al. (2006).* It is also called traditional structuring approach where, despite of the CAD software employed in ship design processes, the connection features conserves its essential characteristics. The hierarchical assembly structure that consists of assemblies, components and features, which owns the set of entity attributes, is a distinctive feature of this approach, *XF et al. (2001)*.

As the maritime industry modernizes, so the tools must (or at least should) follow up with the same pace of improvement. Therefore, there is a new non-conventional approach in the market, the so-called 4th Generation Design (4GD) to overcome the current challenges of 3D modelling a vessel. 4GD combines the effective virtual design environment with rich PLM data management, *NN (2013).* It is a component-based approach which provides effective and independent data management, and controls the design. 4GD is dedicated for industries specifically with large amount of data products and is declared to be beneficial for easier re-use across the product families, such as different ship types with a certain segment. 4GD environment is an integral part in Siemens NX (a 3D modelling software, later NX) together with Teamcenter (a PLM software, later TC) integration for NX, which are used for this research.

In this paper, a simplified conceptual ship design case is used to evaluate the functionality of 4GD against the traditional approach regarding the exchange and 3D remodelling facilitation. The 4GD concept will be employed to perform configuration and arrangement alterations of a simple ship design case in virtual design environment. The case study is performed in cooperation with Ulstein Design & Solutions AS and investigates a Platform Supply Vessel (PSV).

2. 4th Generation Design

2.1 Generations of CAD systems

4GD concept evolved as an improvement from the previous CAD design management systems. Therefore, to understand the differences of 4GD, the previous generation are described further and the evolution is illustrated by Fig.2.

The first generation of CAD system had high complexity collections of files with multiple copies of parts due to individual storage of each part which made the files very large. Whereas the 2nd generation was already an improvement by introducing the assemblies to facilitate the management of large scale data by storing the components in separate files and inducing the reuse possibility. Due to single-part-per-file approach the components could be used in different positions at a time with no duplication required. Even if this generation gave great advantages it still revealed several drawbacks as the complexity of assemblies increased due to lack of track keeping of files in different versions of large products, *Reffat (2006).*

The 3rd generation of CAD brought new concepts as the PLM system was introduced, *NN (2013)*. It enabled the access to multiple revisions of assemblies, tracking product data through the lifecycle and sharing among the designers. This CAD generation requires well organized hierarchical structure of the product to have a rigid model because only one designer can work on and modify an assembly part at a given time.

As a refinement, 4GD introduced new possibilities for large scale data management which obviated the drawbacks of previous generations and extended the field of potentials. This approach introduced a flexible working environment where assembly definition is made to fit certain working practices, allows to check-out only necessary data which keeps the designing process efficient, stores and manages data independently given the possibility of working with more than on taxonomy.

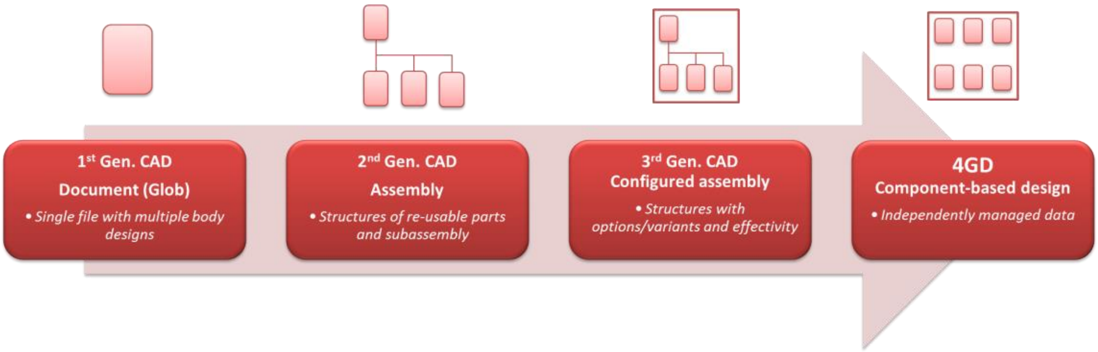


Fig.2: Evolution of large amount data management (adapted from *NN (2013)*)

2.2 4GD Features

The non-conventional approach of the 4GD encompasses several data management objects, which are different from the ones used in conventional assembly and are significant to be understood for further discussion. The relationship of the data management object in 4GD environment is illustrated by Fig.3. The collaborative Design (CD) is a data management object in Teamcenter where the entire design data defining product(s) is accumulated. The design element (DE) is an independently managed object and is collected in the CD. DE contains its unique geometric and locating data, and are constituents of one or more partition schemes.

The partition in the 4GD environment is an organizational container that organises and helps finding data in the assembly but does not control the position or any other property of a design element. Due to partitions the structuring flexibility for the product is ensured and allows multiple organisational breakdowns. In other words, the multiple taxonomy of the product is ensured where physical, spatial or any other division of a product can be incorporated within the same assembly. Plus, one DE can be assigned to multiple partitions and is not restricted to one system. Consequently, the DEs are managed and searched by subsets which in 4GD are the collections of filtered design data in workset. A subset is considered as a part of the workset, where further investigation of the 3D model is performed. A workset is the collection of DEs in specific user's design context in NX session but can be created, modified, navigated and visualised in both, Teamcenter and NX. It might consist of several subsets depending on the design task. As the workset is opened the elements are checked out.

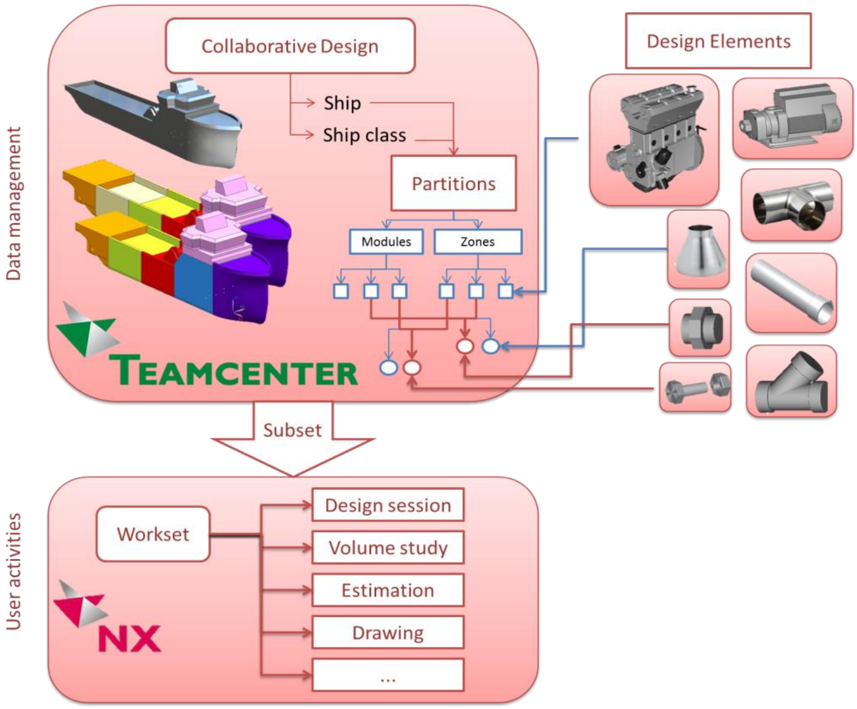


Fig.3: Relationship of 4GD data management objects (adapted from *Slagsvold (2016)* and Siemens AG)

2.3 4GD Theoretical capabilities

As described in *NN (2013)*, the 4GD exposes several advantages as compared to previous CAD systems. The non-conventional approach retrieves only the relevant design-in-context data by means of multiple organizational breakdowns without loading the overhead data. It ensures simplicity to the working environment due to ability easily to reposition and modify only necessary design elements in particular context.

Working on different design elements within the same spatial or functional environment is ensured by concurrent access to the product in 4GD environment. Instead of a fixed subassembly structure where only one designer can work on a certain part in a product, 4GD provides a dynamic working environment that updates modifications performed by another designer. This feature of 4GD reduces the designing time and time-to- market of a product due to the ability for multiple teams to work on the same assembly at a time.

The design element is an independently managed component of collaborative design with unique and declared characteristics as access privileges, maturity status, position in ship, set of attributes, revision history, unit effectivity, and locking status. In other words, for controlling, accessing and managing the design data the components in the assembly do not need to be hierarchically ordered. Thus, it leaves an option for the ship designers to decide on the level of detail in assembly by making separate parts or subassemblies as design elements in 4GD environment.

The non-conventional assembly approach enables multiple organizational breakdowns of a ship which obviates data duplication. This means that multiple taxonomies/views of an assembly such as functional and physical, Fig.4, which loads required unit once even if it belongs to multiple views, instead of predetermined subassemblies of a product which add duplicates. This approach facilitates the day-to-day tasks by reducing the complexity while loading and maintaining the design elements.

Fig.4: Organizational breakdowns **(Siemens PLM software, 2013)**

4GD is theoretically able to generate different configurations of a structure by means of the so-called Effectivity. It allows the user to configure the product with several effectivities which are several configurations. The data effectivity can be configured to specify the content based on date, specific intents, or unit number. The effectivity specification should be done directly when the CD is created but it might also be added while designing in NX. The effectivity configuration can be applied to the entire CD, separate DEs, worksets or subsets.

In summary, the theoretical advantage of the 4D concept is the capability to configure and re-use only relevant data among the ship family due to the PLM configuration management. In other words, only certain data can be selected from one ship, configured and re-used in another ship providing variations only when necessary and avoiding common data duplication. Higher flexibility to the design process and 3D re-modelling facilitation is promised by Siemens using this approach.

3. Case study on the Platform Supply Vessel

3.1 Methodology

The method to follow up in this research is concentrating on the comparison of the two approaches based on the theory and individual experience as there are no current studies on 4GD. The methodology, Fig.5, covers the investigation of the modelling and change processes accomplished in two designing environments, the conventional assembly approach and non-conventional approach. It consists of eight steps, as follows:

1. During the base case a 3D model in NX using the conventional assembly approach is created which documents are stored in TC. Simplified components of the vessel assembly are created and located in the 3D model.
2. The change case covers the assumption of a change request in the project where four different modifications are performed using the conventional assembly approach. The changes are performed from the 3D designers point of view and concern only the modelling software. The change case assumptions derived for this research are:
    a) The stern exchange by a slightly different design stern to evaluate how does this influence the surrounding components and how smooth the exchange process is.
    b) New engine and generator are introduced in the assembly which requires repositioning and readjustment of other identical parts.

   c) Due to new part introduction required remodelling is performed. It includes designing of additional links to the new engine, exchange components in relation to comply with the 4 engines configuration.
   d) Two configurations to the same vessel are created which are two cargo hull PSV and three cargo hull PSV.
3. The results derived from the challenges in base and changes cases are summarized here by pointing out the ease of re-usability, the exchange of the parts, impact on re-modelling and the influence of changes to the surrounding components. The results are expected to provide pros and cons of using the conventional assembly approach.
4. The PSV 3D model is adapted to the 4GD environment to fit certain design features in this step. The parts weren't model in this step because the changes cases and not the modelling are under investigation.
5. The change case in 4GD environment is performed identically as in the step 2. Due to the theoretical advantages of 4GD it is expected that the changes cases will be performed more smoothly when compared to the traditional assembly approach.
6. The results from the 4GD approach are established based on the experience performing the tasks and changes focusing on the exchange process, action taken and influence on the other components.
7. The comparison of the conventional assembly and non-conventional approaches is carried out based on four criteria in concern: exchange, re-modelling, restrictions of constraints, structure importance.
8. Finally, the evaluation is performed to verify the 4GD applicability for specific ship design cases against the conventional assembly approach.

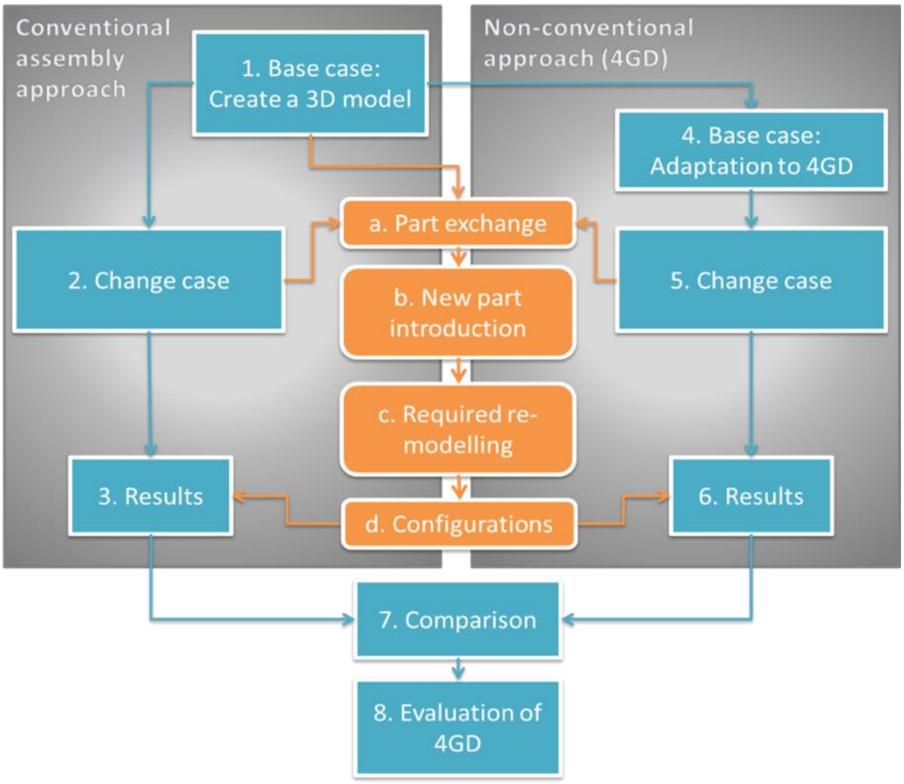


Fig.5: Methodology of 4GD evaluation to ship design analysis

The methodology is applied to a simplified PSV, Fig.6, and the 3D model of the PSV hull divided by modules is retrieved from the Ulstein/NTNU EMIS project and adapted to this case. Due to the modular division of a vessel, the ship design application is not used for modelling of the decks and compartments. Moreover, this case study focuses on the concept of modelling and reuse mainly as well as how the systems interact between the modules and different systems across the ship.

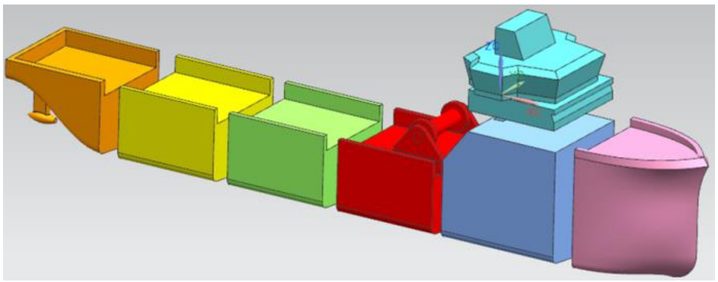


Fig.6: Simplified PSV modularization (exploded view)

3.2 Product taxonomy

To ease the 3D modelling process a vessel containing millions of parts needs to be grouped into systems and subsystems. The division of a product into sections is called taxonomy and can be done by following different rules and approaches adapted or most suitable for certain maritime company. There are several taxonomies currently used in industry such as SFI Group System, spatial, functional and physical, *NN (2013)*, and modular divisions, *Chaves et al. (2015)*. We shortly discuss three taxonomies which are used for this case study: functional, physical and modular.

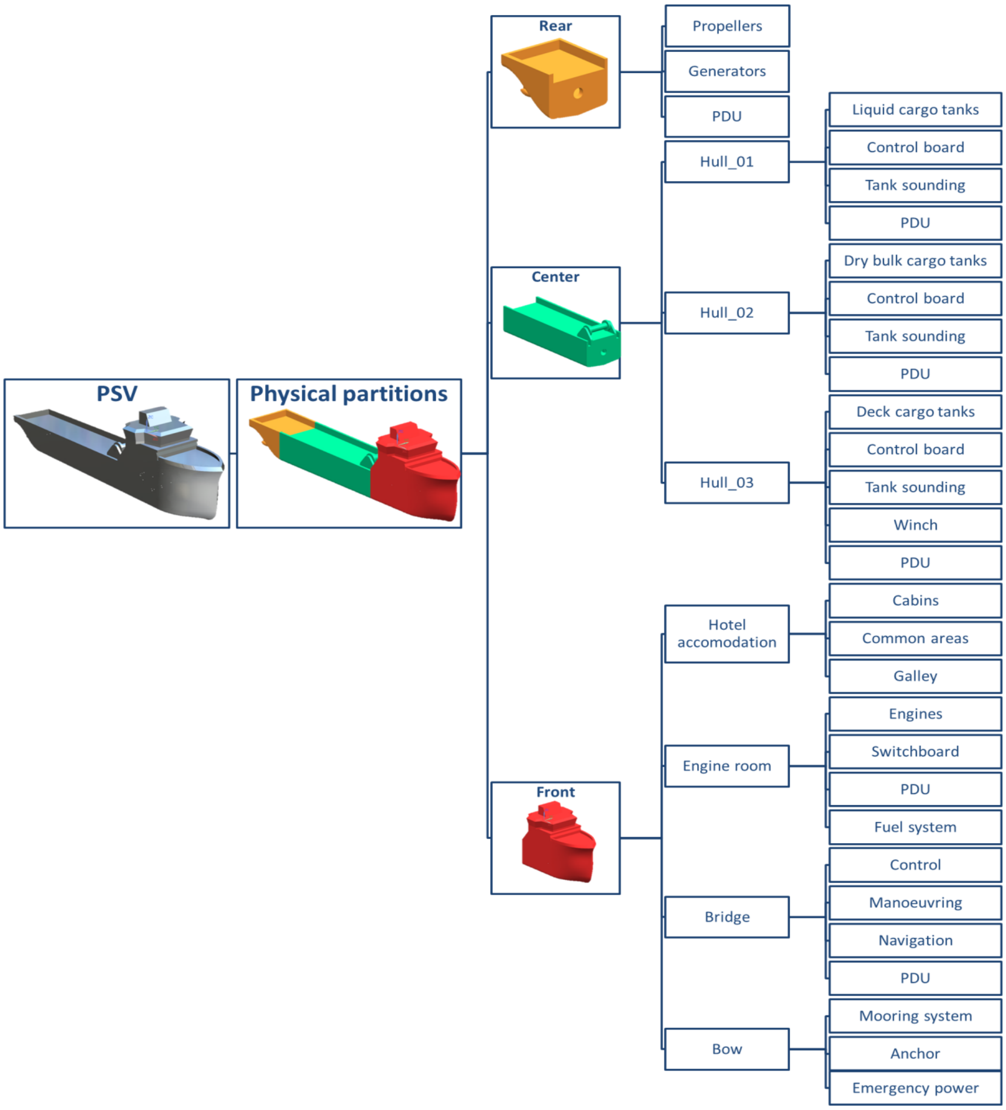


Fig.7: Physical PSV structure

The functional organisational breakdown divides a vessel based on function of the systems. Each of the system includes sub-systems which are composed of assemblies. For the functional division of the PSV only several systems were used, as the PSV 3D model is simplified. As the functional partitions the auxiliary system, mission oriented system, accommodation, propulsion and hull are defined for functional breakdown.

The physical organisational breakdown defines a vessel based on the location of the systems within a vessel. In some case, the systems might be extended over couple of the dividing objects which requires dividing that system to add it to a certain object, for instance the propulsion from the stern through machinery until control on the bridge. In this case study, the PSV was divided as presented in Figure 7, where the main structure consists of 'Rear', 'Centre' and 'Front' partitions of the vessel.

As proposed by (Chaves, et al., 2015) the modular organisational breakdown in ship design is one of the ways to divide a vessel. The modular taxonomy is defined based on specific maritime company's business processes and might be unique in each case. Using this divisions, the modules are created by decomposing a vessel into certain modules and sub-modules (Figure 8). The modular division of a product is widely used in ship design due to flexible breakdown of a vessel which is adjusted by setting up the boundary criteria depending on the final use.

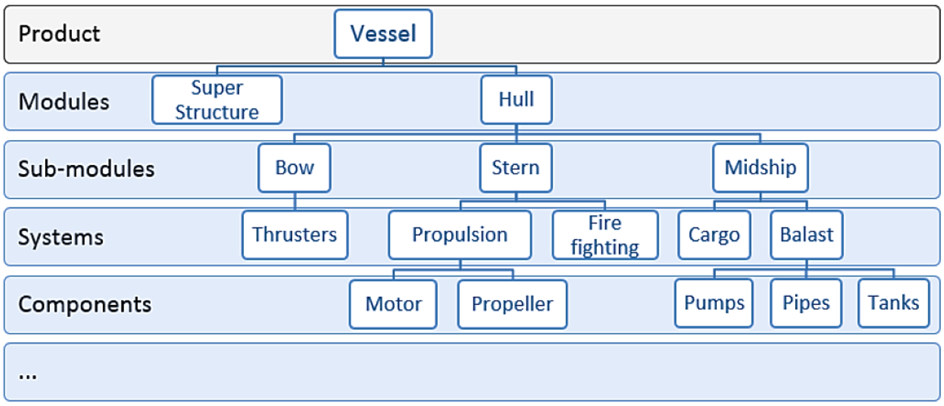


Fig.8: Modular taxonomy, *Chaves et al. (2015)*

The conventional assembly approach requires well defined taxonomy beforehand to ensure a hierarchical structure to follow. It is significant because the division then is used through the entire lifecycle and it should meet the needs of each designer and stakeholder. Therefore, for the case study of the conventional assembly approach, the organisational breakdown is established to be the modular as the vessel is already modelled in such manner. Whereas the 4GD approach doesn't require such a decision prior the modelling process and allows using several taxonomies, which can be added up during the process. Therefore, the modular division is firstly used for importing the model in 4GD environment and later is supplemented by the physical and functional divisions.

3.3 Conventional assembly approach applied to ship design

To investigate the 4GD approach, the methodology defined by Fig.4 is applied first to the conventional assembly approach to have data for comparison and after on the non-conventional (4GD) approach. This method provides the analysis on the same tasks and problems from two points of view.

The first step is the base case where the 3D model of a vessel is created. As mentioned before a simplified PSV is used which is already divided by modules. Therefore, to have several interactions between components and systems, a propulsions system was modelled as well as some surrounding components in the vessel, Fig.9. All modules and components in NX are constrained one to another starting from the bow module. Some components in the vessel assembly were only created to generate the complexity and higher order hierarchical structure.

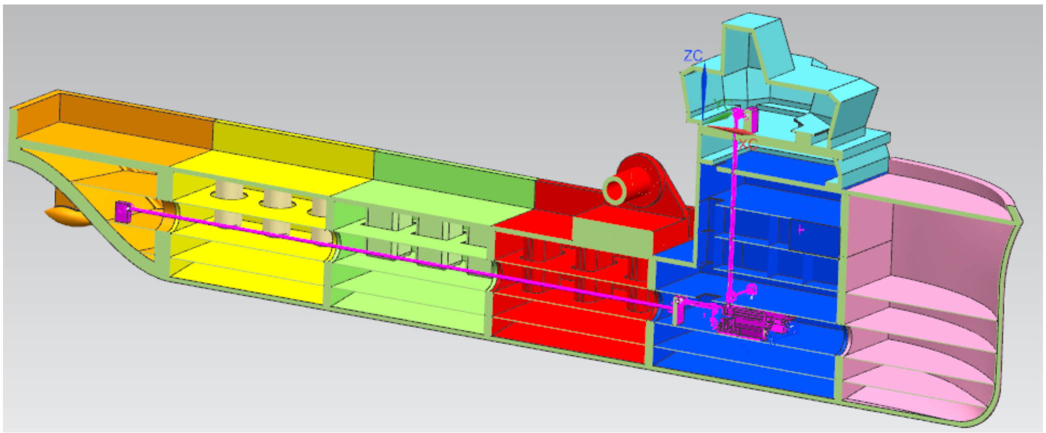


Fig.9: Cross section of the PSV (in Siemens NX) showing a simplified propulsion system across the whole vessel (in pink)

The four change cases were performed according to the methodology. First, the stern was exchanged by different design using the *Replace component* function, which aids keeping the constraints of very similar geometry. Secondly, a new engine is introduced in the assembly in the context of propulsion module. Due to the new components in the assembly some components had to be relocate and constraints changed to fit with the new pattern of the engines. So, the third change case was performed consequently where the routing was adjusted, switchboard was exchanged and the interconnection between the modules was restored.

The last step of the change case includes the assumption of two different product configurations within a vessel. Different possibilities how to create such configurations were explored but due to software capabilities and no right solution could be established directly, which is why several different approaches were assumed: using revisions, arrangements or creating copy of the assembly and then modifying it. The revision method means that a revision *B* is created to a PSV where different configurations are executed. In the new revision, which is dedicated for the two-cargo hull PSV, the unnecessary components were deleted and required components were relocated to new positions. However, the revision rule doesn't support unique repositioning and re-modelling of the parts and applies changes to both revisions. Therefore, for the necessary components the revision *B* was assigned separately that allowed to perform changes, Fig.10.

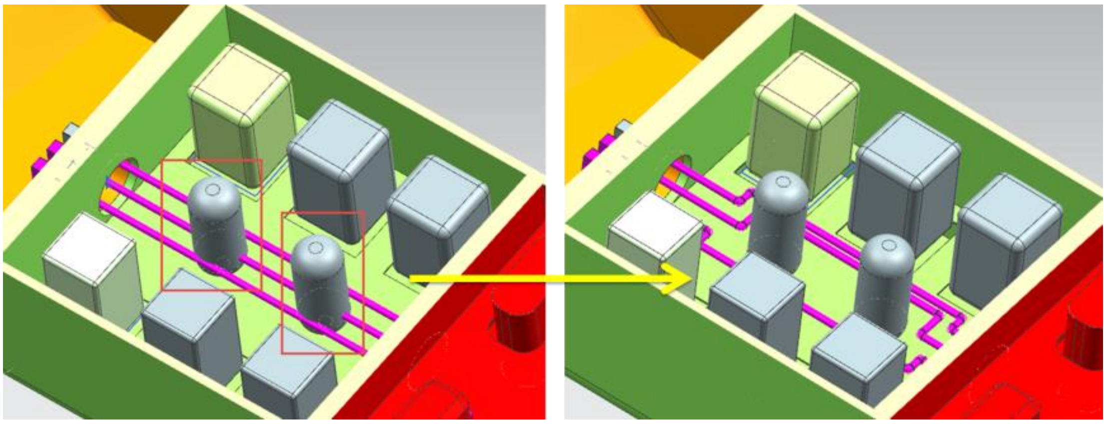


Fig.10: Modification of the links for revision B

Another way to create two configurations is by setting the arrangements of the assembly. It allows presenting the sub-assemblies with alternative position or content within the same assembly. However, when applied to this specific case it proved to be inefficient as the elimination of a sub-assembly only in one arrangement is not possible. The arrangements are constituents of one single assembly file where only the position of different components can be modified. Therefore, this was approach was denied during the application process.

Finally, using Copy & Paste, the current model in NX can be duplicated and renamed. It solves the problem, but makes any change in the copy of the assembly independent from the original and requires performing the changes separately. Moreover, it adds duplicates in PDM system and complicates the management.

3.4 4GD Applied to Ship Design

Following, the adaptation of a PSV 3D model to 4GD environment is performed. The overall assembly was introduced as a collaborative design, the division objects as partitions and components as the design elements in 4GD. The 3D models were imported directly to the created design elements which automatically converted the part into reusable design element. During this process, there were some issues related to the import of assemblies and introducing them as design elements. The problems aroused due to misconfiguration of the software which requires customisation. Consequently, the design elements were assigned to the appropriate partitions to have multiple organisational breakdown of the PSV. These operations are performed in PLM software and following steps are done in 3D modelling environment. As first task, a workset is created, which consist of the whole PSV 3D model. To have all the components of the assembly in one working environment, a subset is created to which the entire partitions in the collaborative design are included. As the partitions to add were defined, the 3D modelling software executed the search and displayed all the components within the PSV. The elements were located randomly as they were created in PLM software. Therefore, the positioning of each DE was performed by moving parts and located them in accordance to the surrounding parts. There are no assembly constraints in 4GD which is why there is no necessity to restrict the parts by three axes.

Later, as all of the 4GD design objects were established, defined and correctly positioned, the 3D model of a PSV was completed and could be observed from three points of view. Fig.11 displays the PSV 3D model in 4GD environment divided by partitions and viewed in multiple organizational breakdowns /taxonomies (a. Modular; b. Physical; c. Functional).

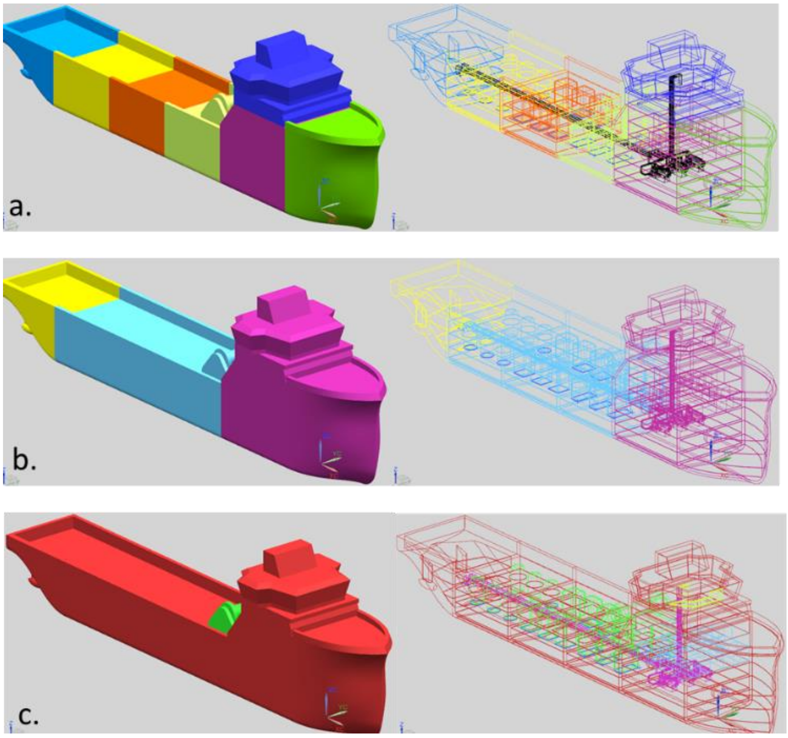


Fig.11: Different organisational breakdowns of PSV: a. Modular; b. Physical; c. Functional.

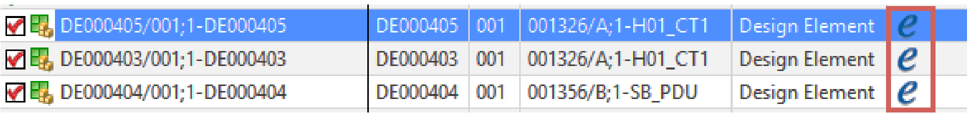
Subsequently, the change cases of this research were performed by completing the assumptions defined in the methodology. This paper described only one modification explicitly, configuration (Figure 5 - d), while the rest are shortly introduced, Fig.5a-c.

The stern was exchanged using the ‘Replace source part’ function which replaces the source part of reusable DE, Fig.5a. 4GD locates the exchanged part at the same location as previous part which means that the coordinate axes need to coincide. It is a useful feature if the designs are only slightly different which makes the part in required position without a need of relocation. In this case study, the stern modules contained the same dimensions and the coordinate axes were located at the same point.

Secondly, additional engine and generator were introduced in the 3D model, Fig.5b. Specific subset for this design task context was defined to avoid unnecessary load of additional parts. The procedure was performed in this subset and the parts were created as new design element which uses the source part from the previous models. Both new parts were manually assigned to certain partitions which add the parts to the overall PSV model. The position of the new parts was defined by simply moving the parts into required position.

Thirdly, the remodelling was performed which means that all the influenced parts due to changes above are corrected, Fig.5c. Some routing parts, switchboard and distributing units were adapted to fit with the four engines in the engine room. The remodelling was smoothly performed by design-in-context and the changes were updated in the overall vessel.

Finally, two different configurations for the PSV were created, Fig.5. It was done by using the effectivity solution which is a specific feature in 4GD. It allows creating different configurations or layout of a product within the same single file. For this case study, a two-cargo hull and three-cargo hull vessels were required and therefore, the effectivity was employed. First, the effectivity was set in the subset which means that any further actions are assigned as certain effectivity and are valid only for this model. If the primary vessel model needs to be viewed, the effectivity needs to be redefined which issues the primary vessel. This can be done by editing the subset and switching from one effectivity to another. The assumption in this change case step is that the two-cargo hull PSV should contain two additional tanks and modified link between switchboard and the generators. Therefore, these components were added to the subset and located using ‘Move’ function ‘By constraints’. Consequently, these elements were directly assigned to the unit effectivity as they were added after the effectivity was assigned. As it is seen in Fig.12, the components with effectivity are marked by the *e* sign.



☑ DE000405/001;1-DE000405	DE000405	001	001326/A;1-H01_CT1	Design Element	*e*
☑ DE000403/001;1-DE000403	DE000403	001	001326/A;1-H01_CT1	Design Element	*e*
☑ DE000404/001;1-DE000404	DE000404	001	001356/B;1-SB_PDU	Design Element	*e*

Fig.12: Effectivity indications

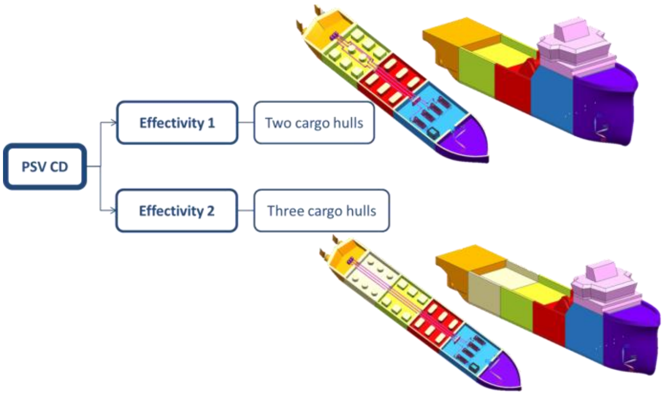


Fig.13: Effectivity solution for different configurations

The parts which are in both effectivities are associative, which means that movement of a part influences movement in both effectivities. Therefore, for this case study the effectivity was assigned to stern and generators in one configuration and introduced as new DEs in the second configuration allowing the movement of stern in the two-cargo hull vessel.

Using the effectivity concept, two different configurations of PSV were generated in one single CD and are subject of choice and necessity for certain customer. Fig13 illustrates how the two configurations are distinguished by effectivity specification.

4. Results from the 4GD and Traditional CAD Comparison

This research was performed as a comparative analysis of the conventional assembly and non-conventional approaches. The comparison results based on the four criteria are displayed in Table I and described further in this chapter. The first criterion is the exchange which in both cases, was performed using particular Siemens NX/Teamcenter functions to exchange one components by another. The difference between the two approaches here is that the conventional assembly approach positions and constraints the new part to a specific location and the 4GD places a new part depending on the coordinate axes of the previous component but does not constrain it. In this manner, 4GD allows easy movement and allocation of the new part. Whereas the traditional assembly approach restricts the motion due to remaining constraints and requires readjustment to properly allocate the new component. Moreover, the function ‘Replace component’ in the conventional assembly approach is mostly used to replace the components by revisions and is not able to exchange the parent part in an assembly as in this case the children parts are lost. This example shows that that by the automatic positioning, no restrictive constraints or hierarchical assembly restrictions 4GD improves the exchange of components.

Table I: Comparison of the conventional assembly and non-conventional approaches

	Conventional assembly approach	**Non-conventional approach (4GD)**
Exchange	▪ Function ‘Replace component’ ▪ Positioning according to the existent constraints ▪ Constraints errors, readjustments ▪ Parent parts can’t be exchanged ▪ Reuse of large-scale data is complex	▪ Function ‘Replace source part’ ▪ Positioning based on the axis of origin ▪ Supported in large scale products ▪ Any DE is exchangeable and reusable
Remodelling	▪ Design-in-context of certain sub-assembly ▪ Loads parent parts of the components	▪ Design-in-context of overall product ▪ Loads only relevant data ▪ Effectivity solution
Restrictions of constraints	▪ Particularly high ▪ Rigid model ▪ Reused components are overloaded	▪ No constraints (certain constraints if needed) ▪ Flexible model ▪ Reused DE are positioned but not constrained
Importance of the assembly structure	▪ Hierarchical assembly structure ▪ Predefined structure ▪ Single organizational breakdown/taxonomy	▪ Flat assembly ▪ Organisation defined by partitions ▪ Multiple organizational breakdowns/taxonomies

Another parameter in concern is the 3D remodelling, which was performed using the two approaches, and the results demonstrate that the design-in-context was straightforward in both cases. The conventional assembly approach requires working with the specific child assembly to which the component belongs whereas in the 4GD the design-in-context can be carried out directly in the context of overall assembly or certain subset. Plus, the conventional assembly approach loads the parent and children components into NX session if the remodelling is done in some part of the sub-assembly. Here the 4GD exposes a great advantage over the conventional assembly approach because it allows using only the necessary set of data in the NX session which does not overloaded the working environment. It is vital feature for large scale products where several designers are working on the same assembly as 4GD environment contains only the significant components and requires only a few parts being checked out.

One more way to reduce or avoid remodelling is the effectivity solution which might be employed instead of remodelling in 4GD by creating an equivalent model in the same file which contains the same information and is different where needed.

The restriction of constraints is another important criterion in consideration which proved to be unusually high in the conventional assembly approach. The constraints are defining the positioning of each component in the assembly which makes any movement, modification or exchange of part complicated and demands readjustments. It makes the assembly very rigid and any change influences surrounding parts and constraints but at the same time, the constraints structure the assemblies and move components together with the parent parts. Plus, the constraints might overload the assembly when some components or assemblies are being reused. The sub-assembly comes with the existent constraints and might mix up with the assembly constraints of the primary model. Whereas in 4GD, the reused DEs are positioned at certain location and remain positioned until moved. As the 4GD doesn't use constraints, it makes the assembly a flexible structure but it also maintains the position of components. This research showed that the 4GD exposes an advantage over the conventional assembly approach due to the absence of constraints system but still sustaining the required position.

Finally, the importance of the assembly structure in the two approaches is compared. As stated previously, the hierarchical structure of the assembly is of high importance in the conventional assembly approach and thus, this research verified this importance and influence the entire design process. The assembly structure was pre-defined to have a product structure before modelling. Several components were not considered and had to be inserted during the modelling process which complicated the interactions between the assemblies, interrupted some constraints and order of the product. Therefore, in large scale products the structure of assemblies and sub-assemblies needs to be clear and meet the requirements of different design teams. In contrary, 4GD supports a flat assembly structure where the parts are not necessary dependent one to each other but the dependency remains an option. The non-conventional approach allows to decide the product structure at the beginning or during the design process due to multiple organisational breakdowns and search capabilities to load only relevant data for design teams. Therefore, it can be concluded that the high importance of the assembly structure in the traditional structuring approach makes the product more rigid and requires well defined process as the 4GD provides flexibility and preparation process mistakes can be solved.

The fourth criteria described above were established to reflect the exchange and 3D reuse capabilities in 4GD environment. It exposed the facilitation of exchange due to the multiple organisational breakdowns and flat assembly structure where each DE is independent. The 4GD provides a more flexible assembly structure of a product which means that there are no constraints and very few restrictions to position components in the assembly. Even the top-level elements that can't be exchanged in conventional assembly approach are exchangeable in the non-conventional approach and do not influence the children parts.

As for the reuse, the comparison results showed that due to the effectivity solution in 4GD the establishment of a series of vessels with the same hull or the same propulsion system within the same collaborative design object is possible. The same configuration is reused across the vessel family which makes it easier to gather the models and documentation from one large scale product to another. Plus, the reuse is facilitated due to the reusable DEs, which allows the previous designs be directly reused in a new vessel design.

The comparison of the two approaches showed that the modelling organisation and component management sequence in 4GD must be perceived distinct from the traditional assembly approach due to absence of constraints and flat structure of the assembly. The 3D designer is required to change the mindset from assemblies and components to collaborative design and design elements which are not the same. Moreover, the data in 4GD is managed differently from the conventional approach by sorting and viewing the DEs by partition schemes. Therefore, as the 4GD requires changing the working approach with product data from the maritime companies the investment risk arises due to demand of competent resources for 4GD configuration, data population, training and deployment. This risk is currently observed with high criticism, especially due to the novelty of the method, with a lack of information and examples of successful 4GD integration in maritime companies. That might be the factors pulling back the maritime companies from implementing 4GD approach in their business processes.

5. Concluding Remarks and Further Work

The implementation and study of the 4GD framework in ship design in comparison to the conventional structuring approach was the main goal of this research. To verify the applicability of the non-conventional approach for improving the exchange and facilitating the reuse, design and change cases were established as the framework for this analysis.

The case study of a simplified PSV 3D model revealed that working with the new 4GD approach requires different perception of the 3D models, product assemblies and designing processes. The concept of the components and features in 4GD is different from the conventional assembly approach. The positioning of the components in 4GD environment is performed by moving the parts to required place and changes are adopted without interruptions due to the absence of assembly constraints as well as the flat assembly structure. These conditions are also significant for the exchange of components which becomes a non-restrictive and fluent process in comparison to the conventional assembly approach. Moreover, for different vessel configurations across the vessel family the effectivity proved to be an efficient solution to avoid remodelling and instead, re-use the 3D models of previous products. In ship design this approach, with a more flexible way of modelling, promises to bring innovative, cost effective, and time saving when handling large scale products such as ship's systems, but requires an engineer mind-set shifting on the understanding of the actual value-chain processes and on the integration of multiple taxonomies, which can be cumbersome and face negative feedback from users working with a single traditional hierarchical viewpoint of the vessel.

This research demonstrated that 4GD is a highly-advanced approach to model and organise the design data requiring high competence people in programming, product management and modelling of the 3D components. Moreover, the non-conventional approach demands well defined needs and requirements to the software from the company to obtain the efficient employment and expected benefit out of the 4GD. Furthermore, it is important to ensure well-defined and customized configuration of PLM and 3D modelling software. Therefore, it can be concluded that the verification of the 4GD suitability for continuous improvement in maritime industry should be assessed by application to a pilot project of designing a full-scale vessel. However, even if applied to a simplified PSV 4GD exposed advantages over the conventional assembly approach but significant improvements of the exchange and 3D re-use across the vessel were not observed. For this reason, the research on 4GD has high potential for further investigation of a more complex vessel.

First, the case study of 4GD was performed from the 3D designer point of view, mainly working with Siemens NX. Therefore, as a further step the investigation of the 4GD capabilities and differences in the Teamcenter when compared to the traditional structuring approach should be carried out. The design process involves people from different disciplines working with different tasks not only in Siemens NX but also other legacy software (e.g. AutoCAD, Catia). The data management, structuring, views on the Bill of Materials, the search of data and data population are maintained in 4GD Designer environment in Teamcenter which is unlike the traditional data management in Teamcenter.

Secondly, it is relevant to analyse 4GD in context of large amount of data to get more reliable results. So far, the 4GD was applied for a simplified PSV design with several sub-assemblies and components only. Therefore, to verify the theoretical advantages of the flat assembly structure, effectivity, absence of assembly constraints and other distinctive features of 4GD the approach should be used to model the general arrangement of the concept design vessel.

Finally, to go on with this specific case study of changes in the traditional assembly approach and 4GD, advanced Teamcenter functionalities should be employed. Teamcenter PLM tool *Change Management* to work with changes in the vessel should be used that might influence the management of exchanged components, design tasks and workflows. The change management tool used together with 4GD could expose even greater advantages and development possibilities in comparison to the conventional assembly approach.

Acknowledgments

This research uses relevant information from Siemens NX and Teamcenter software which is owned by Siemens AG (Germany) and distributed in Norway by Digitread AS. Part of this work is based on the MSc thesis Implementation of 4GD framework in Ship Design for improving exchange and 3D reuse, NTNU 2016, written by the first author and under supervision of the co-authors.

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Sea Currents and Waves for Optimal Route Planning with VISIR

Gianandrea Mannarini, Giovanni Coppini, Rita Lecci, Giuseppe Turrisi,
Fondazione CMCC, Lecce/Italy, gianandrea.mannarini@cmcc.it

Abstract

The open-source model for marine-weather ship routing VISIR (visir-model.net) was designed in a modular way for easily modifying and adding functionalities. In particular, the impact of ocean currents is the subject of the latest development. The model has been extended for using forecasts of surface sea currents from the European service CMEMS (marine.copernicus.eu). However, fields from other providers can be easily used. Currents are shown to have an impact in the percent range on route duration - even in presence of waves - and can also affect route topology in specific cases, demonstrating that even short-sea shipping could benefit from accounting for forecast ocean state.

1. Introduction

Meteo-oceanographic forecasts may be exploited for optimising navigation between given end-points with respect to some strategic objective such as route duration or fuel oil consumption. The International Maritime Organization recommends to avoid "rough seas and head currents" among the ten measures within the Ship Energy Efficiency Management Plan (SEEMP), *Bazari and Longva (2011)*. The SEEMP is one of the main instruments for the mitigation of the contribution of maritime transportation to climate change, *Mannarini (2015a)*.

A reconstruction of the Kuroshio current by means of drifter data is employed by *Chang et al. (2013)* for demonstrating that it can be exploited for time-savings when navigating between Taipei and Tokyo (about 1100 *M* distance (1 M = 1850 m)). In that work, suggested diversions from the great circle route are seemingly ad hoc chosen, without any automatic optimisation procedure. Nevertheless, the authors find that the proposed route, despite extra mileage, leads to savings in the 2-6% range for super-slow-steaming (12 kn) vessels. The largest savings are obtained for the south-west-bound route (against the Kuroshio).

Lo and McCord (1995) report significant fuel savings in the Gulf Stream region (up to 6-9%) for routes with or against the main current direction. Per construction, routes of constant duration and constant speed through water (STW) were considered. The horizontal spacing of the current fields employed varied from 5 to 0.1 degree, with best performances in fuel savings at the highest spatial resolution. The same authors also developed an algorithm that tackles the problem of the predictability of ocean currents, especially where they are stronger and thus more dynamic, *Lo and McCord (1998)*. Their approach is based on a stochastic variant of the dynamic programming technique by *Chen (1978)* or *Zoppoli (1972)*. As such, there are inherent simplifications of the route geometry, e.g. it cannot sail trough the same longitude on more than a single waypoint (WP) and it is unclear how to deal with coastline and other topological restrictions.

An exact method based on the level set equation has been developed by *Lolla et al. (2014)* and it can deal with generic time-dependent flows and vehicle speeds through the flow. It is based on two-step differential equations governing the propagation of the reachability front (a Hamilton-Jacobi level-set equation) and the time-optimal trajectory (a particle backnracking ordinary differential equation). The paper by *Lolla et al. (2014)* contains a careful analysis of the mathematical scheme and the computational cost. The level set approach was extended to deal with energy minimisation by *Subramani et al. (2016)* showing the potential of intentional speed reduction in a dynamic flow. This method appears to be quite promising, though is not yet employed in an operational environment.

The above recognition of literature shows that the question of the impact of sea/ocean currents on navigation, despite its classical appearance, is still open. In fact, the available results are hardly comparable to each other, since they employ different methods in different regions of the global ocean. Also, none of the cited works considers the impact of ocean currents and waves altogether. Finally, the published methods are just applied to case studies and are not operational.

The latest development of the VISIR model *Mannarini et al. (2016a,b,c)* would like to contribute to these issues. The VISIR model is at the heart of an operational marine-weather routing system for the Mediterranean Sea, www.visir-nav.com. It has been applied also to sailboat routing in *Mannarini et al. (2015b).* Its algorithm for computing the shortest routes has been validated versus analytical results in case of static wave fields. VISIR is coded in MATLAB and its first version was released with a GPL licence, www.visir-model.net.

2. Model structure

The VISIR model was documented in highest detail in *Mannarini et al. (2016b)*. The inclusion of ocean currents required a few developments that are summarized in this section.

2.1. Speed over ground

Assuming that the vessel speed over ground (SOG) is given by the linear superposition of surface ocean current and vessel speed through water (STW, see Sect.2.2), the rudder can be employed to instantaneously adjust vessel heading for compensating the cross current.

A formal definition of the above statement allows inferring following general features:

a) The cross flow always reduces the SOG, as part of vessel momentum has to be spent for compensating the drift. The flow component along the route instead may either increase or decrease the SOG;
b) The ratio of the cross flow to the magnitude of the STW determines the rudder angle.

The SOG resulting from a) is then used by the VISIR routine for path optimization, as explained in Sect.2.3.

2.2. Speed through water

The STW is defined as the SOG in the absence of ocean currents. Following *Mannarini et al. (2016b),* the STW is determined by the sea state only. In particular, the STW results from a balance of thrust and resistance at the propeller. In the resistance, a term related to calm water is distinguished from a “wave added resistance”. The calm water term depends on a dimensionless drag coefficient C_T that, within VISIR, has a power-law dependence on STW: $C_T \sim (STW)^q$. For the wave added resistance, its directional and spectral dependence is neglected, and just the peak value of the radiation part is considered. The latter is obtained by *Alexandersson (2009)* as a function of vessel’s principal particulars, starting from a statistical reanalysis of simulations based on *Gerritsma and Beukelman (1972)*’s method.

Finally, VISIR employs sea-state information also for performing a few checks of vessel intact stability, namely related to: parametric roll, pure loss of stability, and surfriding/broaching-to. The algorithm then constructs the optimal route by ensuring that vessel intact stability is always satisfied.

2.3. Discretisation and graph-search method

The SOG obtained using both ocean currents (Sect.2.1) and the STW depending on sea state (Sect.2.2) are the key ingredients for the computation of the optimal routes. These routes result from a shortest path algorithm on a graph, whose edge weights are given by the rate between the distance between couples of graph nodes and the SOG. Since the SOG depends on time-dependent environmental fields (Sect.2.4), the edge weights too are functions of time. Thus, a classical shortest path algorithm (Dijkstra's one, cf. *Bertsekas (1998)*) is adapted to time-dependent edge weights in *Mannarini et al. (2016b).*

Furthermore, several variants of the edge weights are computed, each corresponding to a different value of the vessel's engine throttle. The algorithm then selects the highest throttle leading to a vessel speed that is still compliant with the stability constraints (Sect.2.2). This way, an option of voluntary speed reduction is implemented into the algorithm.

Table I: Connectivity parameters for graphs with squared meshes

Order of neighbours	Min resolution	Max resolution
2	26.6°	18.4°
4	14.0°	4.4°

In the VISIR version described in *Mannarini et al. (2016b)*, a graph mesh with a 1/60 degree spacing (i.e., about 1 M in the meridional direction) and an angular resolution of about 27° were considered. Angular resolution affects route smoothness and, thus, route accuracy and duration. This is especially true in presence of ocean currents, since they form eddies with a radius of curvature about one of order of magnitude smaller than the typical extension of rough seas areas, www.sea-conditions.com, Fig.3. For this reason, the angular resolution of VISIR was improved by considering edges between all nodes up to the fourth and not just the second order of neighbors of a squared mesh. As reported in Table I, this implies that the angular resolution is now between about 14 and 5°, depending on direction.

2.4. Forecasts fields

The developments of VISIR require hydrodynamic and sea-state forecast fields in input. They are both obtained from the CMEMS operational system, marine.copernicus.eu. However, fields from other providers can also be used, just adapting the VISIR functions for field reading.

2.4.1. Surface currents

Forecast fields of surface ocean currents are employed. They are produced by an operational implementation of the hydrodynamic forecasting model NEMO in the Mediterranean Sea, *Tonani et al. (2014,2015)*. The Cartesian components of the current field are horizontally discretized on a 1/16 degree (3.75 M in the meridional direction) mesh and the time-resolution of the output is hourly.

2.4.2. Waves

Forecast fields of significant wave height, wave direction, and mean wave period are employed. They are produced by an operational implementation of the Wave Watch III (WW3) model in the Mediterranean Sea, delivered by INGV (Istituto Nazionale di Geofisica e Vulcanologia), see *Clementi et al. (2017)*. The model is horizontally discretized on a 1/16 (3.75 M in the meridional direction) mesh and hourly output fields are employed.

3. Results

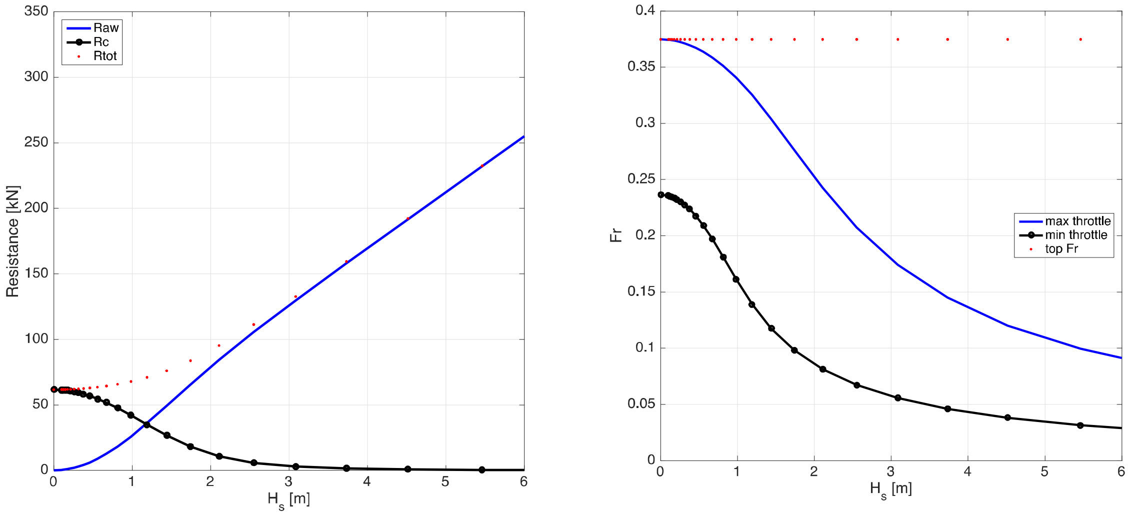
In order to demonstrate the impact of ocean currents on optimal routes, we perform a case study in a marine region at the boundary between the Atlantic Ocean and the Mediterranean Sea. This region comprises the eastern part of the Gulf of Cadiz and most of the Alboran Sea, whose eastern boundary is conventionally set at about 1° W, *Foucy and Lorvelec* (2012). The ventilation in the Alboran Sea is typically characterized by zonal winds: either westerly winds through Gibraltar or easterlies, *Ardhuin et al*. (2007), *Macías et al*. (2008). Both of them can easily lead to waves exceeding 3 m in significant height over distances of the order of 100 M.
The surface circulation in the Alboran Sea is normally characterized by two main anticyclonic eddies

formed by the surface Atlantic jet entering the Mediterranean Sea. These eddies have a radius of curvature of about 10 M and their magnitude can occasionally exceed 2 kn. The western eddy or WAG is typically centered at about 4º30’ W, while the eastern one or EAG is centered at about 3º W. The WAG is the more robust of the two eddies, with the EAG weakening and eventually disappearing during the winter months, *Peliz et al*. (2013).

The vessel considered for the case study is a trawler whose parameters are provided in Tab. II. The drag coefficient C_T of its hull is modeled with an exponent $q=2$ (Sect.2.2), corresponding to a calm water resistance scaling with the fourth power of STW. Both the calm water and the wave added resistances as functions of significant wave height are displayed in Fig.1a. They determine the sustained STW, that is displayed in Fig.1b at both the full and minimum throttle. The Froude Number is given by STW/$\sqrt{(g\ L)}$, with the vessel length at waterline L of Table II and the standard gravitational acceleration g=9.80665 m/s^2.

Table II: Vessel propulsion parameters, principal particulars, and drag coefficient exponent used in this work

P_{max}	Max engine brake power	650 hp
v_{max}	Top speed	10.7 kn
L	Length at waterline	22 m
B	Beam	6 m
T	Draught	2 m
T_R	Natural roll period	5.4 s
q	Exponent in drag coefficient C_T	2



a) b)

Fig.1: Dynamic properties of a vessel with parameters as in Tab.II. a) Calm water (Rc), wave-added resistance (Raw), and their sum (Rtot). b) Sustained Froude Number at maximum and minimum (=10% maximum) engine throttle. For both panels the independent variable is the significant wave height.

In the first two case studies considered in this work, F1 and F2, the vessel departs west of Gibraltar and reaches a location at the same latitude and about 200 M East, in the Alboran Sea. In the latter two cases, B1 and B2, departure and arrival location are swapped and the departure date is more than one month later.

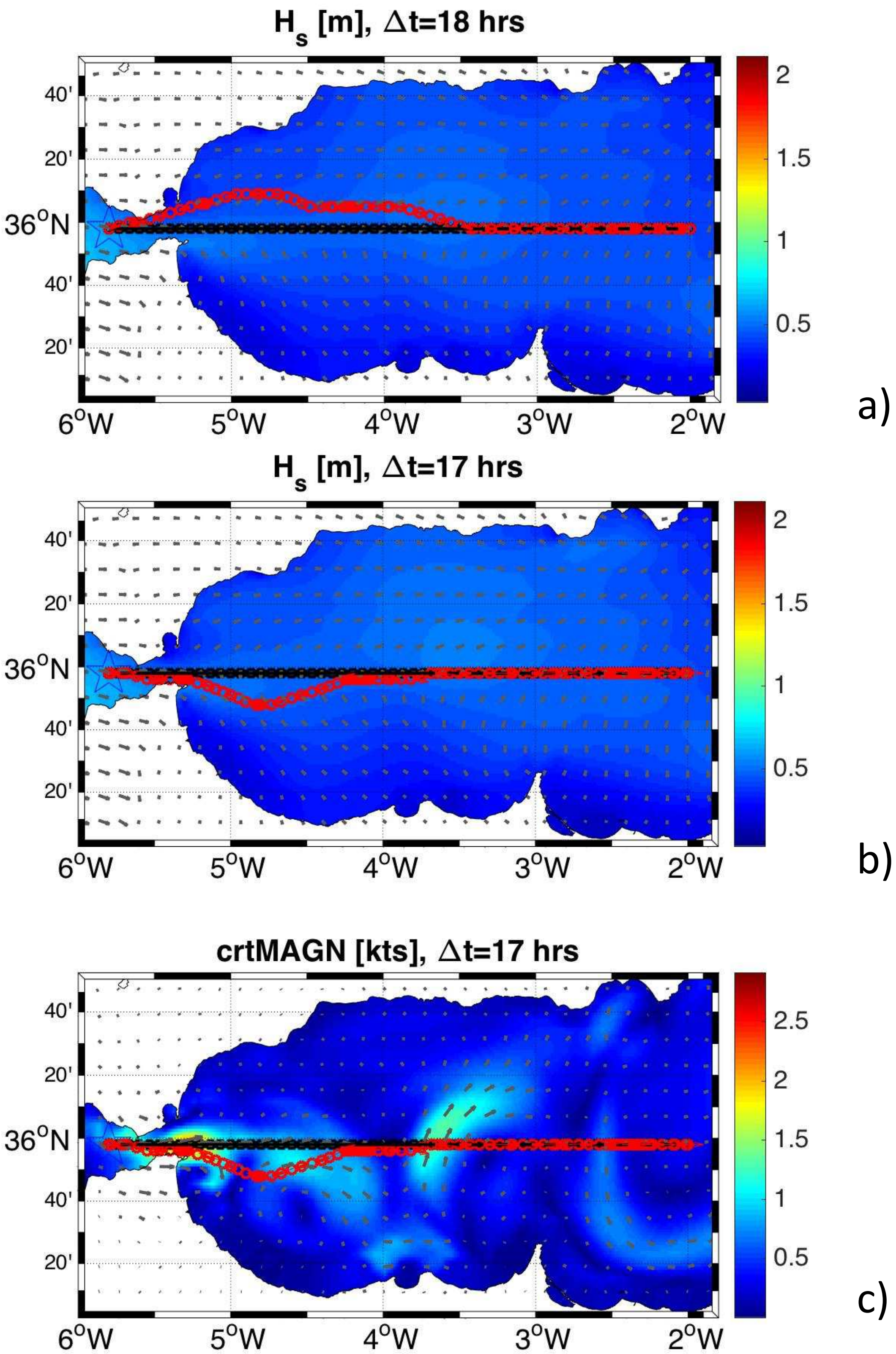


Fig.2: Case studies F1 (no current) and F2 (with current). Geodetic route in black and optimal route in red. The fields in background refer to the time of arrival of the optimal route. a) F1 and wave field; b) F2 and wave field; c) F2 and surface current field. Red arrows in b) and c) denote vessel heading. Route animations available at https://av.tib.eu/media/21737, https://av.tib.eu/media/21738, https://av.tib.eu/media/217439 for panel a), b), and c) respectively.

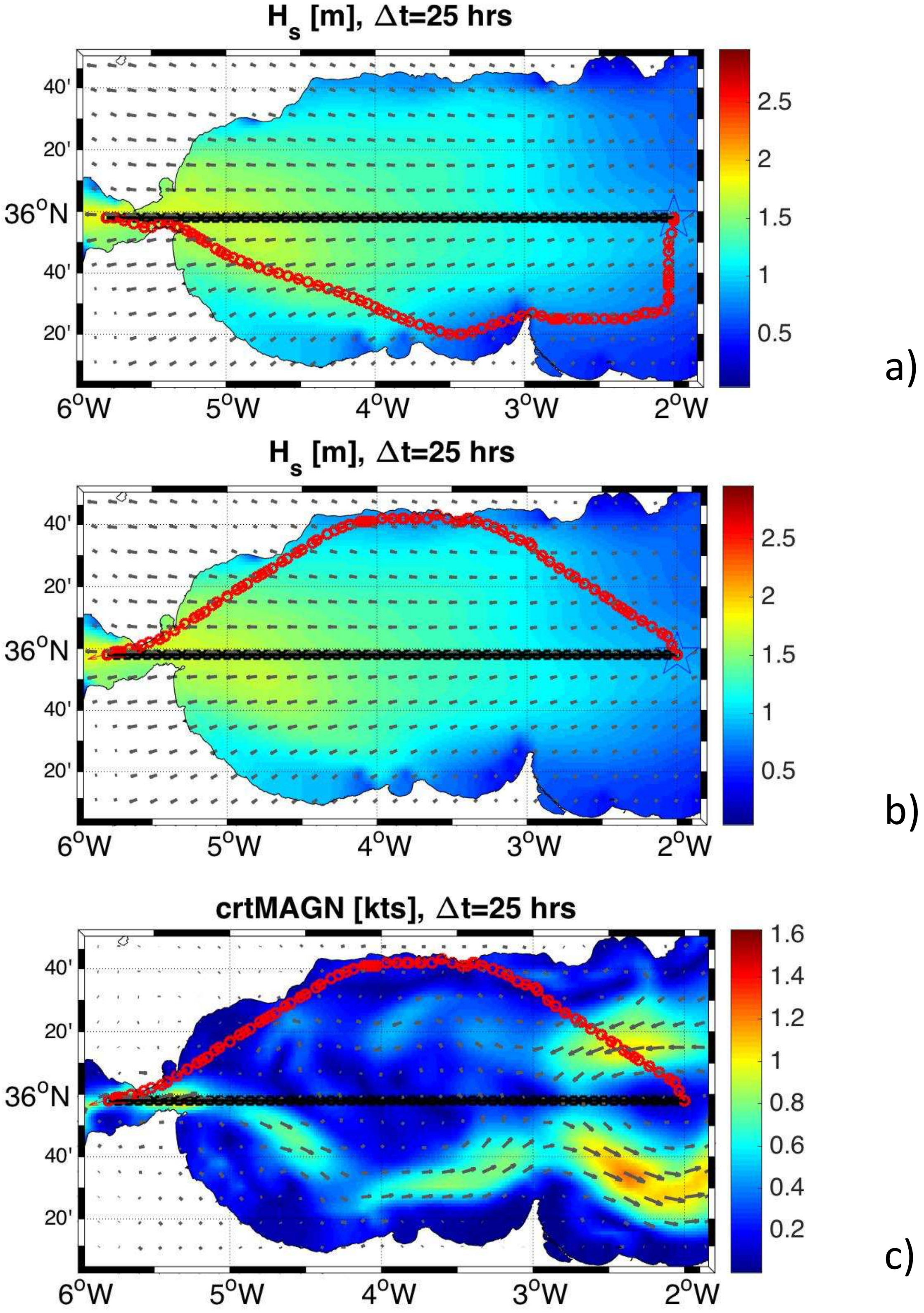


Fig.3: Case studies B1 (no current) and B2 (with current). Geodetic route in black and optimal route in red. The fields in background refer to the time of arrival of the optimal route. a) B1 and wave field; b) B2 and wave field; c) B2 and surface current field. The red arrows in b,c) denote vessel heading. Route animations available at https://av.tib.eu/media/21740, https://av.tib.eu/media/21741, https://av.tib.eu/media/21742 for panel a), b), and c) respectively.

For each case, both a geodetic and an optimal route are computed. The geodetic route (black markers in Fig.2 and Fig.3) is the shortest route keeping into account the coastline and the under keel clearance only. The optimal route (red markers in in Fig.2 and Fig.3) also considers the impact of the environmental fields (Sect.2.4) on STW and SOG and the dynamical constraints for vessel intact stability (Sect 2.2).

The presentation strategy of the case studies is the following: first, the geodetic and the optimal route in presence of waves only are displayed on top of the significant wave height field (panels a in Fig.2 and Fig.3); then both routes in presence of waves and currents are displayed on top of either the significant wave height field (panels b) or the surface current field (panels c). The main computational and dynamical parameters of the routes are summarized in Table III and IV respectively.

Table III: Computational parameters of case study routes. Departure date is on the day following the model analysis date. The total CPU time does not include the time for the graphical rendering of maps and time series. The number of nodes and edges in the graph is respectively 19’271 and 1’468’703 for each case study.

Case study#	Currents considered?	Model analysis date	Depart time	#time -steps	Opt. route CPU time [s]	Total CPU time [s]
F1	No	2016-08-28	21:00 UTC	19	6.9	54.5
F2	Yes			18	7.0	61.9
B1	No	2016-12-28	03:00 UTC	26	8.2	123.6
B2	Yes			26	8.2	138.5

Table IV: Dynamical features of case study routes. Δ is the relative change of metrics (length, duration) of the optimal route with respect to the case with surface currents neglected.

Case study #	Currents considered?	Length [m]			Duration [hh:mm:ss]	
		Geodetic	Optimal	Δ [%]	Optimal	Δ [%]
F1	No	184.9	188.2	0.0	18:00:06	0.0
F2	Yes		188.4	+0.1	17:28:01	-3.0
B1	No		223.0	0.0	25:28:33	0.0
B2	Yes		211.0	-5.4	25:24:30	-0.3

Table V: Route analysis dates and some marine weather features. Departure date is on the day following the model analysis date. For each date departure times at 00:00, 03:00, 06:00, 09:00, 12:00, 15:00, 18:00, 21:00 UTC are considered, which makes the 40 dots per panel of Fig.4

Analysis date	Case study	Prevailing wave direction	WAG?	EAG?
2016-08-28	F1, F2	eastbound	Yes	North-western meander only
2016-10-24	-	East- and then southwestbound	Yes	Yes
2016-12-28	B1, B2	westbound	southern meander only	cyclonic
2017-01-12	-	eastbound	Yes	No
2017-01-25	-	southwestbound	Yes	Yes

In the “wave-only” forward route, F1, the vessel sails with following waves. A northbound diversion (Fig.2a) instrumental in avoiding a condition of surfriding/broaching-to is computed (not shown). In the “wave&current” forward route F2 instead a southbound diversion is observed (Fig.2b,c). This is not surprising, as the algorithm exploits the favorable eastbound jet (more than 2 kn velocity) of the Atlantic current that feeds the WAG. The optimal route is 3% faster than the case not considering currents, Table IV. In this case, the currents allow not just recovering the involuntary speed loss due to the added resistance in waves, but even achieving a voyage-average speed of 10.8 kn, i.e. nearly 1% higher than the top speed of the vessel in calm waters, Table II.

In the "wave-only" backward route, B1, a westbound route leg follows a sudden southbound diversion (Fig.3a), and this is due to avoidance of both pure loss of stability (not shown) and rough sea (cf. route animation at https://av.tib.eu/media/21740). The algorithm also computes throttle reductions down to 55% brake power (not shown). In the "wave&current" backward route, B2, a large northbound diversion is found (Fig.3b,c). This allows avoiding a SOG penalty in sailing across and then against the southern meander of the WAG and allows exploiting the favorable northern meander of the EAG. The route then continues in the coastal waters of Andalusia where calm seas are encountered, realizing that "route refraction" that was already explained in *Mannarini et al.* (2016b) and aimed to benefitting from to the larger STW in calmer sea. During the crossing of the northern meander of the EAG, the rudder must be set more than 10° starboard of the Course Over Ground (COG, not shown). The B2 route is more than 5% shorter than the B1. However, the maximum SOG along B2 is about 1 kn less than along B1.

4. Conclusions

The ship routing model VISIR has been generalized for accounting for both sea state variables and surface currents. If the vessel course is prescribed, currents affect both the SOG and the rudder angle of the vessel, while the STW is determined by the sea state only (specifically, by the significant wave height).

Case studies in the Alboran Sea are discussed. VISIR attempts to maximize the sailing with currents and minimize navigation against or cross the currents. The duration of the resulting least-time routes can differ in percent range from the ones neglecting the currents and their topology can be dramatically different.

However, the ocean circulation and the sea state obtained from data-assimilative forecasting models show such a variability to rule out not only the use of climatological currents and waves, but also to limit the conclusions drawn from individual time-dependent case studies.

Thus, these numerical results from VISIR should be consolidated through a wider set of routes and vessel types in different regions of the global ocean. Nevertheless, these results already provide first evidence that, at least for not too fast fishing vessels, ocean currents may have a measurable impact on route duration and topology, even in presence of waves.

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Pre-Crash Advisor –
Decision Support System for Mitigating Collision Damage

Hasan Deeb, Mohamed Abdelaal, Axel Hahn, University of Oldenburg, Oldenburg/Germany,
hasan.deeb@uni-oldenburg.de, mohamed.abdelaal@uni-oldenburg.de, hahn@offis.de

Abstract

This paper describes a decision support system looking at possible options minimizing ship accident consequences for unavoidable collisions. The proposed algorithm takes in consideration the ship maneuvering and collision scenarios. Ship maneuvering is represented using the first-order Nomoto model with speed correction, and damage is constrained by the collision angle. The developed approach predicts all the possible collision scenarios and proposes best rudder angle to minimize damage.

1. Introduction

The International Maritime Organization (IMO) safety goal for passenger ships is: "ship is its best live boat". From this goal mitigation of ship accident consequences comes as essential need. Risk of ship collision is increasing with the increasing of the maritime transportation activities, where more than 90 percent of the international trading is done by ships. Ship collisions may cause human casualties, economical loss and environmental pollution. Taking in consideration these serious consequences, there is a need to investigate options in addition to risk assessment and collision avoidance, once collision is inevitable. Many researches have been done concerning risk assessment and collision avoidance using most advanced technologies. However, the number of ship collisions is still on a constant, *HELCOM (2013,2014).* In addition to the trend for unmanned ships which put the maritime traffic in challenge of absence of the crew experience.

Damage mitigation exists in maritime industry through regulations and standards developed by classification societies regarding extent and location of damage due to collision and grounding *Norsok (2010), DNVGL (2015) Norsok (2004).* The International Maritime Organization (IMO) also requires the use of goal-based standards (GBSs) to improve ship's hull resistance against collision damage. Many research have been done in order to predict collision damage and ensure ship survivability in case of ship accidents *Hogström (2012), Wang (2002).* Most of development on ship structure regarding the improvement of ship safety came as reactive actions after certain catastrophic accidents. The Risk-based design is a proactive research developed as an improved alternative to the traditional design process to integrates safety as additional design objective *Boulougouris and Papanikolaou (2013).* Another proposed solution to reduce collision damage is the concept of buffer bow developed to minimize the damage along the struck ship, which supposed to absorb most of collision impact *Yamada and Pedersen (2008).* In general these methods affect ship design, structural arrangement and cost, it is based on statistical and probabilistic analyses. However, there is no research concerning damage mitigation based on changing encountering situation using ship's maneuvering capabilities to reduce collision impact.

2. Collision effect mitigation

2.1 Requirements and background

Ships collisions despite all applied advanced technologies are in a constant – see, for example, *EMSA (2015), HELCOM (2013,2014)* – as ship collisions are a complex phenomenon consist of complicated ship motion and structural damage, *Tabri (2010).* In normal navigation the situation can be shifted from commonplace to critical in very short time. Accidents investigations show that poor judgment and less than adequate communications, as well as lack of situational awareness are major reasons which can lead to collisions. Mitigation of ship collision damage concerns a very critical phase of collision scenario, where any hasty action from the captain under stress and illusion of the relative motion between the two ships would make the consequences worst. In the same time it is very difficult to define whether or not collision is unavoidable due to complicated ship movement and precision of AIS data, *Tabri (2010)*.

In any ship that experiences collision, it is the navigator's job to assess the possibilities for an evasive maneuver in situ. When a ship performs an emergency maneuver, its consequences could be disastrous, if collision is inevitable and maneuver is not based on rational decision. This requires information on the maneuverability and damage constrain of both the foreign vessel and his own vessel. By damage constrain we understand the parameters which play role during impact scenario, the options available for maneuvers given the ship type, encountering angle and speed. A ship's maneuverability denotes its ability to accelerate, stop, and to turn at different speeds. Damage reduction as last option available for the navigating crew requires understanding what information the crew needs in order to perform wise evasive maneuver with minimum damage.

2.2 Related work

A collision is defined as a meeting of two ships in a distance named the ”collision diameter” *Montewka et al. (2011)*. This definition may lead to an understanding that in any ship-ship encounter at a distance greater than the ”collision diameter” these ships are able to avoid a collision, which in most cases is not true. *Montewka et al. (2010,2012)* proposed the so called Minimum Distance to Collision (MDTC) for estimation of ship-ship collision probability. According to the definition of MDTC, collision is unavoidable if the distance between two ships is less than a specific value. This distance is not fixed value but it is calculated dynamically, it depends on ship maneuverability and relative bearing. *Rymarz (2007)* proposed method to calculate the minimum distance, where if the give a way vessel did not take a clear maneuver according to the rules, the stand on vessel should take evasive maneuver in order to avoid collision. However none of the model listed above have collision mitigation as main objective and there is no specific rule or distance which gives definite collision criteria.

The concept of damage reduction is applied in automobile industry such as Nissan cars, *NN (2006)*. It uses a radar sensor to measure the distance from a vehicle being followed and gives an audible and visual warning. If the system judges that a collision remains unavoidable even after driver action, brakes are applied to slow the vehicle and help reduce injuries and damage.

Ship collisions are complex: many different factors are playing a role during collision scenario in addition to the complicated ship dynamics. Many research have been done to estimate ship-ship collision damage which led to the definition of so-called “collision event variables”, *Chen (2000)*. *Brown and Chen (2002)* have defined collision event variables as following: ship type, ship design, bow geometry and stiffness, ship mass, ship draught and trim, ship speed and ship dimensions. Depending on the objective of the study, the effect of the collision event variables on the structural and environmental aspects have been investigated *Goerlandt and Montewka (2014)*.

Zhang studied the effect of collision angle and location on collision damage between two ships of the same type and have the same collision speed, Fig.1. According to Zhang study, the collision impact energy is minimum when two ships are moving in the same direction with minimum collision angle and have minimum relative speed.

Ståhlberg et al. (2012) studied how input models for dynamic parameters affect the results of collision energy calculations and thus probability of an oil spill. The results of this research indicates that especially the parameters which navigators have a possibility to affect in evasive maneuvering, i.e. vessel speed and collision angle, play a determining role in the evaluation of the consequences.

Very little research has been dedicated to modeling the impact scenarios conditional to encounter scenarios. Most of the researches concerning modeling of impact scenarios take a statistical approach based on historical accident data *Ståhlberg et al. (2013)*. Theses research do not describe the link to impact scenario, they consider impact scenario equal to encounter scenario based on the concept of blind navigator. Damage mitigation as a novel concept in the maritime domain is an attempt to discover the possibilities to change encountering scenario and their effect on impact scenario. Therefore, it uses a maneuvering model to predict the possibility to perform an emergency maneuver in order to modify the encountering scenario to the most convenient impact scenario with minimum damage. However, some of collision event variables which control damage estimation are constant during collision scenario, such as ship mass, bow geometry, trim and draught.

3. Proposed Pre-Crash Advisor (PCA) Decision Support System:

The decision support system aims to provide ship crew with rational advice based on ship maneuvering capabilities through the prediction of the results of all possible maneuvers. The proposed Pre-Crash Advisor heuristic is based on changing collision event variables using the concept of ship maneuvering area developed by *Baldauf et al. (2015)*. It links the encountering scenario and most convenient impact scenario for minimum damage using the ship maneuvering area.

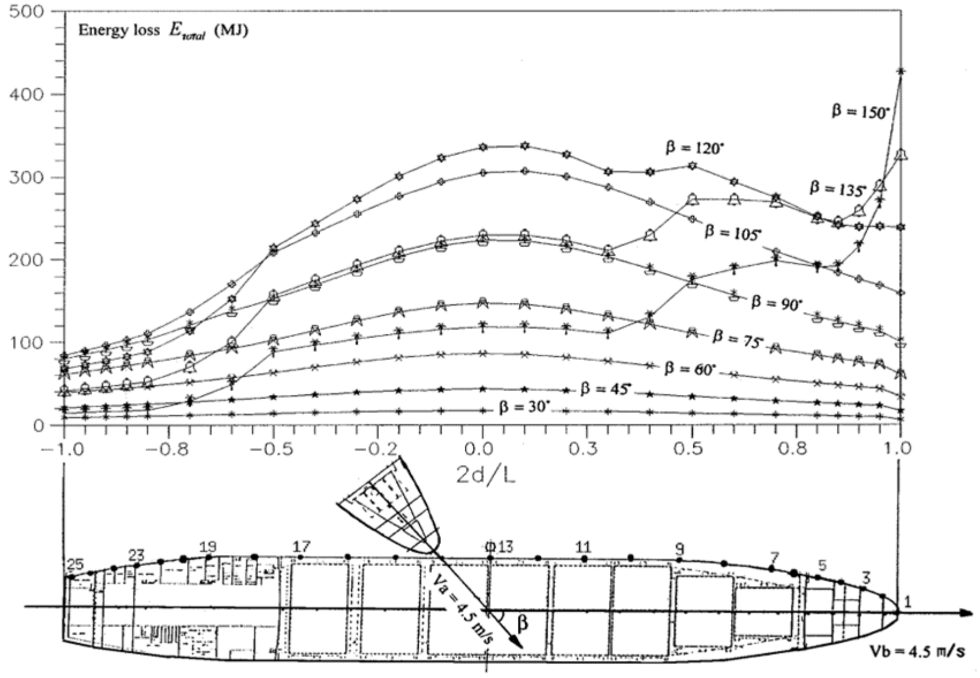


Fig.1: Collision energy loss vs collision angle (Zhang model)

An accurate ship maneuvering model requires numerous parameters, in addition to the computing time for simulation studies. To reduce the computational demand several simplified calculation methods have been developed to predict ship response for rudder actions. The most famous simplified mathematical model for ship movement was proposed by Nomoto in 1957. He was the first to propose the simplification of ship motion to require only two parameters which are K and T. The first parameter K represents the ship turning ability and the other one T represents the course keeping ability. Nomoto model has proved it's robust and practicality, since it is the first choice for autopilot design.

Maneuvering area is defined as the area which covers all potential positions that a ship could theoretically reach in a certain time period according to its maneuvering capabilities, Fig.2, represented by the following first-order Nomoto model:

$$T\,\dot{r} + r = K\,\delta \tag{1}$$

where r is the yaw velocity, δ is the rudder angle, and K and T are the ship hydrodynamics indices. It has been used to predict ship paths according to possible rudder angle actions with the aid of the ship simplified kinematics:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\varphi} \end{bmatrix} = \begin{bmatrix} U\cos(\varphi) \\ U\sin(\varphi) \\ r \end{bmatrix} \tag{2}$$

Where U is the assumed constant ship speed, φ is the heading angle, and x and y form the position of the ship. Nomoto model is the one of the simplest mathematical models for ship maneuvering dynamics as it is robust and fast model specially for damage mitigation, where time is an issue. All the aforementioned equations are discretized using a proper sampling interval.

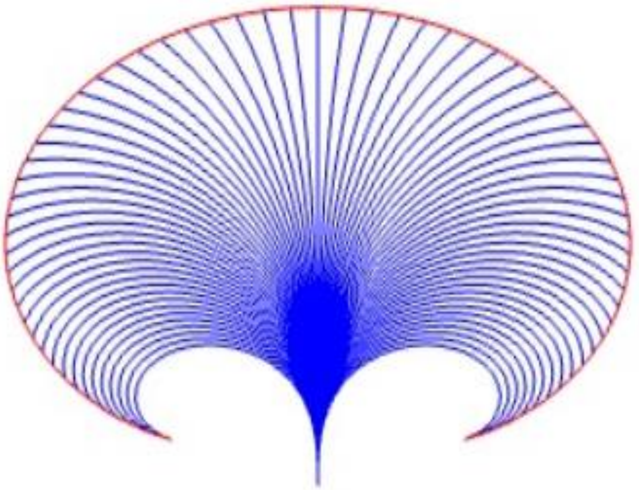


Fig.2: Concept of ship domain (rudder angle -30 to + 30 degrees)

Pre-Crash Advisor must be linked to the installed collision avoidance system. It is activated after collision avoidance fails (i.e. when the distance between the two ships becomes less than specific value (MDTC) and collision supposed to be inevitable *Montewka et al. (2011)*). But in order to define the inevitable collision candidate Pre-Crash Advisor (PCA) updates its input data from the Automatic Identification System (AIS). It calculates the expected initial collision point and angle using AIS data. In the same time AIS provides other information such as ship length which is required for defining striking and struck ship. The algorithm calculates and compares the distance between the two ships with the (MDTC). In the current version of the PCA this distance is taken equal to struck ship length. The hydrodynamic indices K and T which represent the manoeuvring capabilities of the striking ship should be available from the manoeuvring test and stored in the PCA memory.

In the Pre-Crash Advisor, the algorithm generates ship manoeuvring area according to its definition i.e. the prediction time is equal to the time required the ship according to its actual speed to turn 180° with full rudder action, *Baldauf et al. (2015)*, Fig.2. When the AIS data refer to certain threat or collision candidate due to intersection between the two ship paths, it compares the distance between each point of the manoeuvring area and the candidate collision ship. If this distance is smaller than the MDTC, it gives an alarm about the paths and rudder angles which lead to collision. If the captain took an action and its results always show that all possible manoeuvring paths lead to inevitable collision. The algorithm calculates all the collision angles and proposes the rudder angle which gives the minimum damage according the minimum damage criteria. A calculation of the collision angle is done by finding the different between both ships heading angles at the collision point for all manoeuvring paths.

The first developed scheme is working in the following order, see Fig.4:

- Step 1: initiator will define the collision candidate and collision scenario according to the current conditions (AIS).
- Step 2: the algorithm will predict and calculate the expected collision location and angle according the actual conditions of both ships (Speed, heading angle and path).
- Step 3: according to ship speed and prediction time, the algorithm generates the maneuvering area of the striking ship and calculates the distance between each point of all manoeuvring paths and collision candidate ship to compare it with the used MDTC.
- Step 4: if all maneuvering paths lead to inevitable collision, the algorithm gives an alarm and calculates the expected collision angle for each possible path inside the maneuvering area at the point of collision along the struck ship.
- Step 5: based on the minimum damage criteria, an advice will be given to the captain as recommended rudder angle as last option before crash.

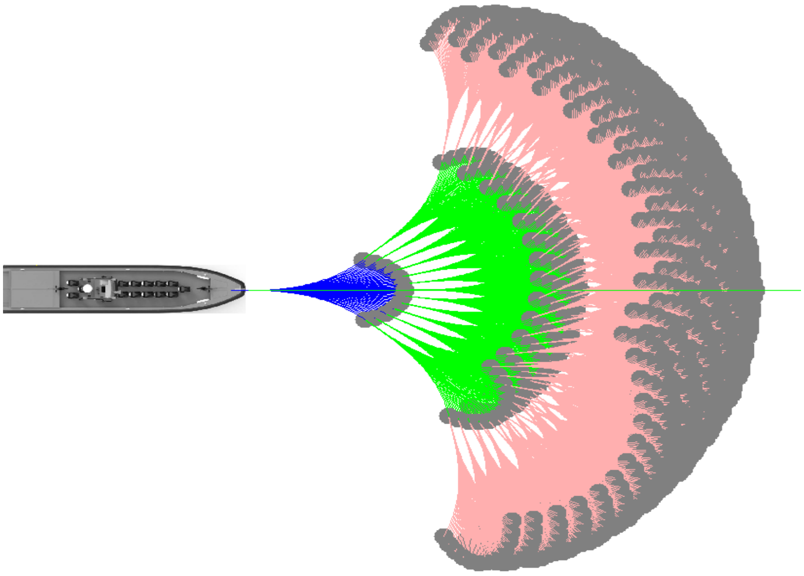


Fig.3: Prediction sequence in 3 successive manoeuvres

4. Case Studies

In this section, the Pre-Crash Advisor is applied to two different scenarios to be validated where collision is inevitable. Each scenario has two ships. The first ship **A** supposed to strike the second ship **B** according to the scenario conditions. The manoeuvring area prediction time depends on the ship speed as ships with higher speeds take less time to make a 180° turn.

Table I: Striking Ship Characteristics

Parameter	**Value**
IMO No	9355094
AIS Vessel Type	Cargo
Overall Length	130.03 m
Breadth	19.3 m
K	0.044
T	35

4.1 Scenario 1

This scenario has two identical cargo ships with characteristics given in Table I, *Nakano and Hasegawa (2012)*, the struck ship has length equal to 300 m. The striking and the struck ship have an impact speed of 8 m/s and 3 m/s respectively. They have heading angles that make the initial collision angle β=95° and the relative positions lead to a collision from the first manoeuvring area as shown in

Fig.5. The prediction time for the striking ship A is equal to the prediction time of the manoeuvring area which is 90 s. This means, after 90 s according to striking ship manoeuvring options and the struck ship path, collision will be inevitable as shown in Fig.5(a). Fig.5(b) shows how can the PCA-Advisor gives only one rudder angle action (δ=-30°) to minimize the damage and make the collision angle as minimum as possible.

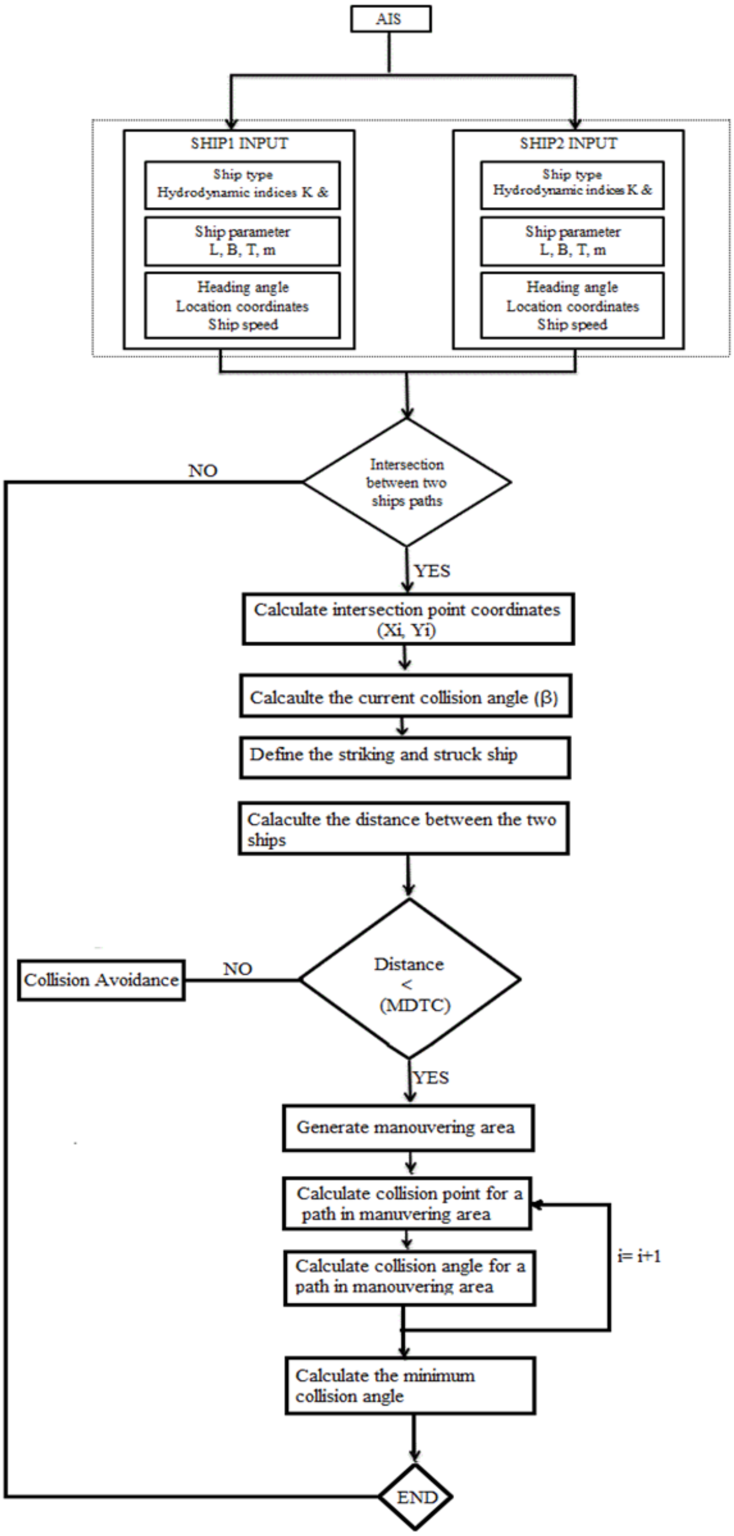
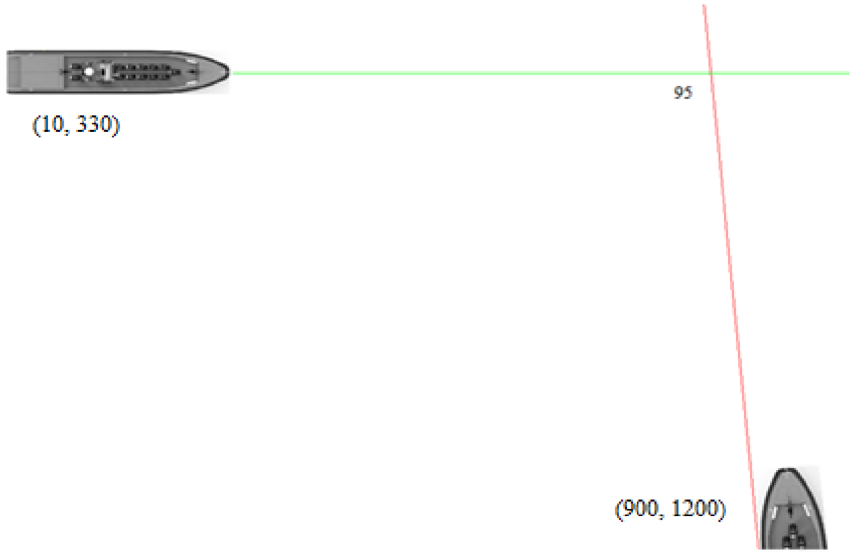
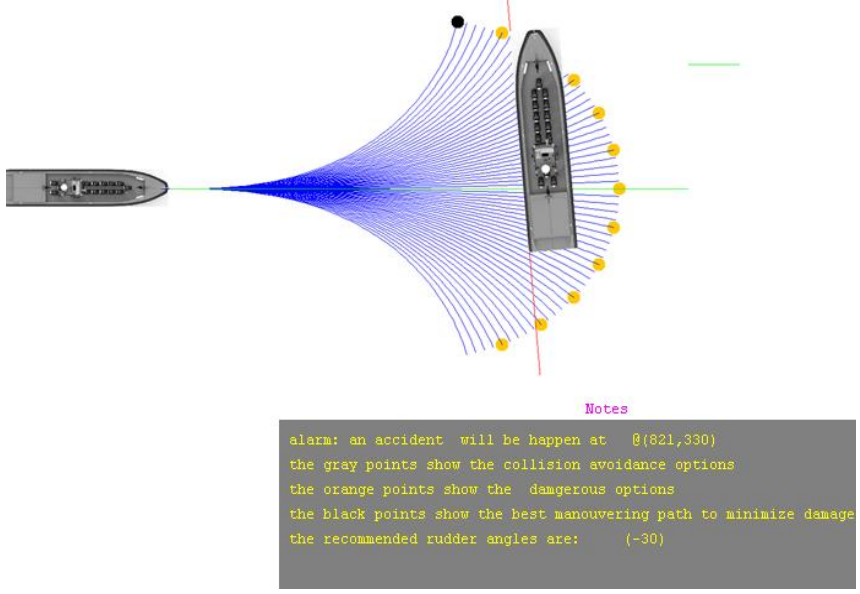


Fig.4: Flowchart Pre-Crash Advisor

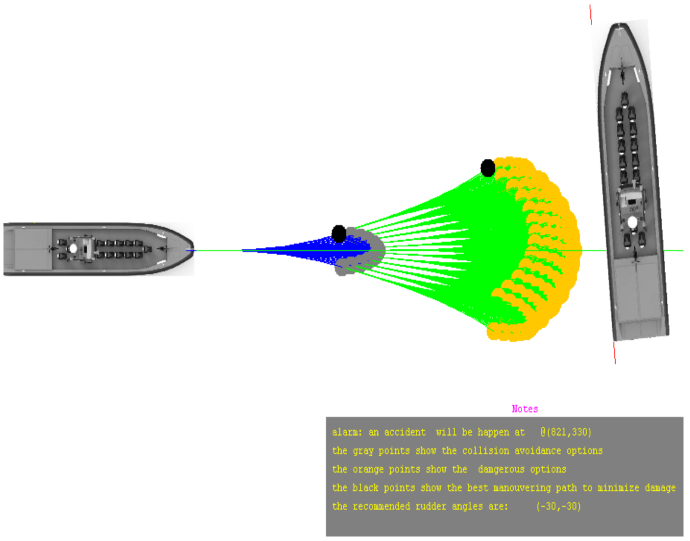


(a): Initial encountering scenario



```
alarm: an accident  will be happen at   @(821,330)
the gray points show the collision avoidance options
the orange points show the  damgerous options
the black points show the best manouvering path to minimize damage
the recommended rudder angles are:     (-30)
```

(b): PCA manoeuvring advice
Fig.5: Scenario 1 Collision



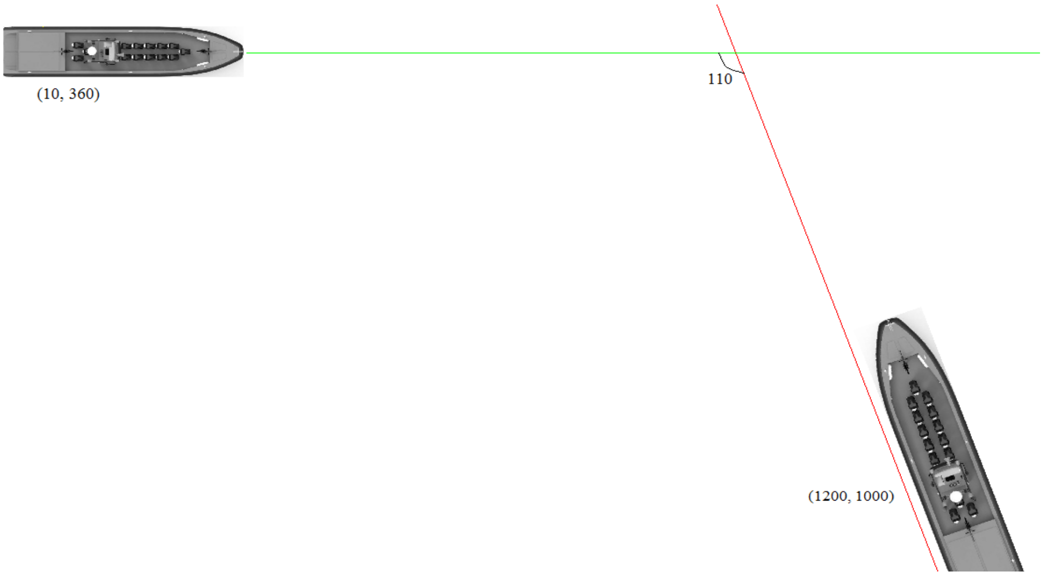
```
alarm: an accident  will be happen at   @(821,330)
the gray points show the collision avoidance options
the orange points show the  damgerous options
the black points show the best manouvering path to minimize damage
the recommended rudder angles are:     (-30,-30)
```

4.2 Scenario 2

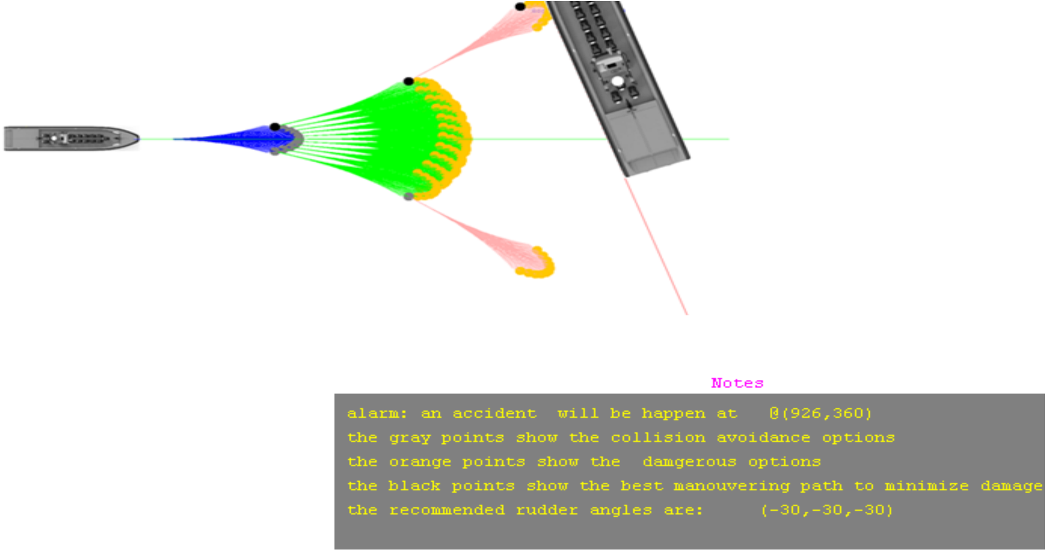
Taking the same encountering conditions as mentioned in scenario 1, based on the concept of successive manoeuvres, if the prediction time 90 s is divided to two prediction areas with prediction time equal to 35 seconds for each, the options in order to have different collision angle and location along the struck ship are different as mentioned in Fig.6.

4.3 Scenario 3

In this subsection, another scenario is presented where the initial encountering angle is $\beta = 110°$. The striking ship has a speed of 5 $\mathrm{m/s}$ and length of 130 m, and the struck ship has a speed of 3 $\mathrm{m/s}$ and length of 350 m. The prediction time for the striking ship is equal to the 150 s. It is divided to three successive maneuvering with prediction time equals to 50 s. Fig.7 shows how can the PCA-Advisor gives the recommended rudder action to minimize the damage with successive maneuvering.



(a): Initial encountering scenario



```
alarm: an accident  will be happen at   @(926,360)
the gray points show the collision avoidance options
the orange points show the  damgerous options
the black points show the best manouvering path to minimize damage
the recommended rudder angles are:     (-30,-30,-30)
```

(b): Successive PCA manoeuvring advice
Fig.7: Scenario 2 Collision

5. Conclusion and discussion

The dynamic parameters at the moment of impact significantly affect the collision damage. Modification of dynamic parameters at the moment of impact are nevertheless little discussed in context of collision damage mitigation. Therefore, a decision support system for ship collision damage mitigation is presented. This paper addresses the main aspects which must be considered for the development of intelligent decision support system for ship-ship collision damage mitigation. These aspects are:

1- Criteria for unavoidable collision (MDTC);
2- Collision event variables which effect collision damage (collision angle, speed and location);
3- Criteria for minimum damage during evasive manoeuvre;
4- Link between encountering scenario and impact scenario using maneuvering model.

Due to the absence of specific criteria that defines case when collision is unavoidable, the authors propose that struck ship length is the criteria for unavoidable collision. The developed algorithm let the door open to use any specific or dynamic value for MDTC, it can be chosen from the captain according to his experience or value of risk he can accept.

Collision angle has been chosen due to its strong effect on collision damage according to Zhang research. Nomoto model is used for the current version of PCA due to its robust and fast prediction for the maneuvering area. The advantage of the maneuvering area that, it is dynamic area, its size changes with ship type and speed. This comes in harmony with the definition of MDTC which depends on different factors such as ship speed and relative bearing.

6. Future work

According to SOLAS, The International Convention for the Safety of Life at Sea, requires that ships are fitted with transverse watertight bulkheads to provide the ship with a certain measure of survival capability. In addition to the classification societies rules for collision bulkheads, *DNVGL (2015), Ståhl-berg et al. (2012)*. Collision location affects the damages according to the ship type, for example, any structural damage along cargo area can lead to economical loss or pollution such as in Tankers vessels or human casualties such as in passenger vessels.

As collision location and speed have important role in collision impact, the authors aim to use a three degree of freedom (3-DOF) nonlinear model of the vessel to account for manipulating the engine speed in addition to the rudder angle; this will give more freedom in damage reduction as a trade-off between collision angle, location, and speed. The successive manoeuvres concept helps to optimise damage mitigation; the authors aim to implement the PCA with successive maneuvers in real time applications.

Acknowledgements

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EPILYSIS, a New Solver for Finite Element Analysis

George Korbetis, Serafim Chatzimoisiadis, Dimitrios Drougkas, BETA CAE Systems,
Thessaloniki/Greece, ansa@beta-cae.com

Abstract

This paper introduces EPILYSIS, the new member of BETA CAE Systems software suite. EPILYSIS is a solver for Finite Element Analysis, which comes to bridge the gap between pre- and post-processing and offer a seamless operation in CAE workflow. Designed for large-scale model analyses, it is ideal for the global strength assessment of large vessels and detailed strength assessment of highly stressed areas. Additionally, direct and modal frequency response and non-linear contact solutions allow more extensive and sophisticated analyses. EPILYSIS together with the pre- and post- processors, ANSA and META, offer a valuable yet affordable tool to the Marine Engineering sector. Two characteristic case studies are presented where EPILYSIS element accuracy and results performance are compared with well-known solvers in the market.

1. Introduction

EPILYSIS is the new addition to the BETA CAE Systems analysis tools. Named after the Greek word for "solution", EPILYSIS covers numerous solution types such as Structural, NVH, Optimization and more. In this paper, two representative applications are presented, where the complete BETA CAE Systems suite is used for the model preparation, process and results interpretation.

In the first part, a typical VLCC vessel is subjected to three different loading conditions. The main target is the determination of the maximum stresses and the critical areas. The complete Model set-up is conducted with the aid of the ANSA pre-processor. First, a detailed Finite Element model of the hull structure is generated, complying with the meshing requirements set by Classification Societies. Then, a series of useful and automated processes make the model "lighter", more sophisticated but still realistic and suitable for the strength analysis. For each loading condition, the hydrostatic equilibrium of the ship is computed and the corresponding hull deformations are calculated. The static analyses are conducted using both the EPILYSIS and a well-known commercial solver.

In the second part, EPILYSIS solver is used on a nonlinear-contact strength analysis for a ship’s rudder. The applied force which is produced by the water resistance, at specific speed and angle-position of the rudder, is calculated by a simplified CFD analysis and used as the loading condition for the structural analysis. The static problem set-up is performed using automated processes, such as the results mapping, the contact pair definition and the batch meshing, which are provided by the ANSA pre-processor. Several runs are performed with EPILYSIS and an industry standard solver. The solvers are compared to each other concerning the performance and the results accuracy.

2. Static Analysis

2.1. Model set-up

The general characteristics of the studied VLCC are presented in Table I. At first, a Finite Element (FE) model of the ship structure is automatically generated. In general, the ship is relatively large so, coarse mesh should be applied to avoid very long simulation time. The whole structure is represented by first-order shell elements; (a small amount of solid tetrahedral elements are used at the stern tube region). A coarse mesh is generated for the whole structure (element length of 0.95 m), except from selected areas, where finer mesh (e.g. 0.2 m) ensures better results accuracy. This mesh strategy was selected to contribute to the solvers comparison.

Table I: Main characteristics of the VLCC vessel of the present study

Type	Crude Oil Tanker
Deadweight	320000 t
Length betw. Perp. L_{PP}	320.00 m
Breadth B	60.00 m
Depth D	30.50 m
Scantling draft T	22.50 m
Service speed V_s	15.9 kn
Main engine	Wärtsilä 7RT-FLEX84T-D
Keel laid	April 2010

The mesh generation is a fully automated process performed by the ANSA Batch Meshing Tool. Meshing parameters and quality criteria can be defined in several meshing scenarios for the various ship areas. Afterwards, re-meshing algorithms act on areas with poor mesh quality, improving the mesh, until the predefined quality criteria (Table II) are reached. The final model comprises of about 402.000 shell elements, 143.000 beams and 17.000 solid tetrahedrals, Figs.1 and 2.

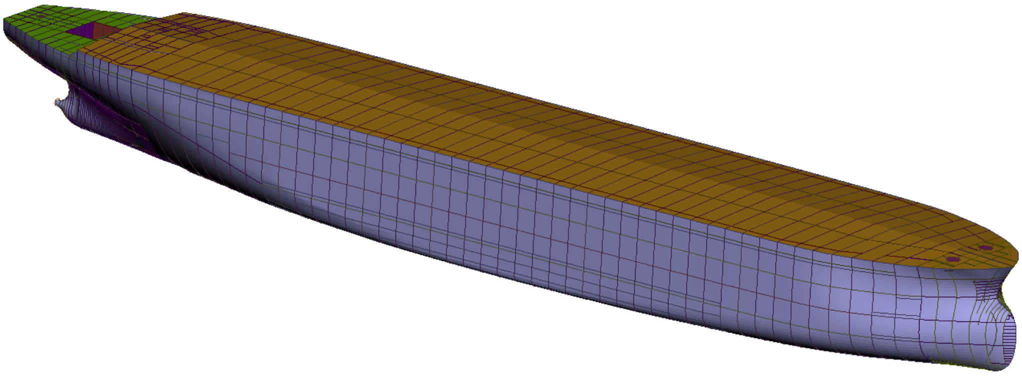


Fig.1: Global FEM model of the vessel

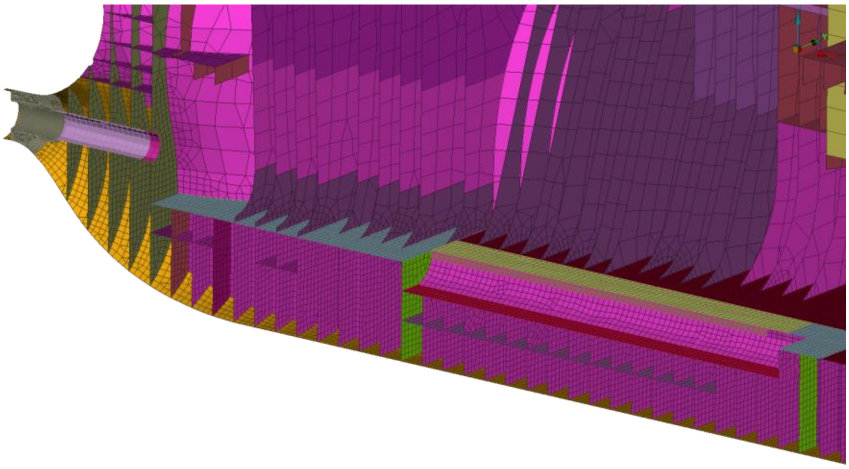


Fig.2: Detail of the generated FEM mesh at the engine room region of the vessel

Table II: Mesh quality criteria.

Quality Criteria	
Skewness (Nastran)	30°
Aspect ratio (Nastran)	3
Angle (Quads)	45-135°
Angle (Trias)	30-120°
Minimum Element Length	0.01 m
Maximum Element Length	1.5 m

In addition, geometrical simplifications should be applied on the model. The first action to simplify the model is to fill small holes that are not significant for the model's behavior. Such holes are automatically identified according to their diameter and filled. This action improves the element quality while reduces the number of elements. This process is prescribed at the meshing parameters of the Batch Meshing Scenario. Thus, the whole process runs in batch mode without any need of user interaction. The second simplification is the replacement of longitudinal stiffeners by beam elements. This method simplifies the model by avoiding the generation of very small shell elements. The properties of the beam elements are auto-calculated in accordance with the cross section of each stiffener.

Machinery, auxiliary structures and small constructions that do not contribute to ship's strength are not modeled in the present FE model. Their mass is applied to the model as non-structural mass. This mass is appropriately distributed over the FE model, so as to reach the prescribed lightship weight and the corresponding center of gravity. The mass of the present structural model is 34442 t, while the lightship weight is 43938.7 t and its center of gravity L.C.G. at 151.338 m. Thus, 9496.7 t of lumped masses are appropriately distributed in holds, stern and bow by the automatic process of the ANSA Mass Balance Tool, Fig.3. Finally, the engine mass is represented by a lumped mass of 990 t distributed to the engine foundation positions by Rigid Body Elements (RBE3-distributing) elements.

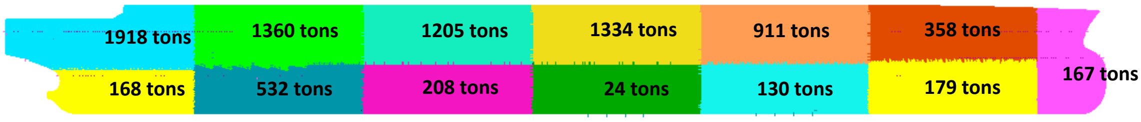
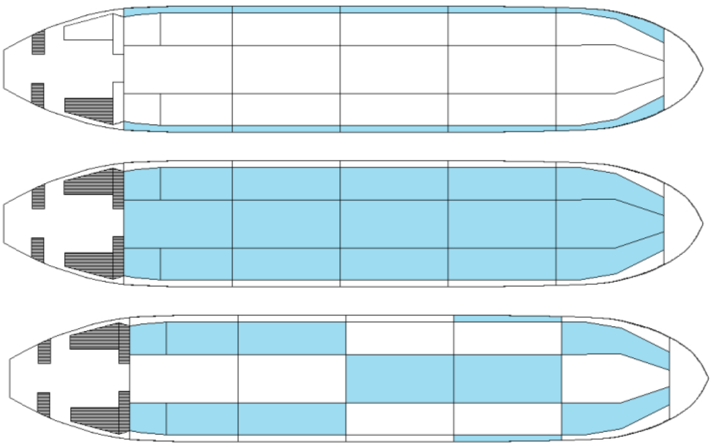


Fig.3: Distribution of non-structural mass in the present FEM model



Ballast arrival (L.C. 1)
Displacement: 145647 t
Draft: 9.69 m
Trim: 2.12 m

Full-load departure (L.C. 2)
Displacement: 364074 t
Draft: 22.52 m
Trim: 0.11 m

Departure, partial load (L.C. 3)
Displacement: 229276 t
Draft: 14.78 m
Trim: 3.05 m

Fig.4: Representative loading conditions of the vessel

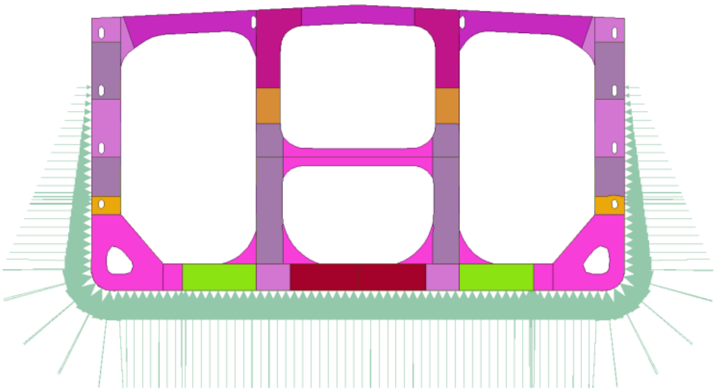


Fig.5: Application of hydrostatic pressure due to buoyancy in the FEM model

Three representative loading conditions (full-load departure, ballast arrival and departure with partial load) are considered in the present analysis, Fig.4. The contents of the tanks are represented by lumped mass connected to each hold bottom with RBE3 elements. The ship is positioned on still water considering the vessel's total displacement and center of gravity. Buoyancy is applied as pressure at the hull underneath the waterline using Pressure Load (PLOAD4) entities, Fig.5. Finally, the vessel is trimmed in order to achieve static equilibrium between weight and buoyancy.

2.2. Analysis Results

The model was solved with EPILYSIS solver, version 17.0.3 and a standard industry solver, with several numbers of CPUs. The results are presented in META post-processor. The maximum developed Von Mises stresses in the ship, hold an area, lower than yield stress of steel. High stress concentrations occur near the engine room. The standardized statistics tool can give an overview of the hull behavior while the areas of interest can be easily identified and displayed using annotations and iso-functions. The general stress distribution (for loading condition 1) is shown on Fig.6.

Hull deformations have been computed for the three different loading conditions that are presented in Section 2.1. For loading condition 1 (ballast arrival condition), the hull exhibits a hogging behavior. For loading condition 2, the hull is bending towards the opposite direction (sagging). For loading condition 3, a hogging at aft and sagging at fore behavior is exhibited.

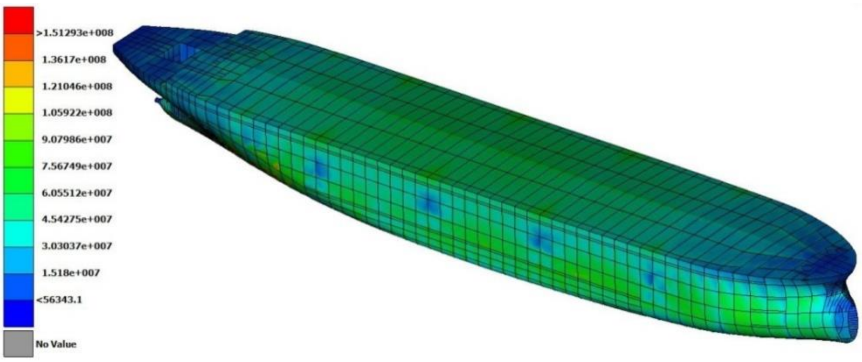


Fig.6: Loading condition 1 (ballast arrival condition): Distribution of Von Mises stresses on hull

2.3. Solver Comparison

Solver Results can be compared in two sectors, accuracy and performance. Concerning the accuracy, a direct comparison between absolute values is of low value, since there is no guarantee for the correctness of the results of numerical methods. Thus, initially it would be more interesting and useful to compare results on a couple of representative benchmark tests that are small problems where analytical results are available. This way it is possible to compare the solver results with the values calculated by Theory and indicate the accuracy of EPILYSIS compared to a widely used solver.

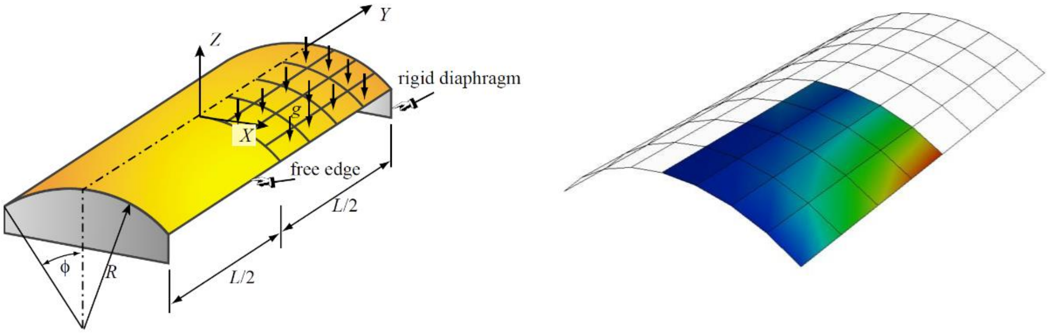


Fig.7: Scordelis-Lo roof benchmark

The thin cylindrical shell roof shown in the Fig.7 is a standard benchmark test problem known as Scordelis-Lo roof. The loading is a uniform gravity load, parallel to the z-axis. The output most frequently displayed in benchmark tests is the vertical displacement at the midpoint of the free edge. Symmetry can be used to reduce the analysis to a quarter of the whole roof.

In Table III, it is seen the relative error compared to the analytical method and also compared to Industry Standard Solver. It can be said that accuracy is one of EPILYSIS' strengths.

Table III: Numerical vs Analytical values

Displacement Z at point A (**Theory : -0.3024**)		
	EPILYSIS	Industry Standard
4-node QUAD	-0.3205 (5.99%)	-0.3205 (5.99%)
8-node QUAD	-0.3032 (0.27%)	-0.3005 (0.62%)

Instead of the benchmarks, some useful conclusions may occur by the direct comparison of the two solvers results. For example, as it is known, accuracy decreases remarkably with the usage of triangular elements. This can be seen also at the direct comparison of the two solvers results, where there is absolute results coincidence on quadratic elements while differences appear on triangular elements. In Fig.8 the fringe color indicates divergence between the results of the two compared solvers; green color indicated zero divergence. It is clear that higher values are concentrated on triangular elements.

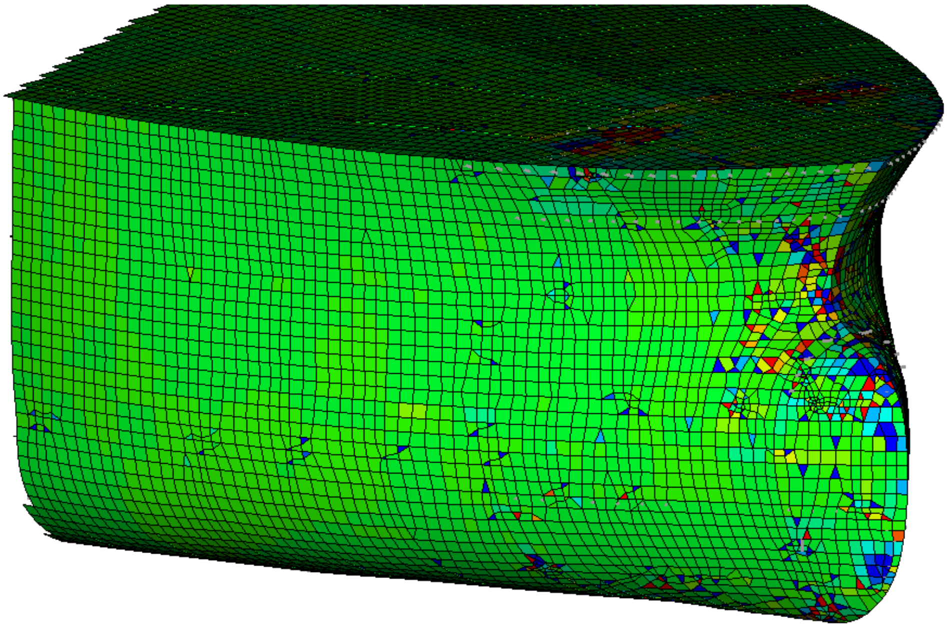


Fig.8: Divergence on stresses results

Concerning the performance comparison, several runs were performed for the three aforementioned load cases, with various numbers of CPUs. In most of the cases using any number of CPUs, EPILYSIS seemed competitive to the Industry standard solver, solving at significantly shorter duration on average. However, what is more than obvious at all load-cases is that the parallelization of EPILYSIS is significantly efficient. When the number of CPUs increases EPILYSIS performs even better. Fig.9 shows a representative diagram for the Static Analysis of the ballast arrival loadcase. The situation in the rest loadcases is similar so there is no need of separate presentation. EPILYSIS managed to finish in considerably shorter time, especially at higher number of CPUs.

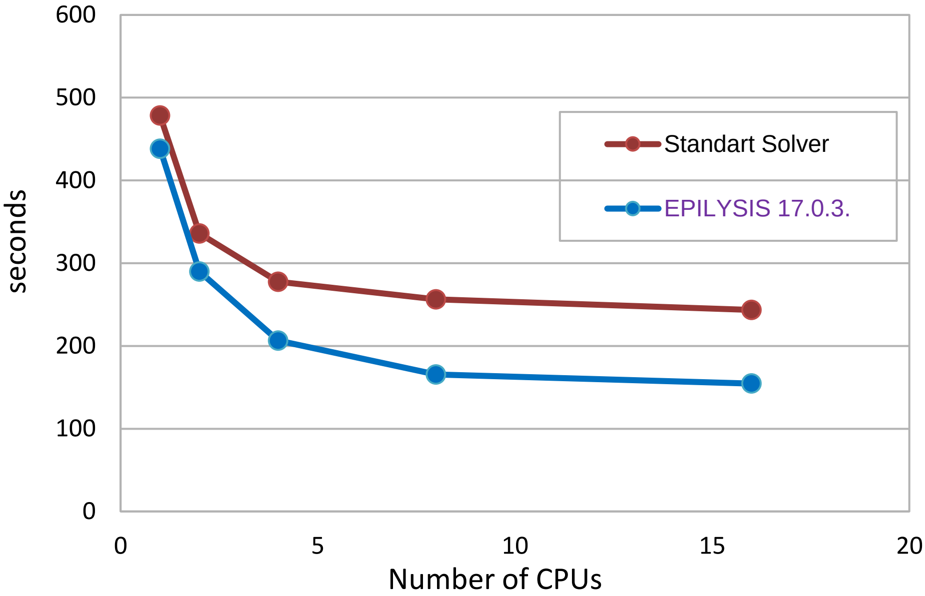


Fig.9: Performance along Number of CPUs

3. Non-Linear Contact Analysis

3.1. Case Study Description

The model for this case study is a spade rudder with rudder trunk of a Handysize class double skin bulk carrier. The ship's length is 169 m and its maximum velocity 15 kn. When the ship is fully loaded the whole rudder and skeg are submerged beneath the sea level. The rudder cross section is NACA 0015 and stock material is steel with Young's Modulus 210 GPa, Yield stress 235 MPa and density 7.86E-6 Kg/mm3.

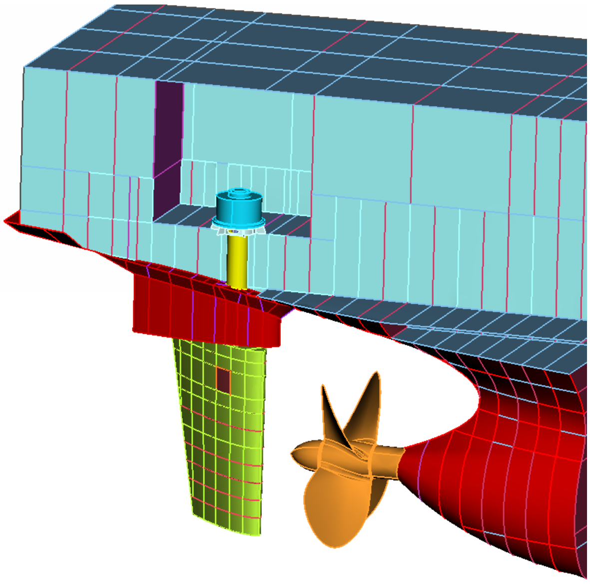


Fig.10: The geometrical model

The stock is supported by a THORDON elastomeric bearing of type SLX, assembled on the rudder truck. The stock connected to the rudder's body by a cone coupling which is welded on the body. Its uppermost part is clamped to a rotary valve which drives the rudder. The elastomeric bearing's Young's Modulus is 440 MPa and its maximum working contact pressure 10~12 MPa.

The main force that strains the rudder is produced by the water flow around it. As expected, the maximum force appears at the vessel’s full speed, when the rudder turns to the maximum angle of 35 degrees. The weight and buoyancy are considerably small in relation to the water flow force therefore they are not taken into account. To evaluate the force that is distributed to the whole surface of the rudder, a CFD analysis is performed for the described extreme conditions. This analysis is performed in ANSYS FLUENT. The results from the CFD analysis are mapped to the structural model and used as boundary conditions to the structural analysis. The geometrical model is shown in Fig.10.

To complete the FE model that will be exported to the solver, the proper materials, shell and solid element properties, and the solver header are defined. Solver output requests are defined for strain and stress.

3.2. Model Set-up

This structural analysis aims to calculate the strength of the rudder assembly and stresses on the contact between the bearing and the stock. The FE representation of the geometrical model that participates in the analysis is shown in Fig.11.

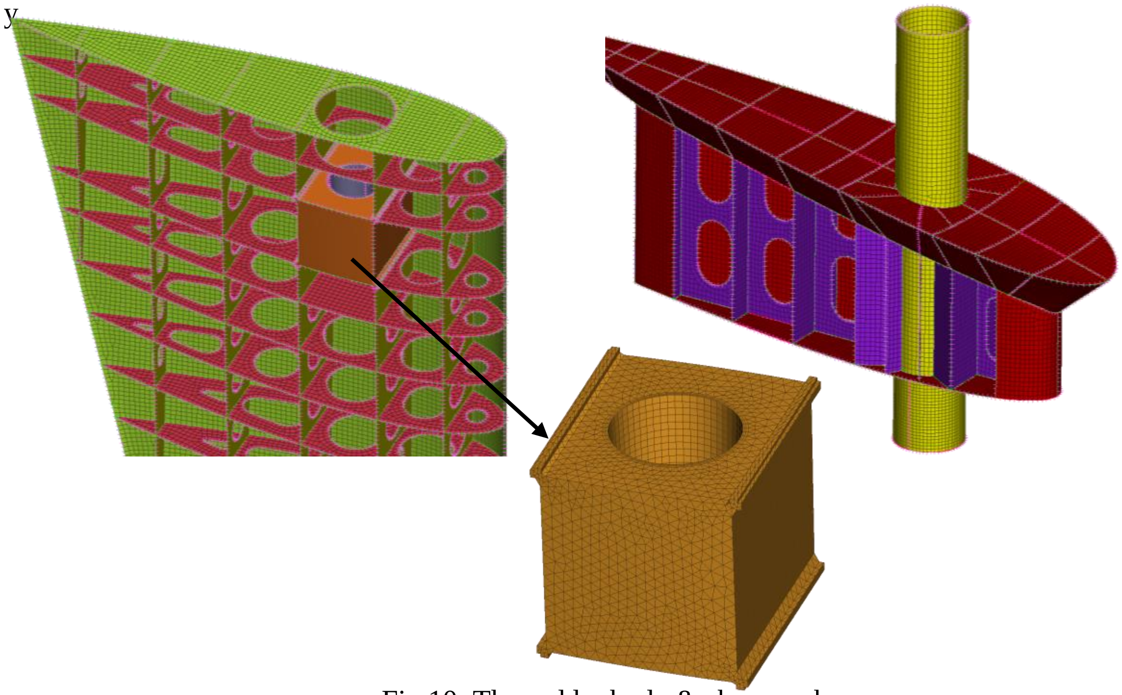
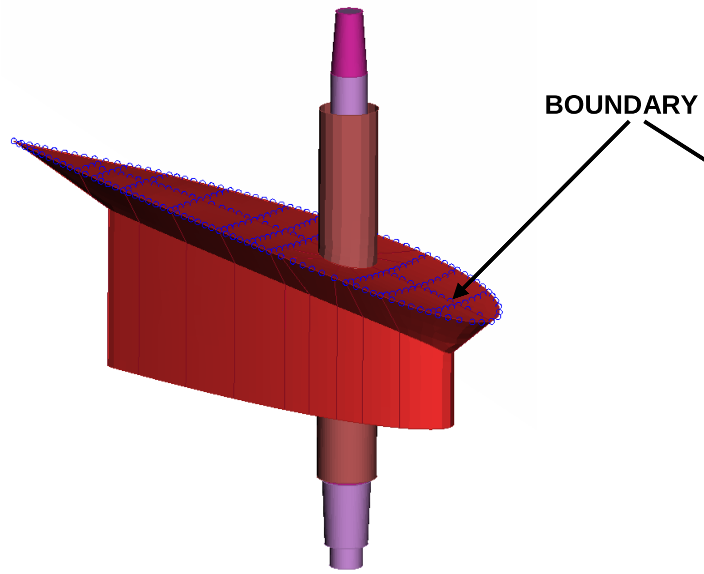


Fig.10: The rudder body & skeg mesh

The rudder stock and the bearing are important parts for this analysis and their results need to be accurate. Thus, thin layers of Hexahedral solid (HEXA) elements are applied on the stock perimeter to ensure the accuracy of the desired results. In addition, the whole stock model is meshed with HEXA elements. The HEXA meshing process is a semi-automatic process in ANSA based on special entities, the Hexa Boxes that are fit on the model. Boxes are re-usable and have their own meshing parameters such as, node number, spacing and number of layers etc. After the definition of the Hexa Boxes, mesh is created automatically. Three layers of HEXA elements are applied on the stock / bearing contact area with small element length of 4.5 mm, while the rest of the part is meshed with 30 mm HEXA elements. The bearing is also meshed with HEXA elements.

The structural analysis is limited to the rudder assembly, so the rest of the ship is considered as rigid. Thus, boundary conditions [Single Point Constraints-SPC] are applied on the upper nodes of the rudder skeg which constrain the displacement and rotation in all degrees of freedom, Fig.11. The rotary valve is also considered as rigid body. The latter constrains the displacement of the stock at all axes and the rotation of the Z axis. To represent this constraint, an extra SPC is created in the center of the coupling which is connected to the stock coupling surface through a Rigid Body RBE2, Fig.12.



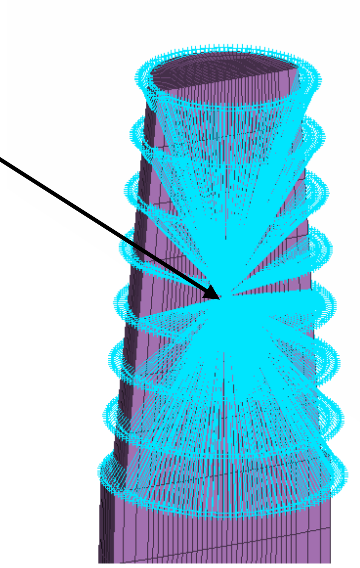


Fig.11: Boundary constraints of skeg

Fig.12: Boundary constraints of stock

3.3. Automatic definition of contacts

The rudder stock is connected to the rudder by the cone coupling and is supported on the rudder trunk by the elastomeric bearing. These connections are simulated by CONTACT entities. An ANSA tool, dedicated to this purpose, identifies the pairs of contact surfaces of the candidate pairs so that the user can decide whether to accept them and define the type of the coupling. The contact pair between the stock and the bearing is defined as BCONECT (Definition of contact between surfaces), according to EPILYSIS, since the connection is not fixed and small sliding is allowed, Fig.13. The actual area of contact and the distribution of the pressure depend on the load case and the rigidity of the stock, trunk and bearing.

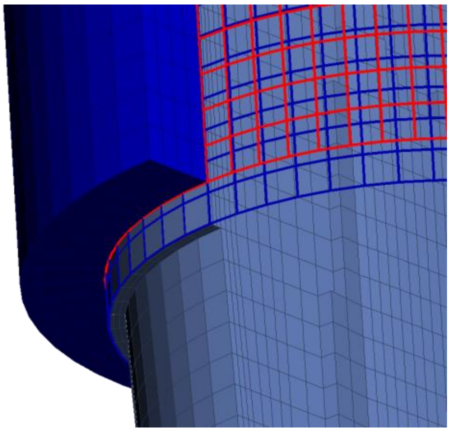


Fig.13: Contact between bearing and stock

3.4. Results Discussion

META post-processor is used to identify the critical areas and create statistics for all parts. As shown in the following figures the maximum value for the Von Mises stress occurs on the rudder trunk near to the supporting webs, Fig.14. The value 193 MPa is high but still far from the Yield stress. Stresses in the contact area are also processed in META for the bearing - stock coupling. As shown in Fig.15 and as expected, the maximum pressure is close to the bearing's lower edge. The maximum pressure value is 5.1 MPa which is at acceptable levels. Furthermore, as expected the maximum deflection of the rudder is measured at the lower nodes of the model at 36.26 mm. Concerning the Stock, the highest stress values appear at the opposite to the bearing area. Maximum stresses on the rest of the parts are not significant at all.

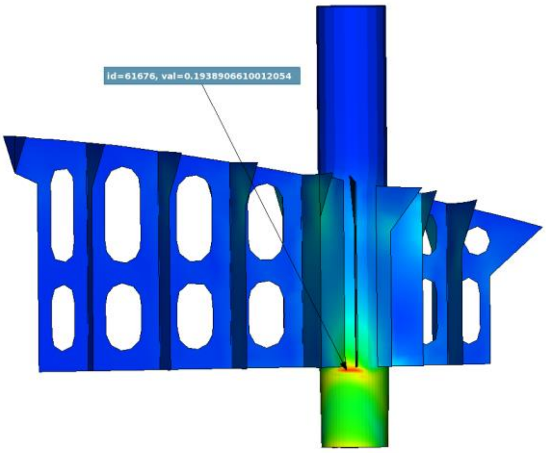


Fig.14: Von Mises stress at rudder trunk

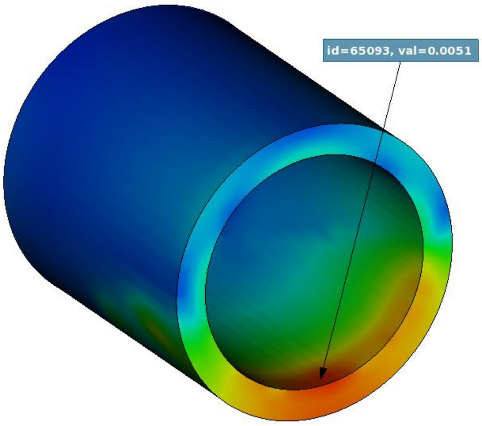


Fig.15: Stresses at bearing contact surface

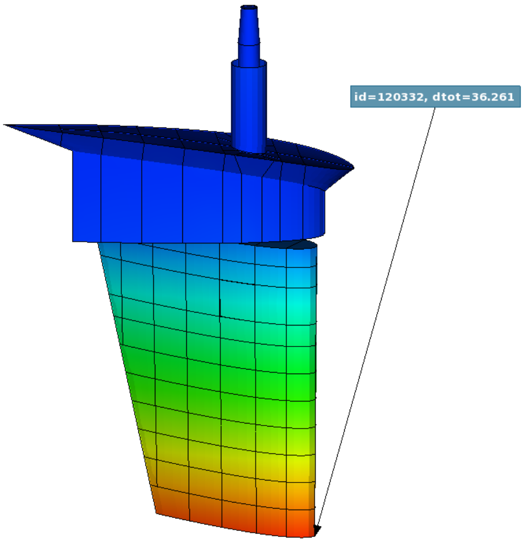


Fig.16: Deflection at rudder body

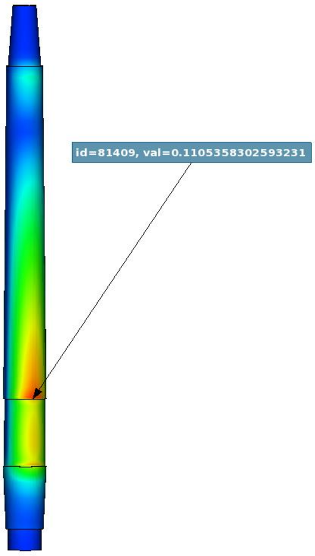


Fig.17: Von Mises Stress at stock

3.5. Solver Comparison

Initially the performance comparison is examined. EPILYSIS version 17.1.0 was used for this process and again several runs were performed, with several numbers of CPUs at the same machine. This analysis is an iterative approach (due to the contact definition) and it highly depends on several values and parameters such as convergence criteria and the number of increments. Thus, the software comparison can be affected by all these settings and may produce spanned findings. However, it is possible to have a quite clear aspect if the runs are performed exactly with the same set of settings.

Fig.18 illustrates the total time spent by the two solvers to complete the same run, on the same machine, using several numbers of cores. EPILYSIS seems in general more efficient. For low number of CPUs (1-2) the difference is much more evident. Another thing that is confirmed here is that the parallelization further than eight cores, offers low "value for money" benefits.

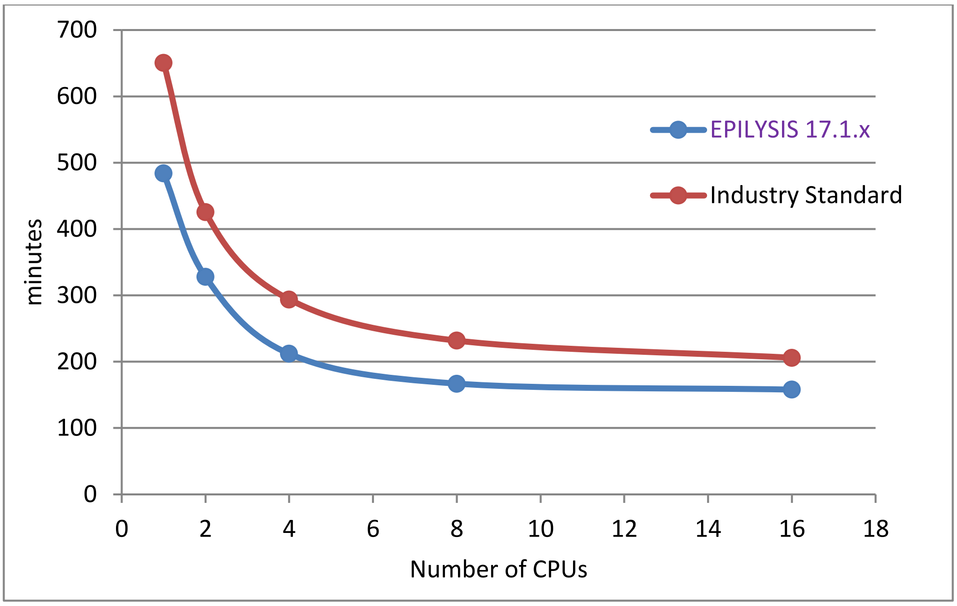


Fig.18: Performance along Number of CPUs

Concerning the results accuracy, as it was mentioned in the first part, a direct comparison between the absolute result values of the two solvers is not very meaningful. Numerical results contain some error by definition. So the absolutely correct values that can be used as comparison criterion are those calculated by Theory, which of course cannot be found for this case study. However, when the compared solver is one of the industry standards, there is some interest in comparing the results.

Concerning the results in displacements, the two solvers are very close. The model's Maximum displacement decline approximately 0.33% and is located at the rudder's body. At all the rest of the parts, divergence is lower than 0.25%. Moreover, the percentage of elements that exceed divergence (between the two solvers) of 0.5% hardly reaches the 0.2%. It can be concluded that the results do coincide.

Coming to the stresses, both solutions identify the maximum on the rudder trunk and on the same specific area. There is a difference concerning the total maximum magnitude about 5%. However, the total situation is much more aligned and can be shown in the table below. It seems that the divergence on the trunk is occurring locally at the maximum stress values:

Table IV: Divergence percentage per Part

	EPILYSIS [Mpa]	Standard Solver [Mpa]	% divergence
Rudder shell	37.643	37.643	0.00%
Rudder inner frame	37.220	37.209	0.02%
Skeg	16.600	16.444	0.97%
Trunk	193.891	204.626	5.20%
Stuck	105.251	104.997	0.24%
Stock Bearing	9.204	9.154	0.54%
Cone	28.140	28.207	0.23%

4. Conclusions

In this study they are presented two cases. In both situations it is used the new FEA Solver of BETA CAE Systems, called EPILYSIS. Another Industry Standard Solver is used on exactly the same model and at the same machine, in order to provide a reference point. In the first case a typical VLCC vessel is imposed to three representative static loading conditions. In the second case a spade rudder was subjected to a load produced by water resistance at the extreme turning position and highest speed.

What makes this analysis more special is the contact definition between the rudder stuck and a bearing made of Thordon material. For the analysis set up of such big and detailed models the use of sophisticated tools that automate and facilitate the simulation process (like Batch Meshing, Results Mapper and Contact Wizard) turns to be a matter of great importance. ANSA and μETA pre- and post- processors have been used successfully for the definition of CFD and structural analysis.

Analysis results, generated by the two solvers, referring mainly to the Stresses and Deformations, are presented and analyzed by META post-processor and compared to each other. In terms of Deformation there is absolute coincidence between the two Solvers. The stress results are also more or less aligned for Quadratic elements while for Triangular elements there is much higher divergence. It is also presented a performance comparison between the two Solvers, for both case studies. Even though in the second case the performance strongly depends on the analyses' characteristic values like convergence criteria, mesh density, material characteristic values etc., in general it seems that EPILYSIS solver reaches quite high performance standards for any number of CPUs. Additionally, the parallelization of EPILYSIS seems quite more efficient especially in the first Linear Static case study.

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Analysis of General Arrangements Created by the TU Delft Packing Approach

Mark J. Roth, Delft University of Technology, M.J.Roth@student.tudelft.nl
Koen Droste, Delft University of Technology, K.Droste@tudelft.nl
Austin A. Kana, Delft University of Technology, A.A.Kana@tudelft.nl

Abstract

This paper applies network theory to understand the physical relationships in the general arrangements generated by TU Delft packing approach. The generated arrangements are converted into weighted graph networks. The authors have developed a new scoring metric using this network and have applied this to quantitatively assess qualitative properties of the different arrangements, enabling direct comparison between concept designs. Finding and understanding these specific physical properties of the arrangements should lead to improved design space exploration of layout features of the designs generated by the TU Delft packing approach.

1. Introduction

During the conceptual ship design phase, problems concerning the overall composition of the vessel can be directly related to the arrangement of systems, compartments and components. Historically, these arrangements have been compiled into detailed drawings of the vessels where the naval architect has decided on the arrangement and connections between these compartments manually. These decisions have been traditionally built upon design rules and the experience of the designer. Furthermore, the designer can usually fall back to comparison vessels to have a decent understanding of the architectural problems and to have a starting point for the current design. A problem occurs when new vessel classes are being designed or in situations where a lack of experience is encountered, *Andrews (1998).*

Currently, projects are being undertaken for general arrangement optimization in an earlier stage of the design process, such as the packing approach, *Van Oers (2011)* and *Duchateau (2016)*, the Intelligent Ship Arrangement platform, *Parsons et al. (2008),* and the Design Building Block approach, *Andrews and Dicks (1997).* These projects all make the use of computing power to generate a concept exploration space. By creating numerous design concepts, a solution space is created where the designer is able to explore trade-offs and eventually select multiple concepts for further examination. This paper is focusing specifically on the layouts generated by packing.

In the packing approach, the actual internal layout of the generated designs is mostly ignored, because the overall quality of the generated arrangement has been considered to be fairly poor. Manual redesign of the most promising design is deemed necessary to create a complete functional layout in later stages of design. This paper seeks to create more insight and understanding into these generated arrangements, facilitating the opportunity to transfer the generated designs into later design phases. To do this, an assessment of physical locations and relationships as well as fundamental interactions between elements of systems in the designs is necessary. One might be able to improve the arrangements out of the packing algorithm by increasing the number of constraints in the model, but this will greatly limit the number of feasible designs and so the explored design space. By allowing the model to have more freedom, the design space should lead to more diversity in the set of designs. Developing a method that would be able to directly compare the generated arrangements without ove rconstraining and the model would be beneficial.

1.1 Introduction to the TU Delft Packing approach

The TU Delft packing approach is a method which uses a parametric model called the Ship Synthesis Model (SSM) composed of 'system objects' describing the spaces and systems of the design. A packing algorithm generates ship designs based on this SSM and calculates their performances. These performances such as speed, weight or costs can be used to quantify how good a design is in terms of those specific metrics. These performances are fed to a genetic search algorithm which uses them to explore the design and performance space belonging to the SSM. Specific details of the SSM can be found in *van Oers (2011)*. This highly automated search process enables fast and extensive exploration of the design space in an early design stage, *Wagner (2009), Wagner et al. (2010), Zandstra (2014). Duchateau (2016)* extended the SSM method to the Interactive Evolutionary Concept Exploration Method (IECEM) which allowed for a more interactive exploration of the design space by including the designer in a feedback loop to the search process. Each of the designs exists of a set of performance metrics, dimensions and a description of the layout of the design. Until recently the results were mainly used to find the approximate dimensions of a vessel and to study the feasibility of a set of design requirements. This work will present a method that aims to understand the layout features of designs.

The packing design is based on a parametric 2.5D ship-design, *Van Oers and Hopman (2012)*. The 2.5D design describes a set of multiple 2D configurations which include a centreline, a port and a starboard slice. Objects in the vessels are placed mostly in the side-view, or x-z plane, of the design. The 2.5D approach introduces a variable width for objects and an available width for every position in the side-view of the design. This enables the packing-approach to fill a 2.5D space, instead of the necessity to describe the entire 3D space. This 2.5D approach is introduced to speed up the packing algorithm, where improvements in speed of a factor up to seven have been attainable, *Van Oers and Hopman (2012)*. This enables the packing algorithm to explore a wider design space by using a simpler model.

This study uses a design set generated for a small exploration cruise ship. The design set originates from *Droste (2016)*. As is discussed in detail in the following case study, the current set of designs showed several flaws in the arrangement and raised the question of whether it would be possible to improve our understanding of the relations between the systems and spaces within the packing approach.

1.2 Analysis of General Arrangements and Rationale Capturing

One of the biggest problems in generating general arrangements, is the analysis of the generated arrangement, *Hope (1981)*. When analysing multiple arrangements by hand, one might find a number of mistakes or aberrations in the physical allocation in the arrangement that are either unhandy or non-compliant to design prospects. For an experienced designer, it should be quite easy to disclose these issues in the design by hand; however, integrating this into computer interactive methods might be quite hard. Furthermore, analysing thousands of designs as generated by the packing approach is also difficult. There may several conflicting interests within the design specifications that algorithms might not be able to analyse in a coherent way. An automated way of general arrangement analysis would need a scoring metric for the algorithm to evaluate the arrangement and to allow direct comparison. The use of a comparative score improves the solutions in a spatial or topological model, as demonstrated by *Gillespie et al. (2013)*. They showed that analysis of a graph model of the design by partitioning and spatial community preferences can give guidance to the arrangement process of the allocation algorithms. To create a comparative score, quantitative assessment of qualitative properties of the designs is necessary.

In order to do this quantitative assessment, one needs to know what qualitative properties are desired in the design. Deciding what designs are either “good” or “bad” depends on personal preference and will most certainly lead to different design decisions between different designers. Since there is no singular “wrong” or “right” solution, but more commonly a “better” or “worse” approach to the problem, it is very hard to describe the rationale behind certain decisions. *DeNucci (2012)* introduced a method of capturing design rationale for complex ship general arrangement design. His method allows multiple naval architects to evaluate both desirable and undesirable features presented in one or multiple designs, accompanied by the underlying rationale. For instance, a generator room should not be placed adjacent to accommodation space to minimise noise levels in accommodation rooms. Using DeNucci’s method and rationale database as quality metrics, one can start to define what is the motivation between certain design decisions and start to analyse which of these decisions are better or worse for the total design.

To analyse these general arrangement rationales for large sets of packing generated ship designs, network modelling is used Network modelling is a mathematical representation of reality, using a collection of points joined by sets of lines, *Newman (2010)*. They are commonly applied to represent social or economic interactions. Since many different forms of information can be stored in these points and links, networks are applicable to many other fields of study including architecture and engineering. Since networks can be a simplified representation of complex systems, it is very suitable for application to the design of ship arrangements. This has been demonstrated by research at the University of Michigan, identifying drivers of arrangements, *Gillespie and Singer (2013)*, or the generation of applicable general arrangements for complex vessels, *Gillespie (2012)*, *Gillespie et al. (2013)*. Furthermore, *Rigterink et al. (2014)* used network theory to model and analyse disparate ship design information, including general arrangements. This paper will present a similar approach to arrangement representation in network form, and will propose a new scoring metric to analyse the generated networks.

2. Method

The method proposed in this paper will transform the designs as generated by the TU Delft packing approach into networks and apply a new scoring metric. This scoring metric will include DeNucci's rationale capturing method and uses this captured rationale to analyse the generated network arrangements.

2.1 Network science

A network or graph is a collection of points, called nodes, which are connected by lines, called edges. It is a simplified representation of a (complex) system, where only connectivity patterns are represented. Nodes within the network can represent any sort of object or entity, with edges showing connections or relations between these objects. A network can be weighted or unweighted. In an unweighted network, edges only show that there is a connection between nodes, whereas in a weighted network edges are given a value, which can add characteristics such as length or capacity to that certain edge, *Newman (2010)*.

This paper represents the layout of the design using an adjacency matrix, similar to *Gillespie (2012)*. For a simple unweighted network, the adjacency matrix **A** is described by the elements as seen in Eq.1.

$$\boldsymbol{A}_{ij} = \begin{cases} 1 \text{ if there is an edge between nodes i and j,} \\ \quad\quad\quad\quad 0 \text{ otherwise} \end{cases} \qquad \text{(Eq. 1)}$$

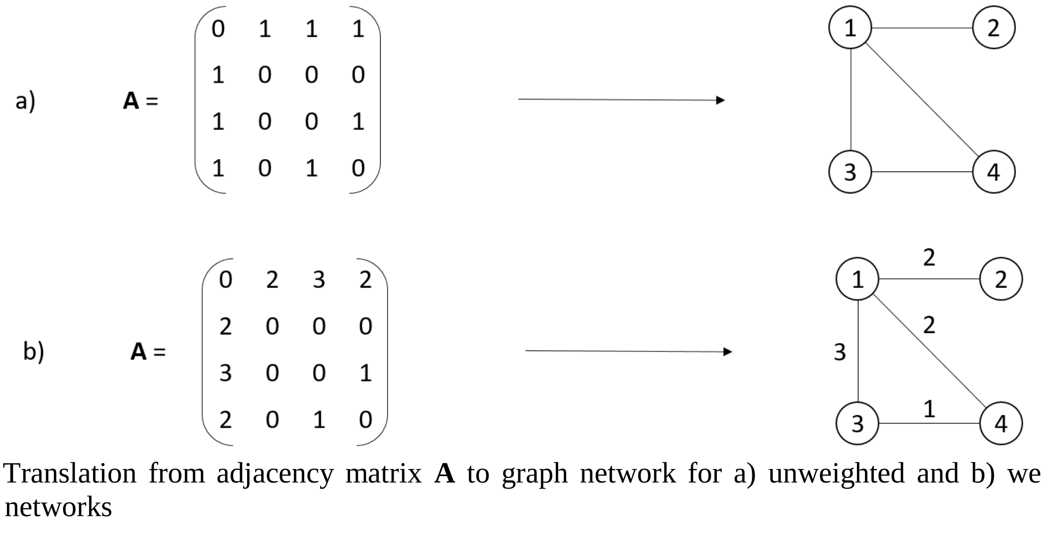

Fig.1: Translation from adjacency matrix **A** to graph network for a) unweighted and b) weighted networks

Adjacency matrices as defined in equation 1 are symmetric, since if there is an edge between i and j, there is also an edge between j and i. Evaluating the adjacency matrix, node and edge lists are established displaying all information of the nodes and edges of the generated network. More information on these nodes and edges can be added into the node and edge list, including weights and node properties. Fig.1 displays the differences in adjacency matrices and corresponding graphs for bot unweighted and weighted networks.

2.2 Generation and analysis of network arrangements

An analysis of spatial relationships is done to analyse which of the arrangements are more promising. Since the networks representing the general arrangements need to represent adjacencies and distances within the arrangement, weighted graph networks are used. Furthermore, the diagonal of the adjacency matrix will be zero, since no systems can be adjacent to themselves.

Nodes represent the "system objects" or individual spaces as pre-defined into the SSM of the packing approach. Whenever two system objects are on the same deck and neighbouring, they are considered to be adjacent. In matrix **A,** a 1 will be added for the objects that are adjacent, introducing an edge into the network. The node numbers, as presented in Fig.2, represent individual spaces.

A second adjacency matrix, **W**, is introduced to calculate the weight of the edges, defining the distance between spaces, of adjacency matrix **A**. Matrix **W** displays a connected weighted network, with values for the Manhattan distances between all objects. The Manhattan distance is the sum of the horizontal and vertical paths between two nodes and is therefore slightly larger than the direct Euclidian, distance. A Hadamard product, or element-wise multiplication, is taken between matrices **A** and **W**, creating a new weighted adjacency matrix **B** as seen in Eq.2. This matrix displays which systems within the design are adjacent and includes the distances between all connected systems. In order to allow transport of information through different decks, systems are connected to their corresponding staircase as they are defined by the International Maritime Organisation, *IMO (2000)*, and *Droste (2016)*. This explains why for example node 5 is not connected in network **A**, but is connected in network **B** in Fig.2.

$$\boldsymbol{B} = \boldsymbol{A} \circ \boldsymbol{W}, or\ \boldsymbol{B_{ij}} = \boldsymbol{A_{ij}} * \boldsymbol{W_{ij}} \qquad \text{(Eq. 2)}$$

Fig.2 gives a visual representation of the generation of these networks.

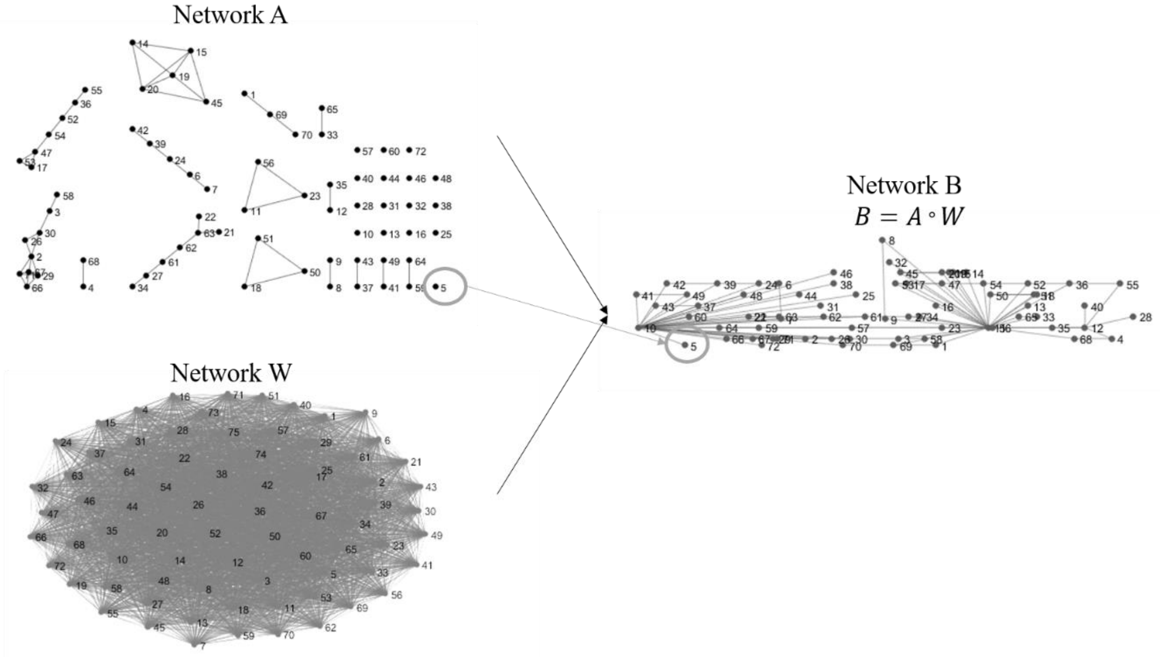

Fig.2: Network formation of packing design: network **A** displaying adjacent systems, network **W** a weighted connected network specifying all distances of systems and network **B** as the resulting network

2.3 Centrality measures

The method needs a way of ranking the adjacencies since the nodes in the network are not of the same relevance to the total arrangement. To create a ranking factor to each node or edge, this paper ranks the nodes by using centrality measures. Centrality can be used to give an indication of the importance or influence, and thus rank, of the nodes in the network. This can be done through multiple algorithms, which differ in complexity and objectives and might give slightly different results. Different centrality methods rate the nodes in different ways, where the "importance" of the nodes is different. "Importance" can be interpreted in many different fashions, similar to the trade-off of objectives in design decisions. For example, centrality based on flow of information will give a high importance to staircases where a lot of information spreads through the network. Two different centrality measures, eigenvector and betweenness centrality, are compared in this paper. More details on these centralities and corresponding algorithms can be found in *Newman (2010).*

The first centrality used is the eigenvector centrality. The eigenvector centrality is commonly used to describe the influence of a single node into the entire network. It is based on the fact that connections to other nodes with a high score are more valuable than connections to nodes with a lower score. For example, a generator room will be connected to many other important systems such as a propulsion room and fuel tanks. Therefore, a node connected to multiple nodes with a high score, will have a very high score itself. To calculate the eigenvector centrality, one needs to find the principal eigenvector $\boldsymbol{x}$ associated with largest eigenvalue λ as defined in Eq.3. Furthermore, the eigenvector is normalised to create an absolute score that can be directly compared between multiple networks. Each element in vector **x** corresponds to one of the nodes in the network representing its relative centrality score.

$$\boldsymbol{Bx} = \lambda \boldsymbol{x} \qquad \text{(Eq. 3)}$$

The second centrality measure used is the betweenness centrality. This centrality measures the extent of which a node lies on paths between other nodes. It is commonly used to analyse the flow of information through a network, since it can easily identify the influence on control of information between other nodes. A high value means that the node will have a high influence on the total flow of information through the network model. This flow can be anything, which in ship design can be used to describe flow in people or goods through the arrangement but also water during flooding. Values for each node can be calculated by Eq.4. For every node *i*, a centrality score x_i is introduced. n_{st}^i is 1 if the node is on the geodesic path between all nodes *s* and *t* and 0 if node *i* is not on this path or the path does not exist. When this is summed over all nodes *s* and *t*, one will get a number of shortest paths node *i* lies on. After dividing this by the total number of geodesic paths between nodes **s** and **t**, g_{st}, the score is normalized allowing direct comparison between networks.

$$\boldsymbol{x_i} = \sum_{\boldsymbol{st}} \frac{\boldsymbol{n_{st}^i}}{\boldsymbol{g_{st}}} \qquad \text{(Eq. 4)}$$

Fig.3 displays a simple unweighted network with eigenvector and betweenness centrality values for each node in Table I.

Table 1 – Centrality scores corresponding to network in figure 4

Node	Eigenvector Centrality	Betweenness Centrality
1	0.1580	0.3462
2	0.2403	0.3077
3	0.1917	0
4	0.1917	0
5	0.1157	0.3472
6	0.0513	0
7	0.0513	0

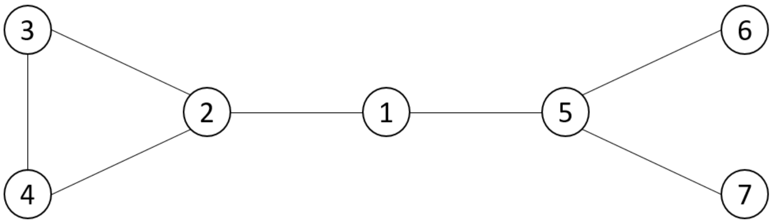

Fig.3: Simple unweighted network

This illustrates which nodes are emphasized by each centrality calculation. What can be seen is the exclusion of nodes 3, 4, 6 and 7 in the betweenness centrality method, because these nodes are on no shortest paths between other nodes. The eigenvector centrality gives a more even distribution of rank through the nodes. For the analysis of general arrangements, this means that there will be exclusion of certain spaces when using betweenness centrality, but will give peak scores on nodes in the system where a lot of information will flow through. Eigenvector centrality will give a more evenly spread out score through the network.

2.4 Capturing Design Rationale

The structure of the design rationale as captured by *DeNucci (2012)* is directly identifiable in the network formation of the arrangements. DeNucci's rationale capturing method developed a database of design rules that describes positive and negative aspects of physical relations or locations of certain systems. Rationale used to analyse the networks is taken from the database captured by DeNucci of seven naval architects at the Dutch Defence Material Organisation (DMO) in 2010. By analysing each edge of the system using these rationale rules, and evaluating the contribution of that connection, a complete qualitative analysis of the arrangement network is possible. Although the rationale lines are based on naval ship design, much of the rationale is applicable to general (complex) ship design. Rationale based solely on naval ship design has been removed from the data set to be able to setup a set of design rules that can be used for general ship design. The deleted design rules involve placement of weapon or radars systems. The proposed method introduces a way of analysing the strong and weak connections in the network.

2.5 Scoring metric

To rate the designs using the proposed method, a manual analysis of the edge list is done by using equation 5. Considering all established general arrangement rules, each edge in the list gets a score of x_i = [-1, 0 or 1] depending on whether it is disadvantageous, neutral or beneficial to the arrangement. The score of the edge is multiplied with the centrality scores of the connected nodes, z_{i1} and z_{i2}. This centrality score can be either the eigenvector or betweenness depending on the analysis. All edge scores are summed for all edges *i* to get a single score for the entire network. Thus, this metric accounts for all rationale and all spaces in the arrangement in a new quantifiable way. This is visually represented in Fig.4, with Eq.5 as the mathematical representation of the scoring method.

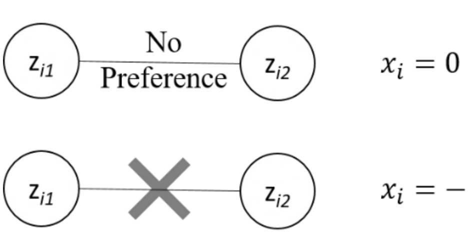

Fig.4: Visual representation of scoring algorithm

$Score = \sum_i \left(x_i * (z_{i1} + z_{i2})\right)$, with $x = [-1,0,1]$ for all edges i in network (Eq. 5)
z = centrality score corresponding to nodes *i1* and *i2*

3. Case Study

The case study explores the utility of this method and metric on the design of a small cruise vessel.

3.1 Identification of issues in chosen design

The cruise ship arrangements showed some flaws after closer inspection. Two examples of issues in the chosen design by *Droste (2016)* are the placements of the emergency generator and the hospital rooms. As shown in figure 5, the hospital rooms are placed adjacent on deck 8 and the generator room is placed within passenger accommodation on deck 7. Hospital rooms should be placed separated from each other to fulfil redundancy and survivability requirements, *DeNucci (2012).* For habitability objectives, it is not desirable to have the emergency generator placed within accommodation space, especially in cruise ship passenger accommodation. The following section will look into whether these cases can be identified in the network representation of the chosen design.

For redundancy goals, hospital rooms should not be placed in the same main vertical zone. Nodes representing the hospital rooms were identified in the node list to see whether they are placed in the same main vertical zone. After taking a closer look at the edge list, the edge between the two nodes representing hospital rooms exists, meaning that the hospital rooms are adjacent. Therefore, issues concerning direct adjacency or separation in main vertical zones can be identified in the network representation.

Analysing the placement of the emergency generator can be done in a similar way. Whereas an emergency generator should rather not be connected to passenger accommodation, or crew accommodation for that matter, edges between these nodes can be identified in the edge list and considered as bad connections. Fig.5 displays the network of 72 nodes plotted within the side view of the vessel.

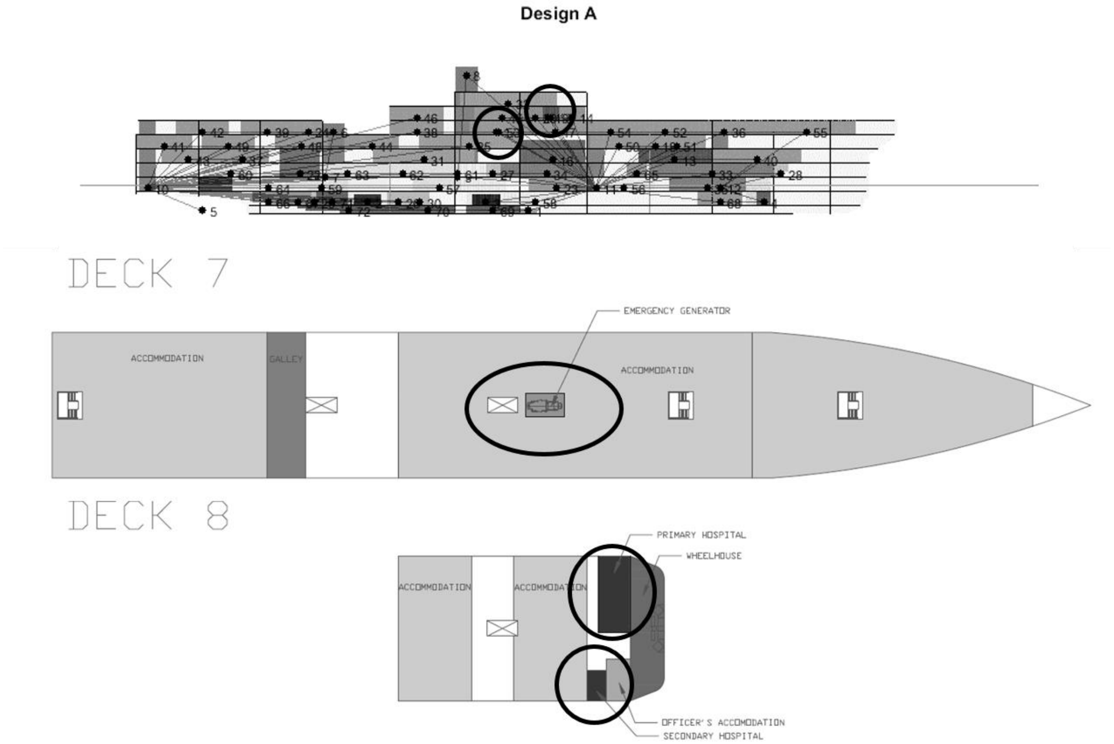

Fig.5: Network representation and deck views of design A, displaying the identified issues of the general arrangement

3.2 Application of scoring metric

However, this previous analysis requires manual inspection of the network and design to identify these problems. The proposed scoring method aims to give a quantifiable score to all arrangement rationale of the database. To test the method, two arrangements out of the cruise ship designs are analysed by the proposed metric. The first is the design as discussed in Fig.5, referred to as design A, the second is taken from the design set, where the issues mentioned earlier considering the emergency generator and hospital rooms are not present, design B. Main parameters of the two designs are given in Table II and a representation of both designs and networks in Fig.6. As is shown, both primary dimensions and internal layouts of both arrangements vary greatly between these two designs. Manual inspection of thousands of varying designs would therefore be intractable. The difference in number of nodes is due to system variations within the designs. Using the method, considering all rationale and systems, gives the scores for the analysed designs as presented in Table III

Table II: Main parameters of compared designs

Design	A	B
Length [m]	135	150
Displacement [m^2]	6907	10008
Cost [M€]	44.1	60.0
Number of nodes	72	74
Number of edges	122	125

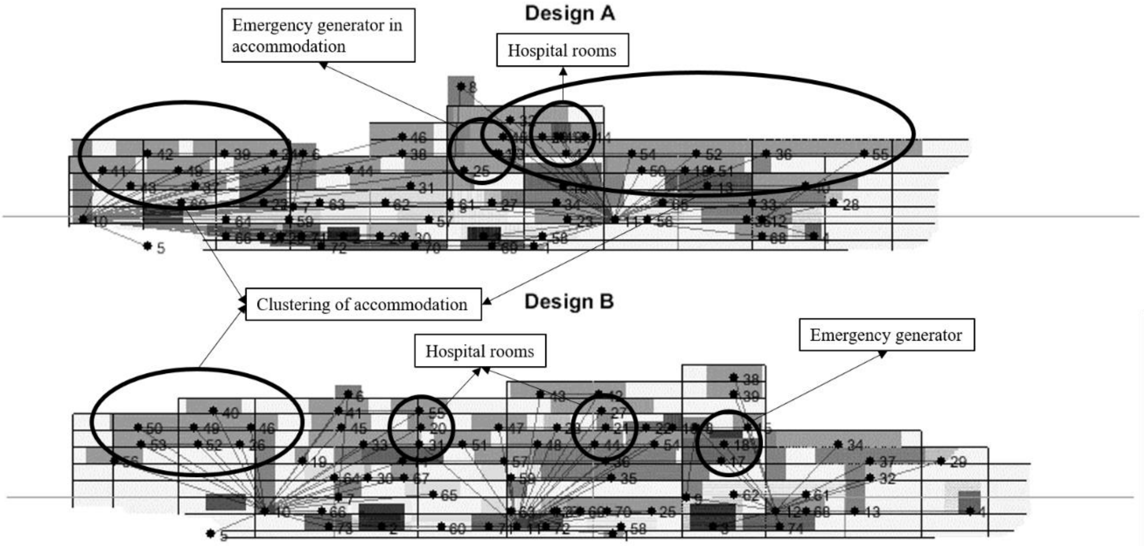

Fig. 6: Designs A and B with different placements of hospital rooms, emergency generator and both showing clustering of passenger accommodation

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Table III: Scores for the designs

Design	Eigenvector Centrality	Betweenness Centrality
A	0.4606	0.5693
B	0.4952	0.3416

One sees that for the different centrality metrics, the highest scoring design differs, identifying that there are differences in the type of analysis. Manually looking at the scores for each node, betweenness centrality gives a higher value for stairs than eigenvector centrality, since these are on a lot of paths because of the nature of the system type. However, there are few design rationales regarding the placement of the staircases in the database. Evaluation of the edges connected to staircases will mostly get no preference. This means that even though these nodes get a high centrality rank, they do not necessarily get a high centrality score.

Apparent is that passenger accommodation contributes a lot to the high score for design A. In the case of betweenness centrality, analysis of the node list shows that accommodation accounts for 0.29 of the total score. In design B, this value is only 0.11. This is likely due to accommodation systems being more clustered in design A, as seen in Fig.6. A same trend can be found in crew accommodation, although the difference is slightly smaller. This can be explained by the fact that there is less crew accommodation than passenger accommodation present in the arrangements. Furthermore, design B has two accommodation systems that are highly penalized by the betweenness centrality because of a connection with a technical/auxiliary systems room. Looking at eigenvector centrality, the score for accommodation placement is 0.16 for both designs. An overview of the breakdown of these scores can be found in Table IV.

Other areas where design A scores better, especially on betweenness centrality, is the placement of the generator rooms. As generator rooms are of high importance to the vessel, there are quite some rationale rules based on the placement of generator rooms. Connections to the generator room are often regarded as positive or negative instead of neutral and are therefore highly represented in the score.

The poor placement of the emergency generator room in design A does not get penalized by betweenness centrality since it is not on any shortest paths, due to the transport through the accommodation surrounding the generator. It is therefore not visible in the betweenness centrality score. It is however penalized in the eigenvector centrality score, accounting for a subtraction of 0.01. This is rather small when comparing to accommodation scores, which lies in the fact that it only involves one node instead of twenty nodes in the case of passenger accommodation.

Because betweenness centrality can give a value of 0 for nodes on no shortest paths, the number of evaluated nodes decreases. For design A, 30 nodes get a betweenness centrality of 0, for design B this number is 38. This is about half of the total number of nodes, which is similar to the simple network in Fig.3. Since these are nodes that are on the ends of paths, these are primarily propulsion rooms and bridge or entertainment systems that are located on the ends of the vessel and are thus not reflected in the betweenness centrality score.

Stating that design A is “better” than design B, depends on the designer’s view. Design B better represents designer’s overall rationale as it pertains to the layout of the general arrangements, as is shown by its eigenvector centrality score. However, if a specific designer is more interested in personnel flow through staircases, design A would be preferred, according to betweenness centrality score. By using this metric, one is now able to give a score to these properties of the general arrangements.

4. Discussion

The first question to be asked is whether quantitative assessment of qualitative properties of the arrangement is possible. The answer to this is yes, using network analysis it is possible to give a score to a general arrangement generated by the packing approach. In order to do this, general arrangement design rationale has been applied, which can be captured in methods as described by *DeNucci (2012).* This is an improvement in the current design decision process of the IECEM, as it now includes analysis of interior design arrangement of the vessel. However, using a single score for the total analysis of the design enables direct comparison, but makes traceability of high or low scores in different objectives difficult without the use of sensitivity studies.

The second question is which of the compared centrality measures would be more promising. Comparing eigenvector and betweenness centrality measures, eigenvector seems to be more applicable for this type of arrangement analysis. This originates from the fact that it is commonly used as a normalized rank and takes all nodes into account in a more similar value in comparison to the betweenness centrality analysis. The betweenness centrality excludes nodes that are on no paths and easily overrates certain nodes in the system that carry a lot of information, such as staircases. Furthermore, the analysis is completely based on the user’s (in this case the authors’) interpretation of the rationale database and implementation of the design rules. Overrating of nodes by betweenness centrality does not seem to be a big problem, since nodes as staircases do not have a lot of beneficial edges within the design rationale. It does however give a bigger penalty on poorly placed accommodation due to the normalization of the betweenness centrality score. Betweenness centrality analysis is applicable in other types of analysis, such as flow analysis in evacuation cases.

What makes concept design complicated, especially applied to complex ship design, is the fact that it cannot directly be validated by existing ship design. Analysis is done in a preliminary ship design phase, where there are still a lot of unknowns and uncertainties in the design and a lot of design decisions are still to be taken. The new method allows the use of captured rationale and shows how certain decisions score in the design trade-off.

5. Conclusion

The authors have developed a scoring metric, that is able to quantitatively identify qualitative properties of designs generated by TU Delft packing approach or IECEM. By converting the designs into weighted networks, a new representation of the packing generated designs is acquired. Using rationale captured by DeNucci, edges in these networks are analysed and identified based on their influence on the arrangement. This gives an overall score of the general arrangement of the packed design allowing the designer to make decisions not merely on costs or primary parameters, but also take the interior design of the vessel into account and allow direct comparison.

6. Recommendation for future work

The method proposes a beginning in the semi-automated analysis of the arrangements of packing generated designs. Future work includes a higher level of understanding of the results of the scoring metric. Understanding differences in scores between different networks should give more insight in how this score can be used, for example as a filtering measure for lower quality arrangements. By filtering, the designer would be able to improve awareness of the quality of the arrangement during design decisions. The networks could be generated in different ways, implementing directed networks or layered multiplex networking. It will be interesting to see if the method is also applicable to different datasets of arrangements generated by the packing approach or other concept exploration methods. Furthermore, the networks could be used together with a search tool algorithm as a filter to look for those designs that either include or lack certain edges.

The biggest next step is the application of this method to an entire dataset. In order to do so, the design rules need to be incorporated into the programming of the network generation. Being applied to the entire dataset, one can use it as an extra objective function for Pareto optimization, or even as a performance input in the genetic search algorithm in the packing approach. Furthermore, it can be used to assess the quality of the layout and filter the dataset of poor quality arrangements.

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A Smart Modular Wireless System for Condition Monitoring Data Acquisition

Anna Lito Michala, University of Strathclyde, Glasgow/UK, anna.michala@strath.ac.uk
Ioannis Vourganas, University of Strathclyde, Glasgow/UK, ioannis.vourganas@uni.strath.ac.uk

Abstract

Smart sensors, big data, the cloud and distributed data processing are some of the most interning changes in the way we collect, manage and treat data in recent years. These changes have not significantly influenced the common practices in condition monitoring for shipping. In part this is due to the reduced trust in data security, data ownership issues, lack of technological integration and obscurity of direct benefit. This paper presents a method of incorporating smart sensor techniques and distributed processing in data acquisition for condition monitoring to assist decision support for maintenance actions addressing these inhibitors.

1. Introduction

Common practices in condition monitoring of the shipping industry have been resilient to change as the industry in general is often reluctant to engage new technologies and computerised systems, *DNV GL (2014)*. Several barriers are often recognised with the most prominent being trust in the technology, security, proprietary data and ownership as well as data transferring to shore, *DNV GL (2014), Latarche (2015)*. One of the main drivers also is that the direct benefit of implementing such technologies is not clearly identified by several key stakeholders in the ship operator or ship owner organisations, *Adamson (2016a)*. However, despite the barriers, in 2015 Big Data growth and importance for the industry has exceeded their predicted trends, *Adamson (2015)*. In that respect, an increasing need is expected for systems that manage and translate the collected data to information that is relevant and useful for the industry.

An area that is particularly expected to generate a large amount of data in the upcoming years is Condition Monitoring (CM). As more ships embrace the continuous monitoring approach the influx of data is expected to exponentially increase. Several technological advances relevant to CM include smart sensors, distributed data processing and the cloud. However, systems that utilise these are not yet widely available in the shipping environment.

The system presented here is based on a smart sensor technique and distributed processing for condition monitoring. Also, it introduces the concept or sensor-servers. The sensors utilised are well established technologies in the condition monitoring sector for marine engines. The presented system's approach is in collecting and pre-processing data relevant to vibration, temperature and pressure prior to wirelessly transmitting it to a central collection point onboard a vessel. Moreover, the smart collection unit (SmartDAQ) is able to derive events from the data at the remote location; thus, prioritising messages based on importance. This reduces the amount of transmitted data and also power required to operate the wireless communications chip. Furthermore, it tackles some of the most prominent issues with modern wireless data recording systems such as false data and gaps in data streams finding their way into the database. The data is then post-processed to assist decision support (DS) for maintenance actions that engineers can take onboard the vessel. These actions are suggested by the DS software based on the recorded condition. The system can connect to a server based database allowing secure data transfers to shore over the internet for further processing if required.

As the system is based on a modular approach in both the components and the algorithms developed, it is able to support integration of new technologies and provide a base for future large scale systems. Hence, answering an existing need for low cost platforms for both academic and industrial projects. For example, as the Cloud matures and internet on ships becomes a lower cost commodity, *Adamson (2016b)*, http://www.satbeams.com/satellites?id=2571, the system could incorporate a new module that allows for reliability analysis to take place on the cloud instead of the local computer onboard the ship. In fact, any substitution of any of the algorithms could be performed independently of the rest of the system thus providing an ideal ground for development and expansion.

2. Methodology

This section presents the methodology followed to develop a novel system that satisfies the industry requirements presented in the previous section. A Systems' Engineering approach was followed in developing the methodology, *INCOSE (2016)*. This approach was further extended to incorporate all the requirements of the system as well as a thorough academic approach and is presented in Fig.1.

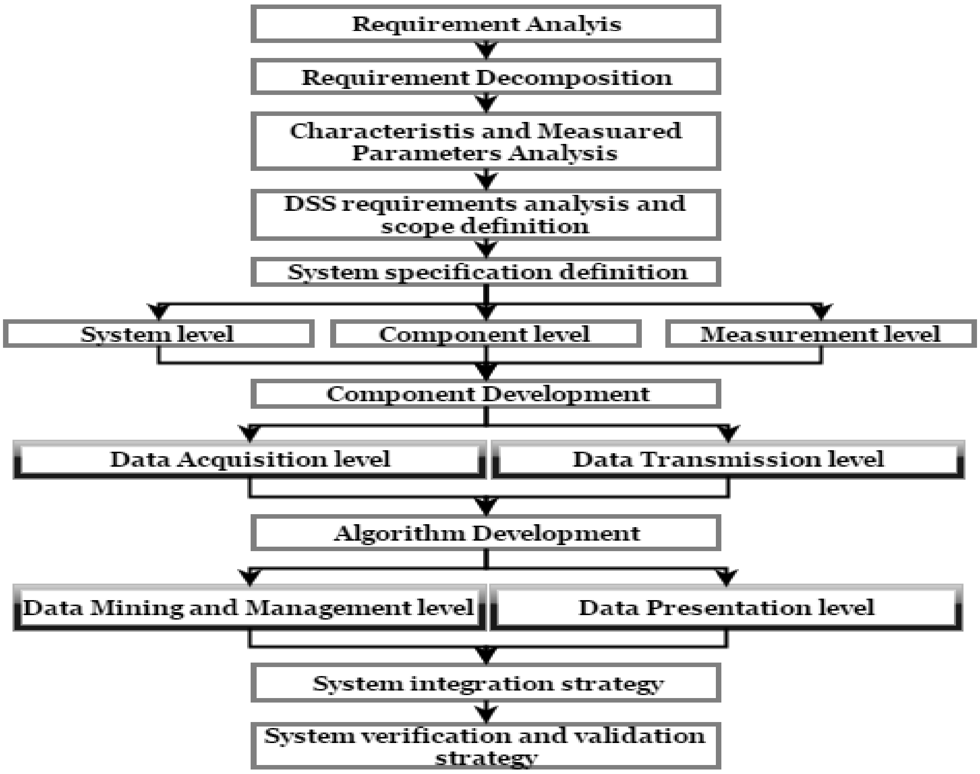


Fig.1: Methodology

Initially a thorough analysis for the requirements was performed which was based on the outcome of a critical literature review of the condition monitoring solutions and research approaches available in shipping and other industries. The key findings of the literature review demonstrated that there is a lack of large scale strategy for whole ship CM and that there is a slow industry uptake mainly due to cost versus benefit barriers. More specifically, system requirements were identified as allowing a large variability of monitoring objectives through a modular approach, providing a low-cost capital investment solution while making the direct benefit and impact more prominent and relevant through appropriate processing and presentation of results. Additionally, reduced personnel training was an identified requirement. Finally, the system must provide an output that is easily integrated with a variety of maintenance strategies but ultimately provides better Class Condition, reduces maintenance costs and has a positive impact on energy efficiency, *Michala et al. (2015,2016)*. Thus, a large complex system is required to provide a suitable and feasible solution to satisfy these requirements.

Based on the analysis of existing CM approaches as well as commercial systems the minimum measured parameter requirements include vibration, pressure and temperature. Also, the ship movement profile should be recorded so that changes in the data can be correlated to the speed and weather conditions extrapolated from the three-axis acceleration and rotation of the ship. Finally, speed is an often recorded parameter for rotating machinery but as vibration is recorded this was considered a secondary requirement to be added to the system on a later stage.

Based on the requirements for identifiable and direct benefit of CM, the proposed system incorporates a Decision Support System. As such, the relevant information extracted from the data can be used to directly affect the maintenance actions and at the same time relate the condition of the ship to cost. For example, reduced performance from degradation of a specific component can be quantified as cost due to underperforming. In that respect, a strategy that commands high performance could utilise the DSS to estimate which maintenance actions would increase the performance of the ship. Performance is also directly affecting energy efficiency so DSS output with high performance costs would also indicate high energy related costs. Overall, the correlation of condition to cost can prove useful for not only the day to day operation but the overall long term maintenance planning and scheduling strategy. However, there is a minimum amount of monitoring requirements that is necessary for the DSS to provide accurate output. This includes monitoring of the main engine’s fuel oil, cooling and lube oil system as well as bearings and where applicable the turbo charger. Moreover, bearings of the propulsion system and auxiliary engines would be important to increase the relevance and accuracy of the DSS. As the system is modular though, a smaller set of components could be initially measured. However, such an option would only be able to provide relevant information for part of the ship’s machinery and equipment.

Considering the requirements, measured parameters and DSS requirements the specification definition identifies the most appropriate system as a modular versatile system that has four main layers. The first layer is data acquisition and includes the SmartDAQ component that is presented in the following section. The second layer is the data transmission for which a wireless method was selected. Then there is the data management and mining layer that describes a two phase of pre and post transmission processing and a system for data management that is also presented in the following sections. Finally, the last layer is the data presentation which is the DSS system, also presented in the next section.

3. Smart Modular Wireless System

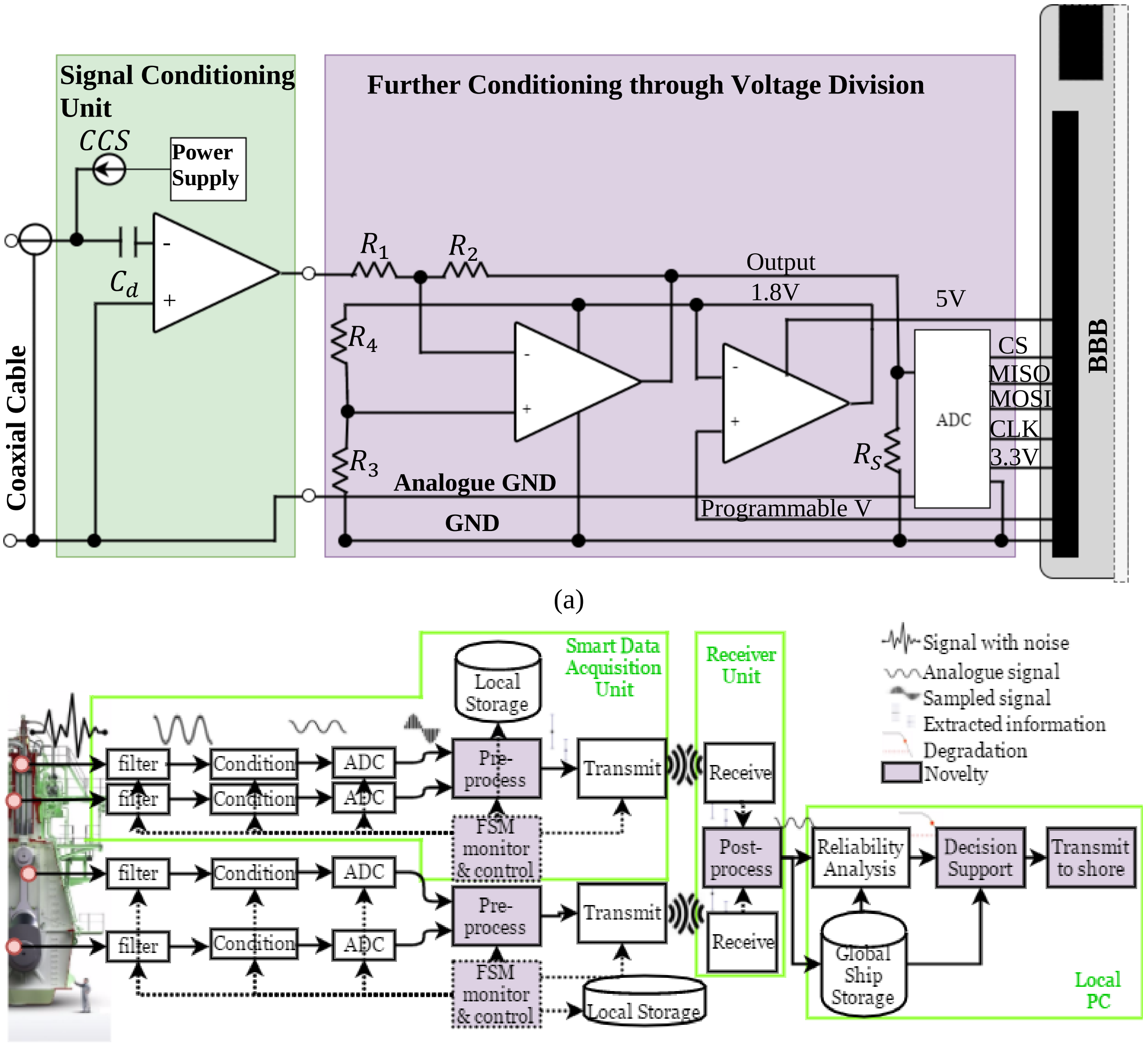
The outcome of the development process based on the above specification is presented in Fig.2. The integrated system is comprised of two physical components, the SmartDAQ component and the receiver unit. In terms of software architecture there are four main components. The pre-processing component, the Finite State Machine (FSM) monitoring and control component, the post-processing component and the reliability, DSS and transmission to shore component.

The Smart DAQ component is comprised of a set of analogue electronics that collectively provide the signal conditioning necessary for valid input to the system, an Embedded Linux Platform and a wireless transmitter. The analogue electronics configuration (Fig.2.a) was developed so that it could be printed on a Beaglebone Black (BBB) cape. On the other hand, the Receiver Unit is comprised of a receiver and a connector to the local PC which is available in the control room. At this point it is assumed that the receiver is in the control room.

By distributing data processing a Cloud inspired approach provides the ability to harness processing power at the edge of the network in a sensor-server fashion. The network of SmartDAQ units can utilise the high processing capabilities of the embedded Linux platform and at the same time minimise the message load of the wireless transmission channel. In that respect, the cross-talk noise between the nodes of the network can also be minimised providing better Quality of Service (QoS). The pre-processing component is an information extraction mechanism that has two main targets:

1) to capture mean, standard deviation or Fast Fourier Transform of the recorded signal and

2) to record events. Events are data points that are outside the “normal” expected range and identified as alarm conditions. Alarm conditions can be either values indicating the necessity of immediate crew action or conditions indicating that the machinery/equipment is not in operation.



(a)

(b)

Fig.2: SmartDAQ (a) and Integrated System (b)

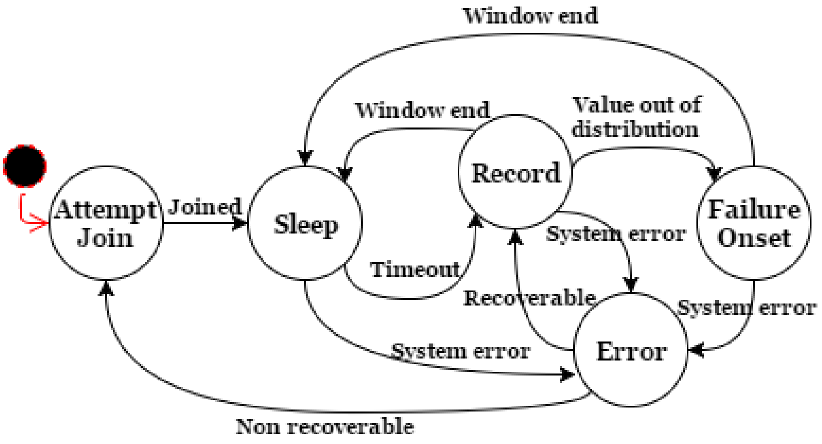


Fig.3: Smart DAQ state machine definition

To meet requirements of power consumption the FSM, monitoring and control unit oversees the operation of the Smart DAQ component. The FSM is presented in Fig.3. Moreover, the system can be contacted from the main collection point with commands that allow the central node to monitor the condition of the network, the statistics of network operation and the error conditions of the Smart DAQ. Finally, the central collection point is able to send commands to each Smart DAQ that allow for the maintenance of the wireless network including healing, removing nodes and forcing the FSM into certain states. This way a remotely located user with appropriate access rights can manage the network without necessitating physical interaction with the Smart DAQ component.

The post-processing component manages the incoming information and is tasked with providing an output that is similar to the initial data stream recorded by the sensor. In that respect, the pre-processing component is hidden to any components requiring the output of the post-processing component. That isolates the physical components and their particulars. The output of the post processing component can be used by any existing analysis method already available. However, this paper proposes an analysis that provides suitable DSS input to the identified requirements.

As part of the proposed system the MRA tool presented in the INCASS project was used for the next step of the analysis of the post-processing output, INCASS (2015). This tool accepts input as raw data which is here provided by the post-processing component and through reliability analysis produces degradation per failure mode per ship machinery/equipment system, sub-system and component. This tool is particularly useful as the output is suitable input for the DSS component. The degradation and association to failure mode is crucial for the identification of relevant maintenance action. However, it requires special training of the crew in order to understand this information and translate it to relevant actions. Therefore, the reliability analysis tool is necessary for the system but the DSS component enhances the system as it is able to directly demonstrate tangible benefits to the user without mandating any training. Thus, satisfying one of the identified requirements.

As a first step the DSS tool identifies which machinery/equipment components are more likely to demonstrate degradation in the forecasted period and priorities them according to likelihood. A system of weighted probabilities is used for this classification as described by Eqs. 1 and 2.

$$\mathrm{W_{c_k}} = \frac{\mathrm{L_{c_k}}}{\sum_{\mathrm{i=1}}^{\mathrm{m}} \mathrm{L_{c_i}}} \qquad (1)$$

$\mathrm{W_{c_k}}$ is the weighted contribution, $\mathrm{k} = 1 \ldots \mathrm{m}$ and m is the number of components contributing to the sub-system under investigation.

$$\mathrm{N_j} = \frac{\mathrm{L_j} \times \mathrm{W_{c_x}}}{\sum_{\mathrm{i=1}}^{\mathrm{n_1}} \mathrm{L_i} \times \mathrm{W_{c_1}} + \sum_{\mathrm{i=1}}^{\mathrm{n_2}} \mathrm{L_i} \times \mathrm{W_{c_2}} + \cdots + \sum_{\mathrm{i=1}}^{\mathrm{n_m}} \mathrm{L_i} \times \mathrm{W_{c_m}}} \qquad (2)$$

$\mathrm{N_j}$ is the contribution of the failure mode $\mathrm{j} = 1 \ldots \mathrm{l}$and l is the total number of failure modes of all the components contributing to the sub-system under investigation, m is the number of components contributing to the sub-system under investigation, $\mathrm{W_{c_x}}$ is the weighted contribution of the component under which failure mode j is listed and $\mathrm{n_1}, \ldots, \mathrm{n_m}$ are the numbers of failure modes listed under each component $\mathrm{c_{k=1 \ldots m}}$.

As a second step the DSS further processes each of the components expected to have failures and identifies the optimal action to suggest. The optimisation is formulated as a multi-objective multi-constrain problem. The failure mode set $\mathrm{M_h} = \{\mathrm{m_1}, \mathrm{m_2}, \ldots, \mathrm{m_n}\}$ and the action set $\mathrm{A_h} = \{\mathrm{a_1}, \mathrm{a_2}, \ldots, \mathrm{a_g}\}$ associated with a failure mode of component/subsystem/system $\mathrm{K_h} \in \mathrm{K}$ were defined where K is the set of monitored components, subsystems and systems on the ship. The function $\mathrm{L(a, m)}$ is true if an action a is associated with a mode m. Also the set of available parts $\mathrm{P_h} = \{\mathrm{p_1}, \mathrm{p_2}, \ldots, \mathrm{p_j}\}$ associated with $\mathrm{K_h}$was defined. The function $\mathrm{U(a, p)}$ is true iff a part p can be used within action a in order to perform the action successfully.

The problem is to find a feasible solution to the partial function F (Eq.3). Where $\mathrm{E} = \{\mathrm{a_1}, \mathrm{a_2}, \ldots, \mathrm{a_l}\}$ is the set of actions for which there are expertise available on the ship and $\mathrm{W} = \{\mathrm{a}_1, \mathrm{a}_2, \dots, \mathrm{a}_z\}$ the set of actions that can be executed under the particular weather conditions. F is an assignment of actions for each component/subsystem/system while obeying the constrains. As F is a partial function the actions that belong to the domain $\mathrm{dom(F)}$ are the selected actions. The constrains of the system are expressed in Eqs.4 and 5. Also the secondary objective is the minimisation of Eq.6.

$$\mathrm{F}: \mathrm{A_h} \rightarrow \{\mathrm{E}, \mathrm{C}\} \rightarrow L \wedge U = 1 \tag{3}$$

$$\forall \mathrm{a}_i^h, \mathrm{a}_j^h \in \mathrm{A_h},\ \left(\mathrm{a}_i^h \in \mathrm{dom(F)} \wedge \mathrm{a}_j^h \in \mathrm{dom(F)}\right) \Rightarrow \mathrm{i} = \mathrm{j} \tag{4}$$

$$\forall \mathrm{a}_i^h \in \mathrm{A_h}: \left(\mathrm{L}\left(\mathrm{a}_i^h, \mathrm{m}_i^h\right) \wedge \mathrm{U}\left(\mathrm{a}_i^h, \mathrm{p}_i^h\right) \wedge \left(\exists\ \mathrm{a}_i^h \in \mathrm{E} \cap \mathrm{W}\right) \right) \Rightarrow \mathrm{a}_i^h \in \mathrm{dom(F)} \tag{5}$$

$$\min(\mathrm{C_T}) \tag{6}$$

Where $\mathrm{C_T} = \mathrm{C_E} + \mathrm{C_S} + \mathrm{C_A} + \mathrm{C_M} + \mathrm{C_P} + \mathrm{C_C}$ but the individual costs may have competing conditions. The sub-costs are relevant to company costs originating from ‘Environment’ ($\mathrm{C_E}$) regulation related charges, ‘Safety’ ($\mathrm{C_S}$) related charges, ‘Asset’ ($\mathrm{C_A}$) purchasing, ‘Maintenance and Operation’ ($\mathrm{C_M}$), ‘Performance’ ($\mathrm{C_P}$) and ‘Commercial Penalties’ ($\mathrm{C_C}$) related to delays in delivery amongst others. The optimisation computation provides an initial allocation of optimum action suggestion. However, as the system records more information it is able to adapt to actions that have been successful in demonstrating a beneficial correction to the degradation curve. This is achieved through a machine learning algorithm presented in Fig.4.

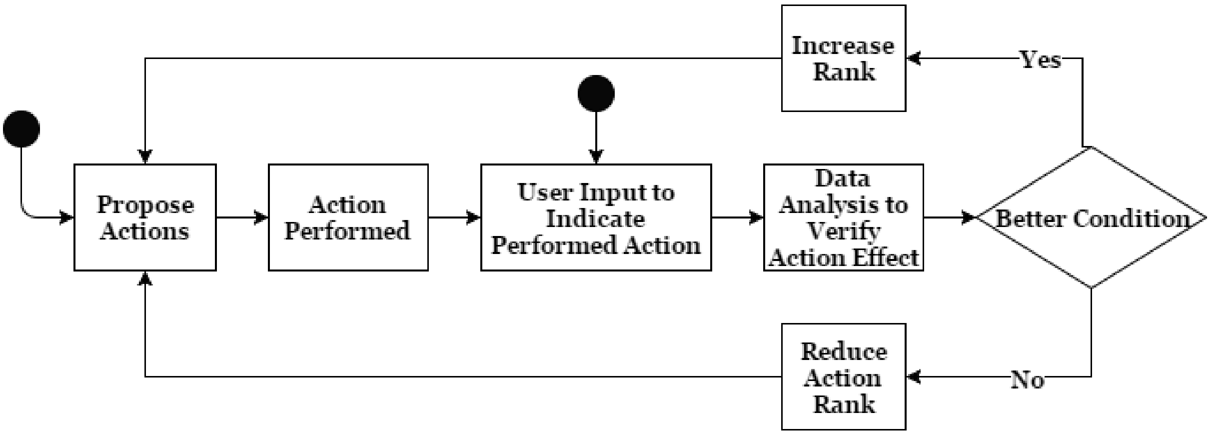
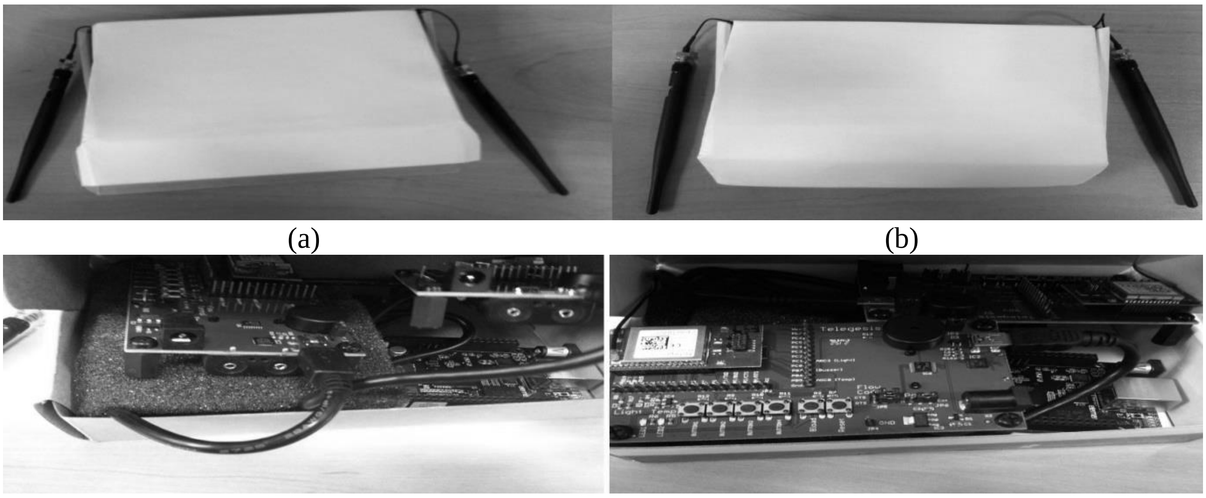


Fig.4: Adaptive action suggestion based on collected information

5. Case study

The case study presented in this section is concerned with demonstrating the systems capability of managing large load of recorded data. To evaluate the load handling capabilities of the system the performance of the network is recorded in regards to the number of attempts required for a message to be successfully delivered. Additionally, this is an indication of the system’s reliability as well as the network’s QoS. Finally, the secondary objective of this case study is to verify that the data delivered by the post-processing tool to the reliability analysis tool are valid.

To simulate high load, 8 virtual sensors were enabled on each SmartDAQ unit and total of 4 SmartDAQs were deployed (Fig.5). Moreover, a 5th Smart DAQ was deployed with 6 virtual sensors plus one actual sensor (Fig.6a). Finally, a single collection point was connected to a PC (Fig.6b). The PC was updated with the required software components to enable the post-processing, reliability analysis, DSS and transmission to shore components. Virtual sensors were used instead of actual sensors for most of the SmartDAQs in this case study because there were no sufficient number of physical sensors available in the laboratory engine room to provide a significant load to the system. A virtual sensor is a bypass of the signal conditioning hardware as the readings are not sampled from the analogue input of the board. Instead the sampling unit is wired to a board analogue output. An additional component is enabled per sensor to read data from a file and send it to the analogue output. The system operates as if it was reading an actual wired signal through the analogue input. Hence, the process is imitating an actual sensor connection and respects the integrity and coherency of the presented system components. Each Smart DAQ was housed in a small non-metal box to protect the wiring (Fig.5a, 5b) apart from the one connected to the actual sensor (Fig.6a).



(a) (b)

(c) (d)

Fig.5: Four SmartDAQs with virtual sensors: (a) and (b) housing and antennas, (c) and (d) wireless transmitter development boards and embedded Linux boards, battery powered.

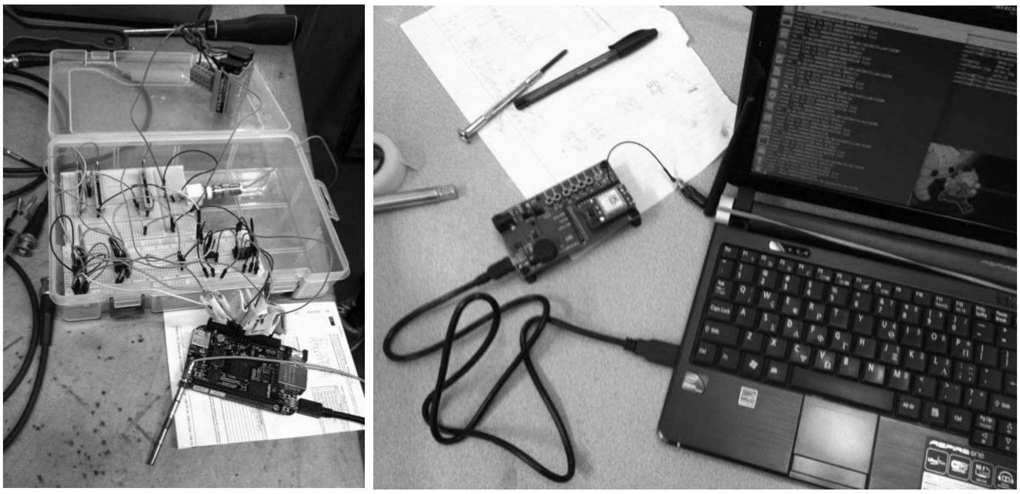


Fig.6: Board connected to signal conditioning circuit and sensor (left) and receiver board connected to local PC (right).

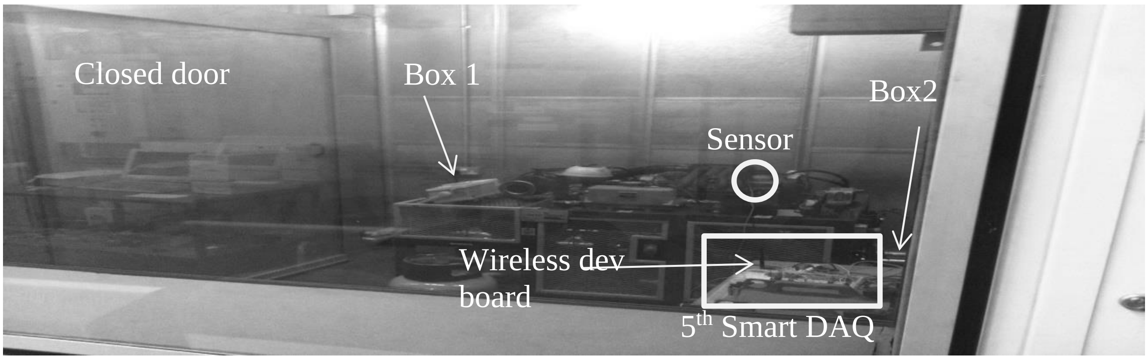


Fig.7: Deployment in Engine Laboratory, image captured from control area through the glass window

The installation at the laboratory engine room allowed for all 5 Smart DAQs to be deployed inside the engine room and the collection point located outside (Fig.7). The engine room is a metal box with a glass window that looks outside to the control area. By closing the door between the engine room and the control area conditions of higher interference from cross-talk noise and reflexion from the metal were generated in the room. The two boxes were installed at the floor behind the engine to increase the distance from the glass window as much as possible and increase the interfering obstacles.

The data supplied to the virtual sensors were data recorded on an existing ship during voyage. In total the 38 virtual sensors corresponded to measurements recorded by actual sensors installed on machinery and equipment of the ship. The list of measurements is presented in Table I. Moreover, the physical sensor was installed to record pressure in one of the cylinders of the engine available at the laboratory. In Table I the temperatures were recorded in degrees °C and the pressures in Kgr/cm^2.

Table I: Measured parameters from ship's main engine

No.	Measurement	No.	Measurement
1	Thrust Bearing LO Outlet Temp	**20**	IntShaft 1 Bearing Temp
2	TCLO 1 Input Press	**21**	IntShaft 2 Bearing Temp
3	TCLO 1 Input Temp	**22**	IntShaft 3 Bearing Temp
4	TCLO 1 Output Temp	**23**	Main Lube Oil Input Pressure
5	TCLO 2 Input Press	**24**	Main Lube Oil Input Temperature
6	TCLO 2 Input Temp	**25**	Cylinder Input JCFW Pressure
7	TCLO 2 Output Temp	**26**	Cylinder 1 Output Exh Gas Temp
8	Scav Air Manifold Press	**27**	Cylinder 2 Output Exh Gas Temp
9	Scav Air Rec 1 Temp	**28**	Cylinder 3 Output Exh Gas Temp
10	Main Engine Start Air Press	**29**	Cylinder 4 Output Exh Gas Temp
11	Piston CO Input Press	**30**	Cylinder 5 Output Exh Gas Temp
12	JCFW 1 Output Temp	**31**	Cylinder 6 Output Exh Gas Temp
13	JCFW 2 Output Temp	**32**	Cylinder 7 Output Exh Gas Temp
14	JCFW 3 Output Temp	**33**	Cylinder 8 Output Exh Gas Temp
15	JCFW 4 Output Temp	**34**	Aft Camshaft Bearing Temp
16	JCFW 5 Output Temp	**35**	Fore Cam Bearing Temp
17	JCFW 6 Output Temp	**36**	Exh Gas Output After Turbo Charger 1 Temp
18	JCFW 7 Output Temp	**37**	Ex Gas Output After Turbo Charger 2 Temp
19	JCFW 8 Output Temp	**38**	Main Engine Control Air Input Press

6. Results

For the above case study this section presents the results. An analysis of the network performance demonstrates that out of the 4176 transmitted packets per sensor over a period of one month there were no packets lost. Moreover, the transmission was successfully received and acknowledged in the first attempt for 90.53% of the cases. A second attempt was necessary for 9.09% of the packets while a statistically insignificant 0.38% of packets required three or more attempts. The standard variation was 5.98, 5.85 and 0.41 respectively for each attempt classification. There were no received packets that were delivered out of sequence and all messages were reconstructed successfully for all the sensors. Fig.8 demonstrates the analysis for the 39 sensors where the sensor instance corresponds to the number presented in Table I above for sensors 1 to 38. Moreover, sensor instance 39 corresponds to the physical pressure sensor.

During the test period no interventions were made to the network and one type of event was recorded. This event type was created due to the physical pressure sensor recording values near 0 Kgr/cm^2 as the engine was not operating. Moreover, some virtual sensors also reported values near 0. The messages reporting events were transmitted asynchronously to the recording mode so they took priority over the recorded data packets and arrived within seconds of their generation alerting the user of the change in operating condition promptly. The system performed unobstructed and the statistical performance of the network was requested at the end of the recording period through the designated remote command. The transmission attempts for each packet were logged on each Smart DAQ locally and were analysed at the end of the case study recording period. No other issues were recorded and no failures of the Smart DAQ system were observed in this period.

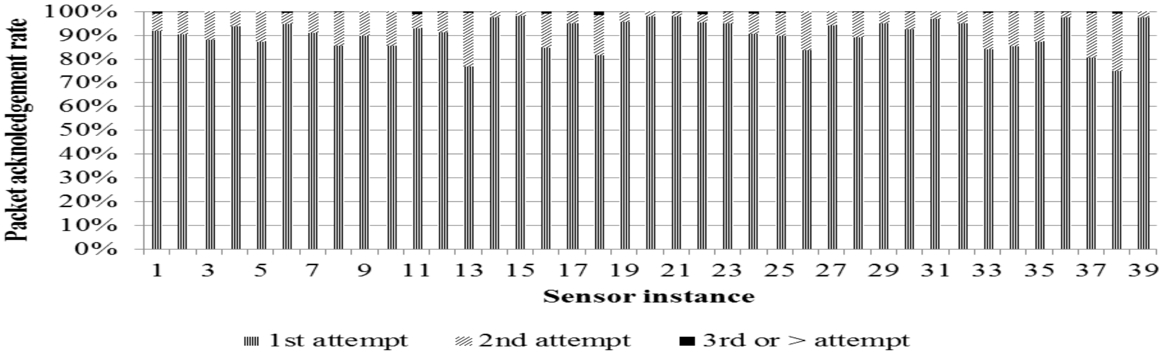


Fig.8: Packets successfully received for each sensor on 1st, 2nd or later transmission attempt

Fig.9 presents the network traffic load in Bytes per day during the experiment. The minimum possible if all packets were sent only once was recorded to be 5616 Bytes for the pre-processed data case while calculated at 43200 Bytes per day if data was to be sent directly in the raw format. This analysis includes the bytes used for the custom message protocol created for this system but does not include the information that is also appended to the messaged by the ZigBee protocol envelop.

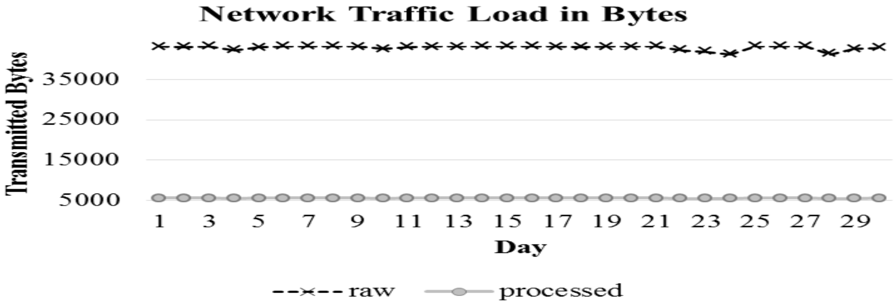
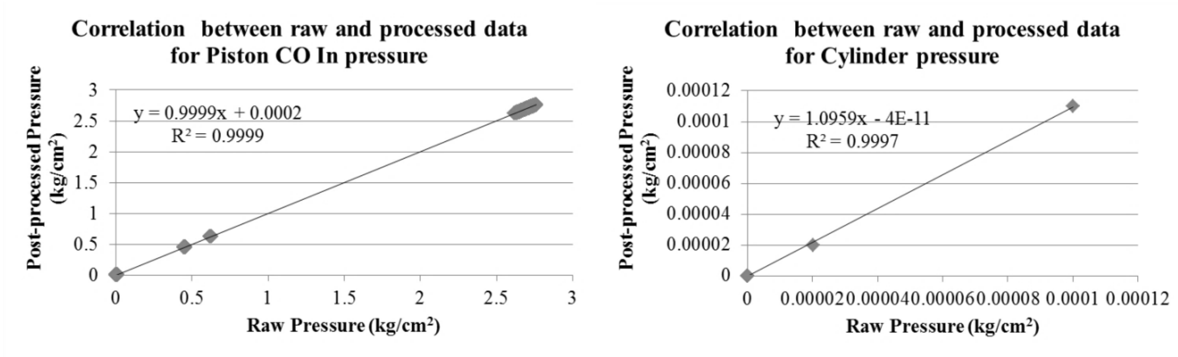


Fig.9: Number of bytes transmitted after pre-processing against raw data bytes throughout the month

After the data was received at the receiver unit, each stream was post-processed independently and the data received for each time window were decomposed to a stream of data points to cover the full length of the window. A 10 minute window was selected and each sensor was sampled for 1 s every minute at a 100 Ksps. The sleep mode was timed to 59 seconds. The post-processed signal was decomposed from the 10 minute statistical information to 10 readings covering minute intervals. This generated set was compared to the original data for each of the sensors. Fig.10 presents an example of the correlation of the two sets for sensor instance 1 (Fig.10a) and sensor instance 39 (Fig.10b). Table II presents the R2 value as a result of the correlation analysis between the two sets for each of the sensor instances.

As demonstrated from the results the changes that occur in the dataset are picked up by the process and no information is lost in any of the sensors either virtual or physical that were included in this case study. Thus, it is demonstrated that reduction of the transmitted information does not result in any loss of information particularly when events can be captured and incorporated in the result. The proposed methodology can thus provide an alternative to sensor networks that suffer from significant interference such as those deployed onboard ships.



(a) (b)

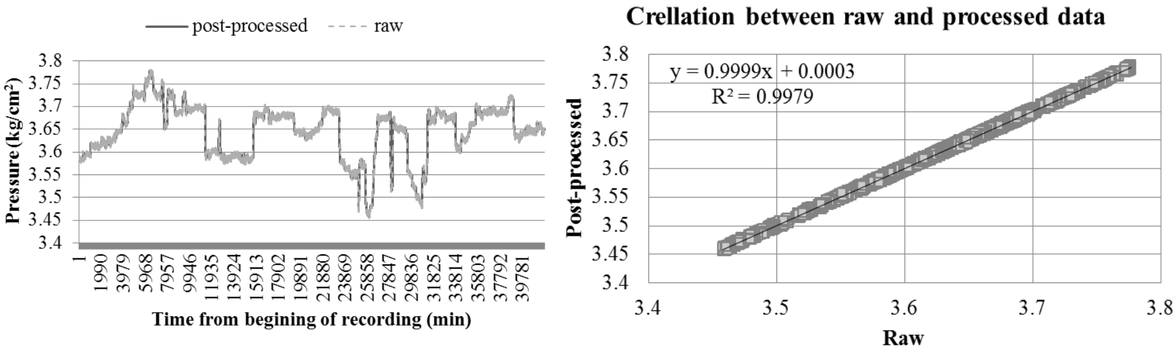
Fig.10: Example of correlation analysis between initial data and post-process generated data for two cases (a) the virtual sensor (No. 11) (b) the physical sensor (No. 39)

Table II: Results of correlation analysis in terms of R^2 values for each sensor instance

No.	**Measurement**	**R^2**	**No.**	**Measurement**	**R^2**
1	Thrust Bearing LO Outlet Temp	1	**20**	IntShaft 1 Bearing Temp	1
2	TCLO 1 Input Press	0.999	**21**	IntShaft 2 Bearing Temp	1
3	TCLO 1 Input Temp	1	**22**	IntShaft 3 Bearing Temp	1
4	TCLO 1 Output Temp	1	**23**	Main Lube Oil Input Pressure	0.999
5	TCLO 2 Input Press	0.999	**24**	Main Lube Oil Input Temperature	0.999
6	TCLO 2 Input Temp	1	**25**	Cylinder Input JCFW Pressure	0.998
7	TCLO 2 Output Temp	1	**26**	Cylinder 1 Output Exh Gas Temp	1
8	Scav Air Manifold Press	1	**27**	Cylinder 2 Output Exh Gas Temp	1
9	Scav Air Rec 1 Temp	1	**28**	Cylinder 3 Output Exh Gas Temp	1
10	Main Engine Start Air Press	0.999	**29**	Cylinder 4 Output Exh Gas Temp	1
11	Piston CO Input Press	1	**30**	Cylinder 5 Output Exh Gas Temp	1
12	JCFW 1 Output Temp	0.999	**31**	Cylinder 6 Output Exh Gas Temp	1
13	JCFW 2 Output Temp	0.999	**32**	Cylinder 7 Output Exh Gas Temp	1
14	JCFW 3 Output Temp	1	**33**	Cylinder 8 Output Exh Gas Temp	1
15	JCFW 4 Output Temp	1	**34**	Aft Camshaft Bearing Temp	0.999
16	JCFW 5 Output Temp	0.999	**35**	Fore Cam Bearing Temp	0.999
17	JCFW 6 Output Temp	1	**36**	Exh Gas Out After Turbo Charger 1 Temp	1
18	JCFW 7 Output Temp	1	**37**	Ex Gas Out After Turbo Charger 2 Temp	1
19	JCFW 8 Output Temp	1	**38**	Main Engine Control Air Input Press	0.999
			39	Cylinder 1 pressure	0.999

From the results reported in Table II the only sensor that reports a R^2 of 0.998 was the Cylinder Input JCFW Pressure (No 25). Fig.11 presents the raw recorded pressures and the processed/generated pressures against time in (a) and as a scatter plot in (b). As demonstrated even in this representative as worst case result, no information loss is recorded.

The two sets were then further processed through the reliability analysis tool and DSS. These results are not presented in this work due to practical limitations. However, as the data sets used for the virtual sensors were collected from a ship that is at optimum condition the DSS did not suggest any actions as no failures or warnings were detected. In that respect, the presented DSS algorithm was able to detect that no action needs to be suggested for all 39 instances. This includes the case were the physical sensor was recording near 0 values. If the event was not generated to warn the DSS that this equipment is not operating a failure would have been identified. Thus the incorporation of events provides benefits not only to data management so that the processed data correlated well with the raw but also to the analysis and decision suggestion parts of the system. The following section describes related work and highlight the differences with the novel approach proposed in this paper.



(a) (b)

Fig.11: Worst-case result of correlation analysis between initial data and post-processed data (a) the two sets presented against time for the duration of the case study (b) correlation analysis

7. Related Work

In the last few years, wireless sensor network systems have started emerging providing solutions for condition monitoring in the shipping industry. Two commercial systems are LAROS and KONGSBERG's wireless CBM system while no reference of academic approaches is made in the literature to the best of our knowledge, http://www.laros.gr/index.php/laros-system, *Katsikas et al. (2014), Katsikas (2013), KONGSBERG (2017)*. These systems are both based on industrial wireless communication protocols but are utilising an embedded system approach with minimal processing at the edge of the network. In contrast to the work presented in this paper that method creates a significantly higher cross-talk noise and interference within the particular environment of the engine room. Moreover, these systems do not utilise an event recognising and response approach. Finally, the referenced Kongsberg system is only operating wirelessly in very short distances and a cable from the antenna to the collection point needs to be installed. In that respect, this system addresses an entirely different issue which is the access and ease of installation of the sensors in specific locations. This view is out of the scope of the proposed system presented in this paper.

Another area of related work is using industrial wireless protocols for data transmission on ships. In this area, the amount of published work is also restricted compared to existing work in other industrial applications. A few publications support the use of industrial wireless protocols and demonstrate that it is possible to deploy such networks for condition monitoring, *Koutsoubelias et al. (2016), Katsikas et al. (2014), Katsikas (2013)*. Thus, this work further strengthens the viability of the proposed approach. *Paik et al. (2007,2009)* present measurements on the utilisation of industrial WSNs in a full ship installation not only within the engine room but also across decks to other areas of the ship. Thus, not only it is possible to establish reliable communication but by employing delay tolerant networking as proposed in this paper and an event based alert system it is even possible to establish highly reliable data transmission suitable for industrial applications. Finally, WSNs have also been used by *White et al. (2010)* in tracking the location of containers onboard a container ship. Once again this is another example of the reliability and viability of such networks in ship applications.

Another area adjacent to the proposed approach is the development of purpose build break-out boards or capes for commodity hardware. Signal acquisition for industrial purposes has traditionally been one of the most expensive areas of embedded systems development. In recent years with the rise of commodity hardware such as the Raspberry Pi, Beaglebone and Arduino there has been an urge to provide speciality break-out boards and component based hardware developments such as capes for the BBB which are purpose build but allow ease of integration, *Lewis (2015), Molloy (2015)*. This trend had recently reach the signal acquisition world and a cape for BBB named PRUDAQ was presented by Google Research, https://groupgets.com/manufacturers/getlab/products/prudaq. This card does not support high voltage industrial sensors as the one proposed in this paper. However, it further strengthens the argument that such systems are required by both industry and academia in order to support the IoT generation of systems, *Weisman (2016)*.

Decision support systems have enjoyed varied attention in several industries of the past few decades. It has been identified that DSS systems cannot be generic for all industries and all applications, *Makowski, (2011), Vallerio et al. (2015).* Hence, publications in the condition monitoring of ship applications have been reviewed. *Jardine et al. (1997)* presents one approach using hazard modelling which takes into account cost and age models along with a system based on maximum likelihood estimations advising strictly on replacement of parts. A control theory based approach is also presented by *Christer et al. (1997)* again to identify the time for replacement of parts. *Khac Tuan et al. (2014)* present a more sophisticated system that is based on degradation, threshold and failure mode integration. However, the interaction between failure modes and components of a system is not considered. A reliability analysis technique is presented by *Dikis et al. (2016)* and *Lazakis et al. (2016,2017)* which considers these interactions but does not include vibration measurements. However, none of the above consider constrains such as availability of parts, crew expertise and weather conditions which may affect the decisions to be made as well as parameters such as performance and energy efficiency. Such a DSS is not previously published in literature to the best of our knowledge. This work proposes a DSS which is a multiple parameter multiple constrain optimisation problem and allows for user defined constrains to be added to the system.

8. Conclusion

Through the proposed methodology some of the inhibitors in acceptance of this technology are addressed such as increased security of data, ensuring data ownership and providing clear benefit to both the engineers onboard the vessel and management through the DSS software. Furthermore, the performance of the wireless network is demonstrating that the proposed system supports highly reliable data transfer. Additionally, through the proposed system the particular noise and interference conditions in the ship engine room are addressed without compromising data integrity, data quality, security and safety onboard the vessel. The results demonstrate correlation between the data recorded onboard a ship in voyage and the data that have been processed through the proposed approach. As such, this novel system can be utilised in real industrial applications to support any post-processing methodology while ensuring data integrity and security.

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Change and Access Control Management to Provide Sister Ships Applicability Capability

Rodrigo Perez Fernandez, SENER, Madrid/Spain, rodrigo.fernandez@sener.es
Jesus A. Muñoz, SENER, Madrid/Spain, jesus.munoz@sener.es

Abstract

The use of specialized shipbuilding CAD Systems in marine environments is crucial for the efficient design and manufacturing of ships. The heart of a shipbuilding CAD System as FORAN is a relational database where the vessel CAD product model is stored. The product model includes geometry, topology, specialized technological and manufacturing information for all ship design disciplines and many relationships between the ship items. The main objective of this paper is to describe how a shipbuilding CAD System, as FORAN, supports management of Ship Unit Series of projects. For this purpose, FORAN has been enhanced to allow the creation of a new ship series and the management of the projects included in it, representing the different vessel units. This capability of handling sister ship management in FORAN can be enhanced when using a complete FORAN-PLM integration, as FORAN sister ship management is also considered in FORAN-PLM integration tools, so PLM can take advantage of it.

1. Shipbuilding CAD Systems in naval environments

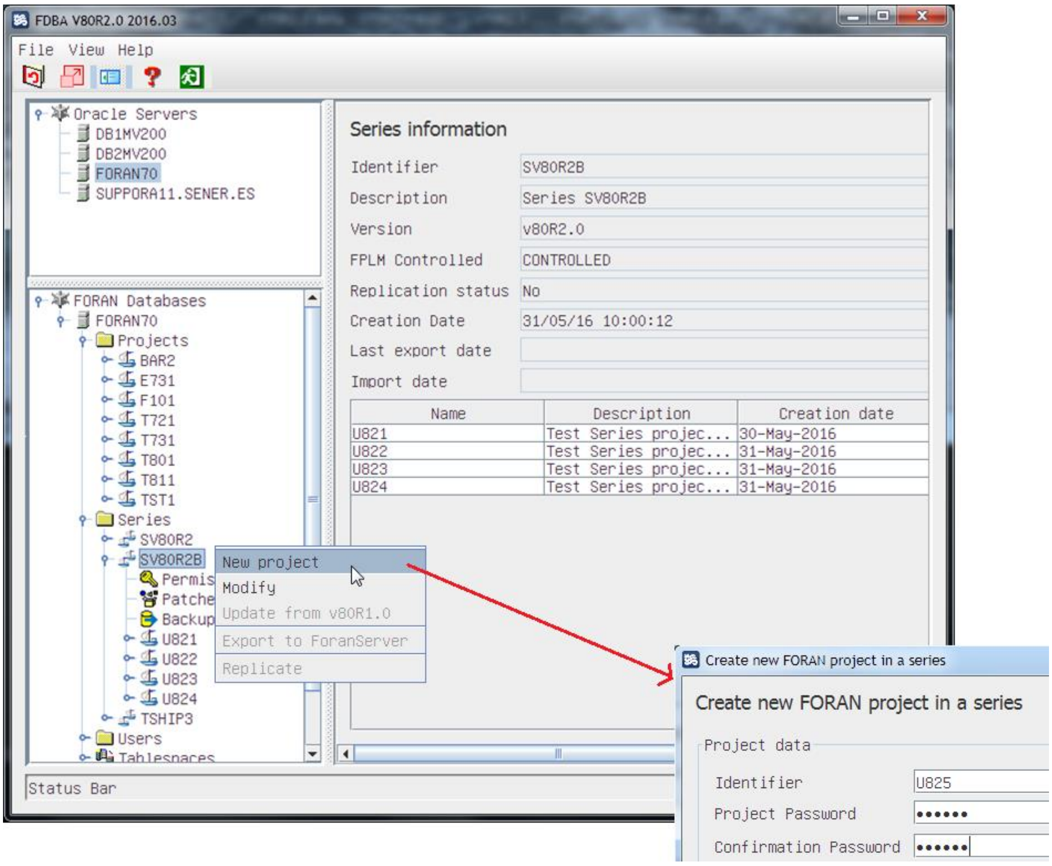
The use of specialized shipbuilding CAD Systems in naval environments is crucial for the efficient design and manufacturing of surface ships and submarines, *Perez and Gonzalez (2015)*. The heart of a shipbuilding CAD System as FORAN is a relational database (ORACLE) where the vessel CAD product model is stored. The product model includes geometry, topology, specialized technological and manufacturing information for all vessel disciplines and many relationships between the vessel items. Shipbuilding CAD Systems working in naval environments offer significant advantages over other generic CAD applications, some of which can be relevant for the purpose of this paper:

- Specifically developed for shipbuilding.
- Availability of shipbuilding smart modelling tools.
- Incorporation of many years of shipbuilding knowledge.
- Outputs adapted to shipbuilding manufacturing processes.
- Proven scalability.
- Proven performance.
- Adapted to military shipbuilding requirements (Dunseath et al., 2015).
- Reduction of design and manufacturing hours over generic CAD applications.

The scalability refers to both the number of CAD users and to the number of vessel items to be handled. Military vessels are very complex products that may be composed of millions of items, requiring a large number of designers, accessing concurrently to the vessel product model, *Perez and Lee (2014)*. The design cycles of these vessels are usually very long and there are many design changes along the whole vessel lifecycle. Performance is another critical requirement, especially in the detail design and manufacturing stages, when the detail design is almost complete, there are hundreds of users working on the model, model changes are constant and information for the production processes must be provided continuously, *Perez and Penas (2015)*.

2. Management of Ship Unit Series

The main objective is to enable FORAN to support management of Ship Unit Series of projects. For this purpose, the FDBA utility (FORAN Database Administrator) has been enhanced to allow creating a new ship series and the management of the projects included in it, representing the different ship units.



Series information

Identifier SV80R2B
Description Series SV80R2B
Version v80R2.0
FPLM Controlled CONTROLLED
Replication status No
Creation Date 31/05/16 10:00:12
Last export date
Import date

Name	Description	Creation date
U821	Test Series projec...	30-May-2016
U822	Test Series projec...	31-May-2016
U823	Test Series projec...	31-May-2016
U824	Test Series projec...	31-May-2016

Create new FORAN project in a series

Create new FORAN project in a series

Project data

Identifier U825
Project Password ••••••
Confirmation Password ••••••

Fig.1: Create a new FORAN project in a series

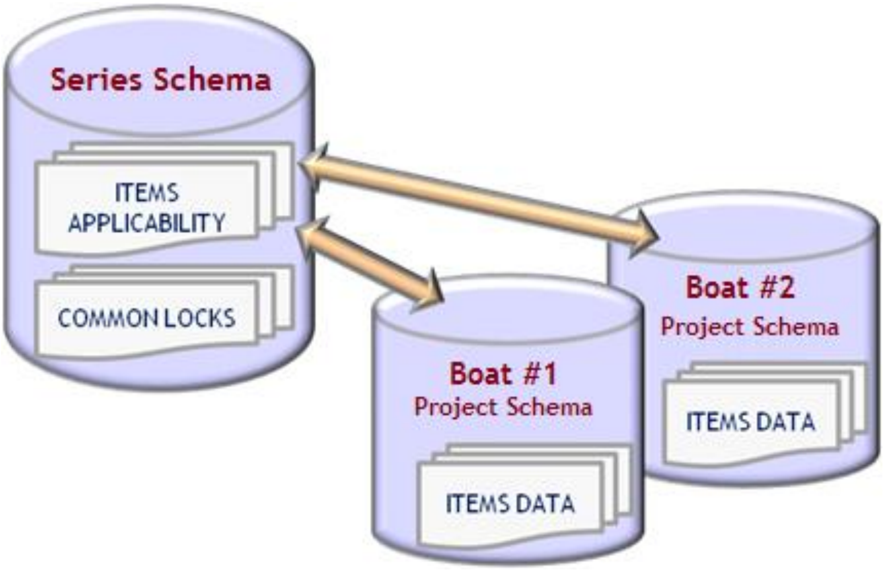


Fig.2: Series Schema and Ship Unit projects. This schema holds common series applicability data and general entity locking.

In the database, these projects are managed internally in different schemas, but being linked to each other, having a schema with objects that are common in the series, like item applicability and locking management, and several schemas with the items data related to each ship. The attributes defined for a series will be, at least, the name and description of the series. Within the scope of the series, the following database objects are commonly managed for all projects in the series and will belong to the series project schema:

- Oracle sequences
- Table of projects included in the series
- Locking tables

Applicability of items in the series (FORAN_APPLICABILITY). This table will include all related data about the ship units in which the entities subject of applicability in a range exist.

2.1 Database Structure in a Multi-Ship Series

In the case of a multi-ship series, the FORAN database is structured in the following components:

- The FORAN Series Schema.
- The FORAN Project schemas. There is one specific FORAN project schema for each ship in the series.

The FORAN Project Schemas in a series context are identical to those FORAN project schemas, except that the COM_LOCK table is not used, as locking is controlled and centralized in the Series schema COM_LOCK table. This is to ensure consistency when several users might be working in different projects, but potentially could be accessing identical data among them, Each FORAN project schema contains all model and PLM data for the ship it belongs to. The entities data identical among more than one ship (sharing the applicability range), is copied identically and automatically by the multi-save FORAN device when a user working in a particular project in the series saves the data.

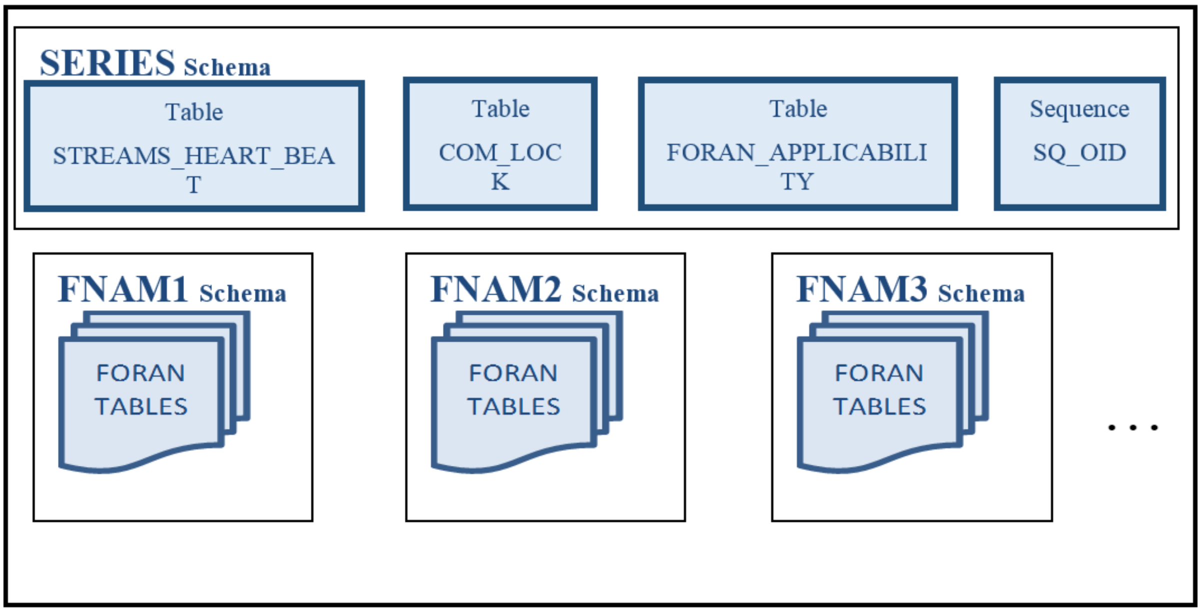


Fig.3: Data controlled in Series Project

3. Changes in FORAN Design Modules

3.1 Storing Design Changes in Project Entities

When a user is working in a FORAN design module in a project belonging to a series and is going to store the changes applied on an entity, the system behaves differently depending on the entity type. If the entity is of a type not included in the applicability management, and so it is no subject of multi-saving, then the data will only be stored in the working project. If the entity is of a type included in applicability management, and so it is subject of multi-saving, the system obtains the information related to the ship units in the series that share the same applicability range with the current ship unit for the entity, before saving takes place. Then, the changes to be stored are done identically in all database schemas for those ship units. With this purpose, the corresponding multi-saving actions have been implemented in all commands that handle entities subject of applicability.

In the case of deletion actions, after removing the entities, the register corresponding to the applicability range in the FORAN_APPLICABILITY table will also be deleted. After the changes are stored, they will be visible from then on, by any other user accessing any other project in which the modified entity was applicable.

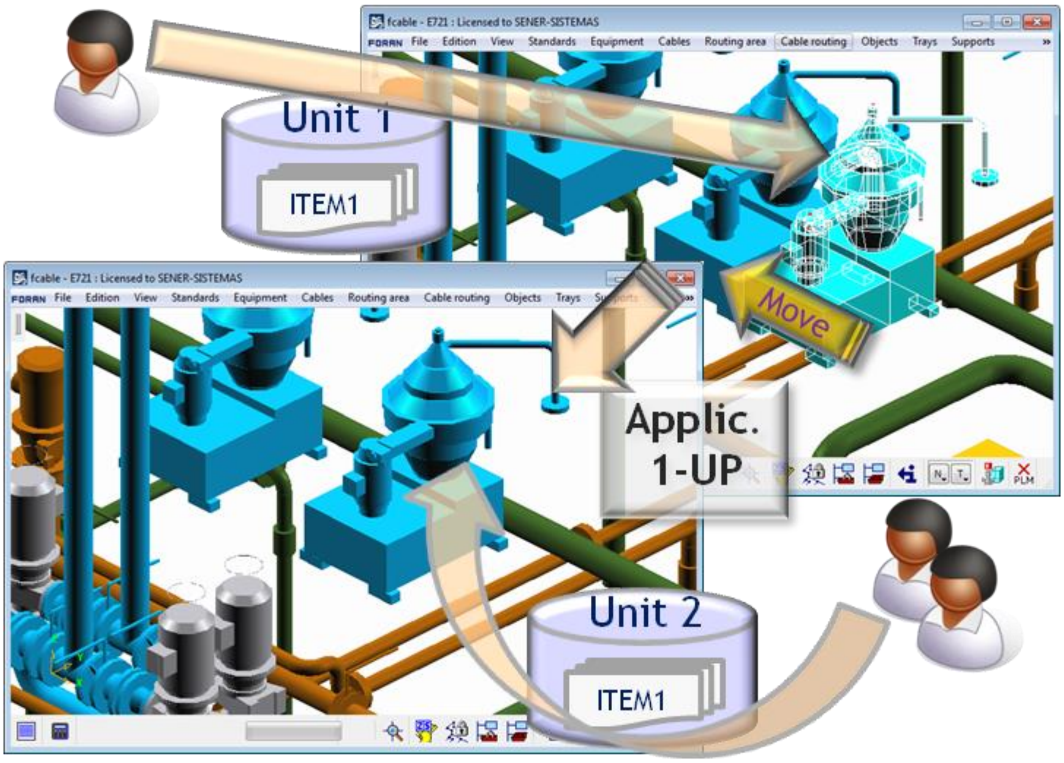


Fig.4: Applicability when creating ad updating entities

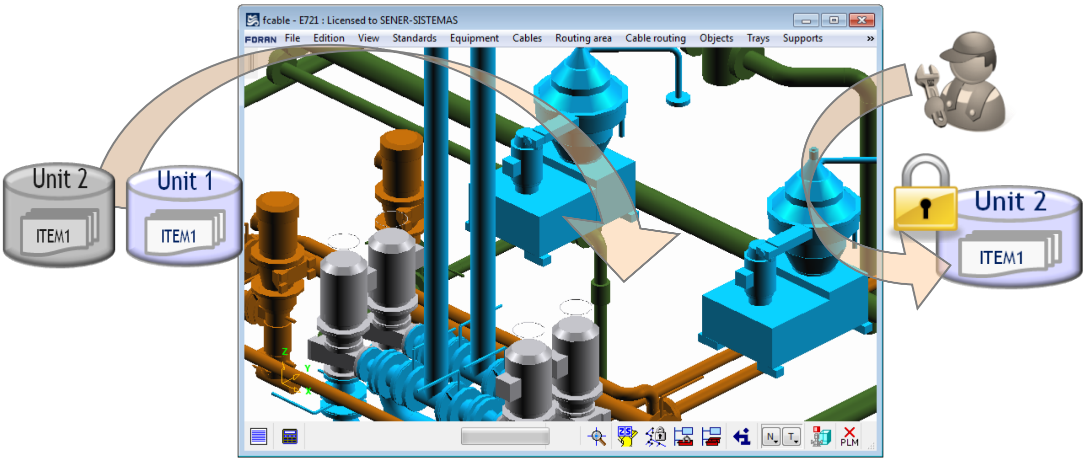


Fig.5: Entity locking mechanism when working in a series context

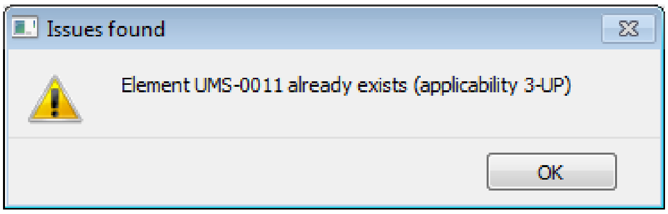
3.2 Unique Lock Management of Entities in the Series

The FORAN locking system has been modified in order to be common to all projects in the series, so if a user locks an entity to work with it in a specific project, this locking must be effective in all projects sharing the applicability range of the entity. This is to ensure that no other user can modify the same data at a time. For example, if a user is working in boat unit #1 and tries to modify an equipment with applicability 1-UP and this element is being modified by another user working in boat unit #2, the system will not allow the item edition by the first user and will show a message to this first user, as it can be seen in the following images.

If this happens, the system does not allow the item edition by the first user. To enable this, it will be necessary to add the applicability range to the existing locking keys in FORAN DB, This will apply to all entity types subject of applicability as well as to the standards.

3.3 Managing Unique Identification of Entities in the Series

The general identification generator system will be modified to be common to all projects in the series, so if a user creates an entity in a project of the series, the system will guarantee that the entity identification will be also unique in all projects in the series.
This will apply to the manual introduction of identifications as well as to automatic numbering templates. If these uniqueness rules are violated when trying to create an entity, a message will be shown to the user.



Element UMS-0011 already exists (applicability 3-UP)

Fig.6: Warning message, when a user tries to reuse an existing identification

The default behaviour will be to not to allow the operation. However, there are some cases in which this could be feasible:

- The case in which an entity was created in the past and then was deleted. The system will allow re-creation of the entity, depending on the entity type and the proper constraints that apply in each case. If the entity was removed in all boat unit projects, it could be re-created again if no other restrictions apply, but if the entity was removed within an applicability range but not in another one, the entity will only be allowed to be re-created in the current working boat unit project, in order to not interfere with the other projects in which it still exists. In all cases, the entity will have to be of the same type as the former deleted one.
- The case in which an entity never existed in the current boat unit project, but it does exist in others with different applicability range. In this case, the entity will be allowed to be created, except if some specific constraints apply to it, by default with applicability just in the current boat unit project, but optionally in some others as well, with the only restriction of not being applicable to other boat unit projects in which an entity of the same type and identification already exists.

With respect to the restrictions and constraints that could prevent an entity, in one of the previous mentioned cases, to be created or re-created, they depend on the entity type and situation. Entities that rely on the existence of other entities to exist (e.g. Cables) are more restricted than others than can exist by themselves (e.g. Equipment Elements). In addition, this will also depend on the context. For example, an Equipment Element can be created or re-created without further applicability constraints from FPIPE module, but if it is created or re-created in a diagram in FSYSD, applicability has to be restricted to that of the diagram, to avoid potential conflicts with other ship units in which the diagram is not applicable. The detailed description of which creation operations could be done in each case, depending on the entity type, will be incorporated to official FORAN documentation for each module. In case of entity modification, if another entity of the same type already exists with the same identification, the operation of changing the Id is not allowed.

4. Applicability Management of Entities in the Series

In FORAN system, it is possible to manage the item applicability in the different ship units. This means that:

- It is possible to determine in which ship units an item exists (applicability).
- It is possible to determine the applicability range in which an item will have the same features (applicability range).
- A change in an item is stored exactly in the same way in the whole applicability range (in all ship units within the same applicability range), regardless the project in which the user is applying the change.
- If, due to any unexpected issue, the change cannot be applied to some projects within the range, the modification is not stored for any of them. So, the storing operation among the projects in the series is transactional.

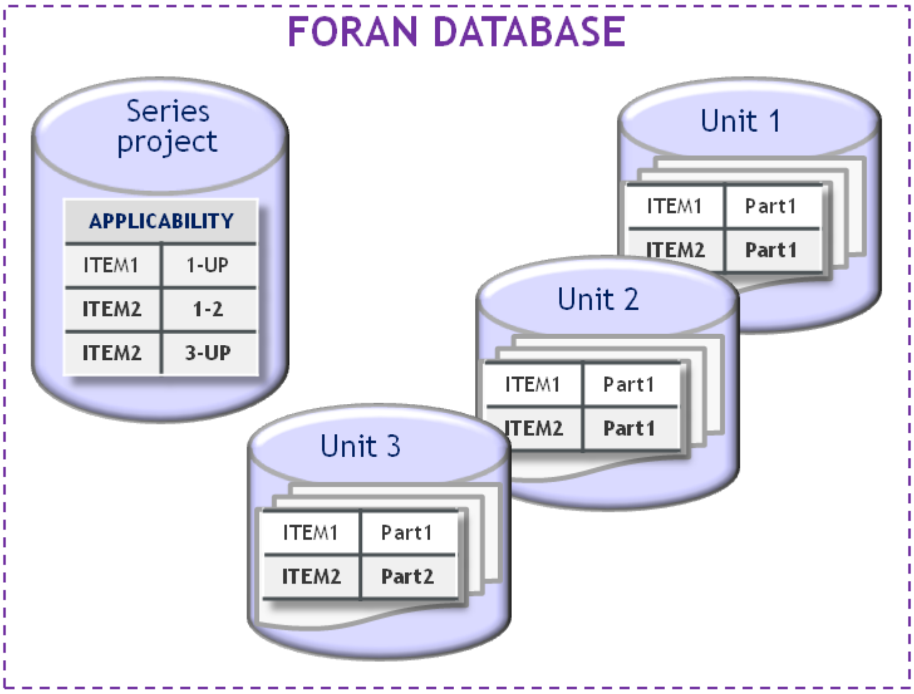


Fig.7: Series and unit projects in FORAN database

4.1 Store Applicability in Database

The applicability values of an item in the series are stored in a new table called FORAN_APPLICABILITY. This table includes the OID (database object identifier) of the entity in FORAN. In addition, it holds information about the applicability range for each entity.

Table I: FORAN_APPLICABILITY table. Simplified schema

FORAN_APPLICABILITY				
FORAN_OID	UNIT 1	UNIT 2	. . .	UNIT n

This table will behave in the following way:

- There is at least one register representing the applicability context of the entities subject of applicability or the minimum container entity.

- In the case of entities that have more than one applicability context, there is one register (table row) for each applicability context.
- For a single entity, it is required to verify that applicability ranges do not overlap.
- When a new item is created in FORAN, a new register is inserted in FORAN_APPLICABILITY table.
- When an item is deleted from a ship unit in FORAN, the register representing the item in the applicability context belonging to that unit is deleted from the table.

4.2 Applicability Value Criteria for New Project Items

At the time a new item is created in FORAN, according to what is stated in the former section, the item already holds applicability info. As a general rule, the default value is that of the ship unit corresponding to the working project. If the entity is created in the last ship unit in the series, and this last ship corresponds to number #n, the applicability range will be [n-UP], so it will also exist in all future units added to the series.

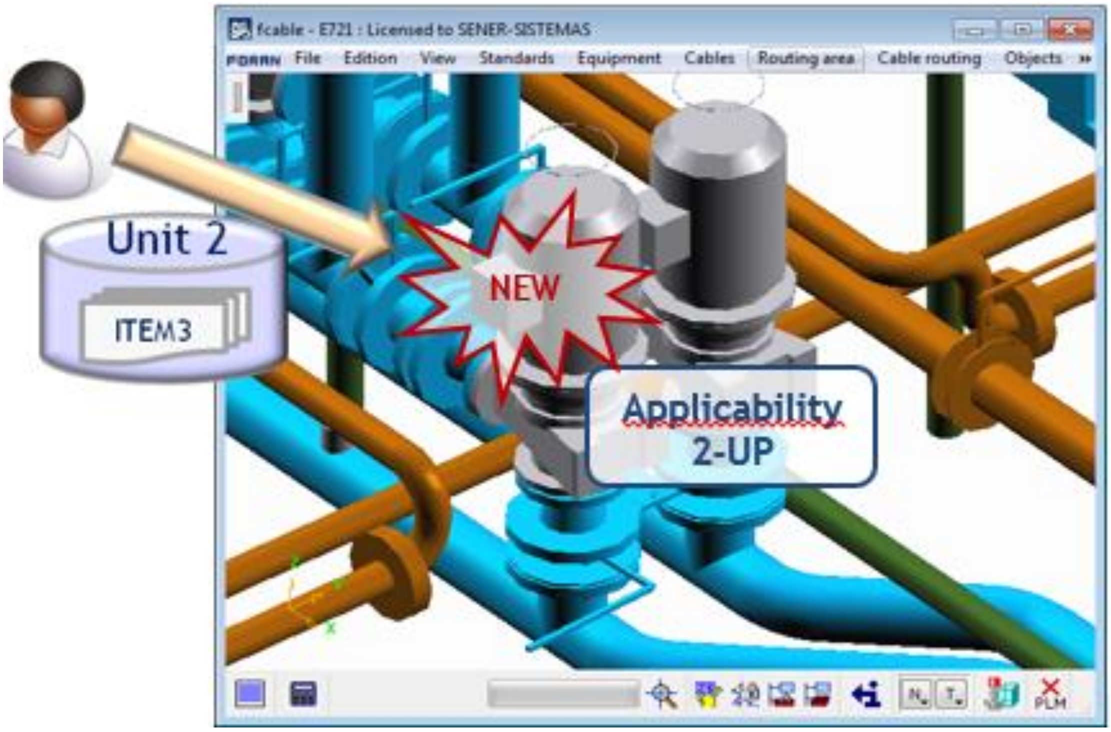
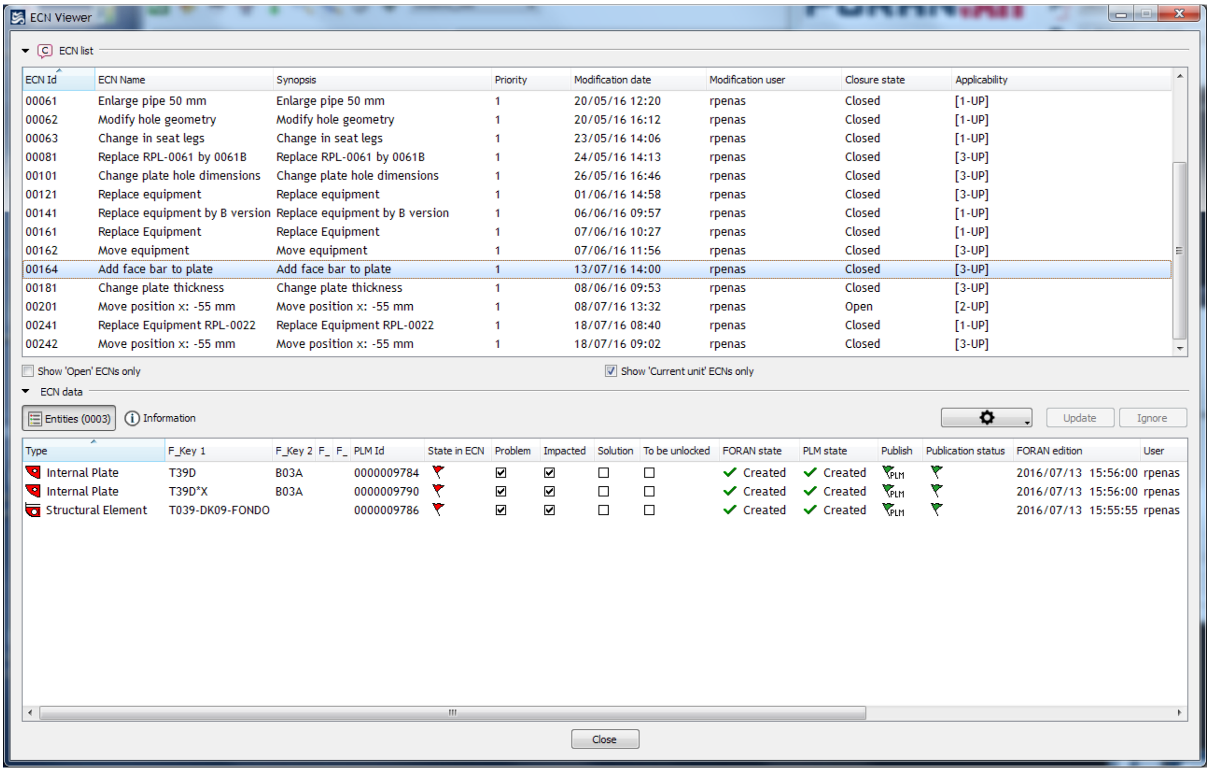


Fig.8: Applicability for new items

In some cases, according to the entity type and the applicability of the items related with the new item, the range could be expanded to other ship units. E.g.: if a new Equipment is to be created in a Diagram, the new equipment applicability could match the applicability of the Diagram. In the case of items that depend on other items at creation time, it cannot be guaranteed that the items related will also exist in other ship units different from the current one, and so, the applicability will be by default restricted to the current ship unit. E.g.: Cables respect to their related equipment, Supports respect to routed elements supported, etc. Depending on each case, applicability value could be wider if it is checked and verify that does not create conflict or is not constrained by the existence or not of the entities they depend.

In the case of entities not depending on other items to be created (e.g. Equipment elements not being created from a Diagram in FSYSD), applicability could receive any value (1-UP, n-UP n, etc.). If an entity is to be created as a result of a synchronization (changes on PLM entities properties and state that are transferred to FORAN through a process handled in FORAN_PLM Integration that is called *synchronization*), applicability will be determined by the value included in the synchronization message for that entity. It will also possible that the applicability value for new items to create will be directly indicated by an ECN (Engineering Change Notice) managed in PLM system. In this case, applicability values of the new entity and that of the ECN must be compatible.



ECN Id	ECN Name	Synopsis	Priority	Modification date	Modification user	Closure state	Applicability
00061	Enlarge pipe 50 mm	Enlarge pipe 50 mm	1	20/05/16 12:20	rpenas	Closed	[1-UP]
00062	Modify hole geometry	Modify hole geometry	1	20/05/16 16:12	rpenas	Closed	[1-UP]
00063	Change in seat legs	Change in seat legs	1	23/05/16 14:06	rpenas	Closed	[1-UP]
00081	Replace RPL-0061 by 0061B	Replace RPL-0061 by 0061B	1	24/05/16 14:13	rpenas	Closed	[3-UP]
00101	Change plate hole dimensions	Change plate hole dimensions	1	26/05/16 16:46	rpenas	Closed	[3-UP]
00121	Replace equipment	Replace equipment	1	01/06/16 14:58	rpenas	Closed	[3-UP]
00141	Replace equipment by B version	Replace equipment by B version	1	06/06/16 09:57	rpenas	Closed	[1-UP]
00161	Replace Equipment	Replace Equipment	1	07/06/16 10:27	rpenas	Closed	[1-UP]
00162	Move equipment	Move equipment	1	07/06/16 11:56	rpenas	Closed	[3-UP]
00164	Add face bar to plate	Add face bar to plate	1	13/07/16 14:00	rpenas	Closed	[3-UP]
00181	Change plate thickness	Change plate thickness	1	08/06/16 09:53	rpenas	Closed	[3-UP]
00201	Move position x: -55 mm	Move position x: -55 mm	1	08/07/16 13:32	rpenas	Open	[2-UP]
00241	Replace Equipment RPL-0022	Replace Equipment RPL-0022	1	18/07/16 08:40	rpenas	Closed	[1-UP]
00242	Move position x: -55 mm	Move position x: -55 mm	1	18/07/16 09:02	rpenas	Closed	[3-UP]

☐ Show 'Open' ECNs only
☑ Show 'Current unit' ECNs only

Type	F_Key 1	F_Key 2	F_	F_	PLM Id	State in ECN	Problem	Impacted	Solution	To be unlocked	FORAN state	PLM state	Publish	Publication status	FORAN edition	User
Internal Plate	T39D	B03A			0000009784	⚑	☑	☑	☐	☐	✓ Created	✓ Created	⚑PLM	⚑	2016/07/13 15:56:00	rpenas
Internal Plate	T39D*X	B03A			0000009790	⚑	☑	☑	☐	☐	✓ Created	✓ Created	⚑PLM	⚑	2016/07/13 15:56:00	rpenas
Structural Element	T039-DK09-FONDO				0000009786	⚑	☑	☑	☐	☐	✓ Created	✓ Created	⚑PLM	⚑	2016/07/13 15:55:55	rpenas

Fig.9: ECN handling sample with applicability [3-UP] affecting several CAD items.

4.3. Applicability Change of Project Items

During a series project design stage, there could be several reasons to make necessary a change of applicability values:

- An item is not required anymore from a specific ship unit on.
- From a specific ship unit on, using a different applicability standard is required, for example because the old library part being used is not provided anymore and needs to be replaced by a similar new one.
- The item position must be different in some ship units.
- In general, some item properties differ in some ship units with respect to the others.

In other words, for applying some changes differently for an item in one ship unit with respect to the others, it will be necessary to previously perform a change in the item applicability range, so that, once the range division is done, design changes could then be done on the item inside the necessary applicability context, without affecting the ship units in the other ranges.

For this purpose, a new utility exists to allow an authorized user to change the item applicability values. This utility is a common usage tool in all requiring FORAN modules, which will be accessible from the corresponding entity edition Managers. From that utility, the following tasks could be performed:

- Add a new applicability range. This will allow to divide a former range into two new ones.
- Change a ship unit to a new range or merge ranges.

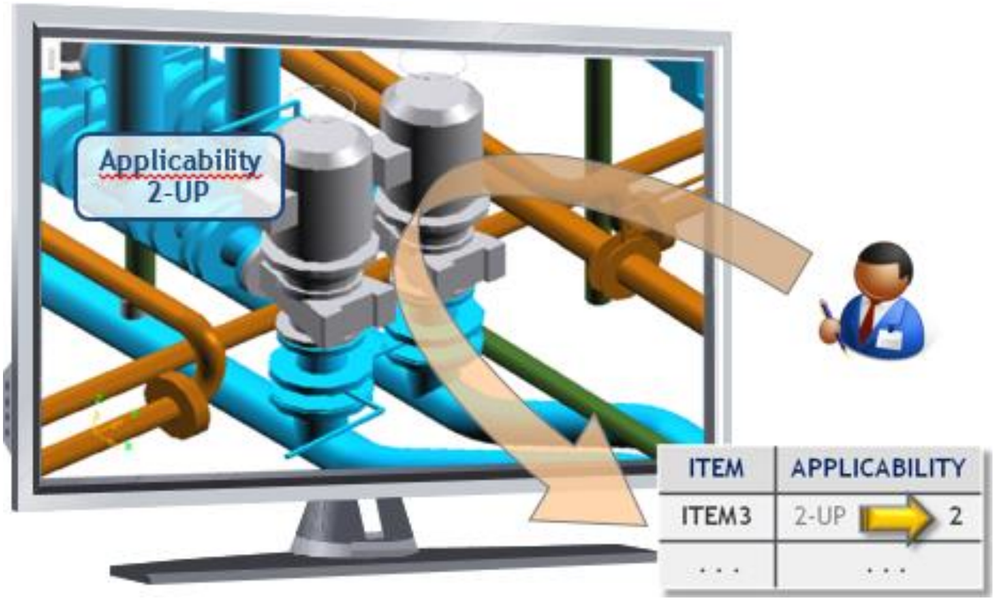
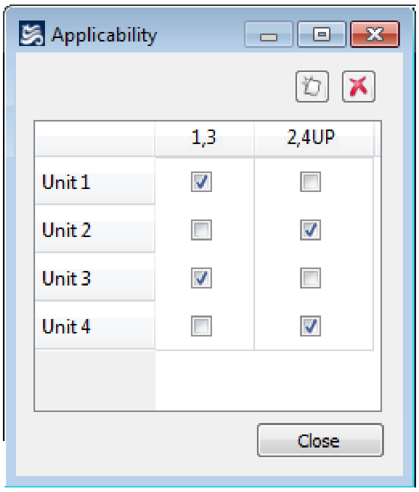


Fig.10: Changing item applicability



	1,3	2,4UP
Unit 1	☑	☐
Unit 2	☐	☑
Unit 3	☑	☐
Unit 4	☐	☑

Fig.11: GUI for changing applicability

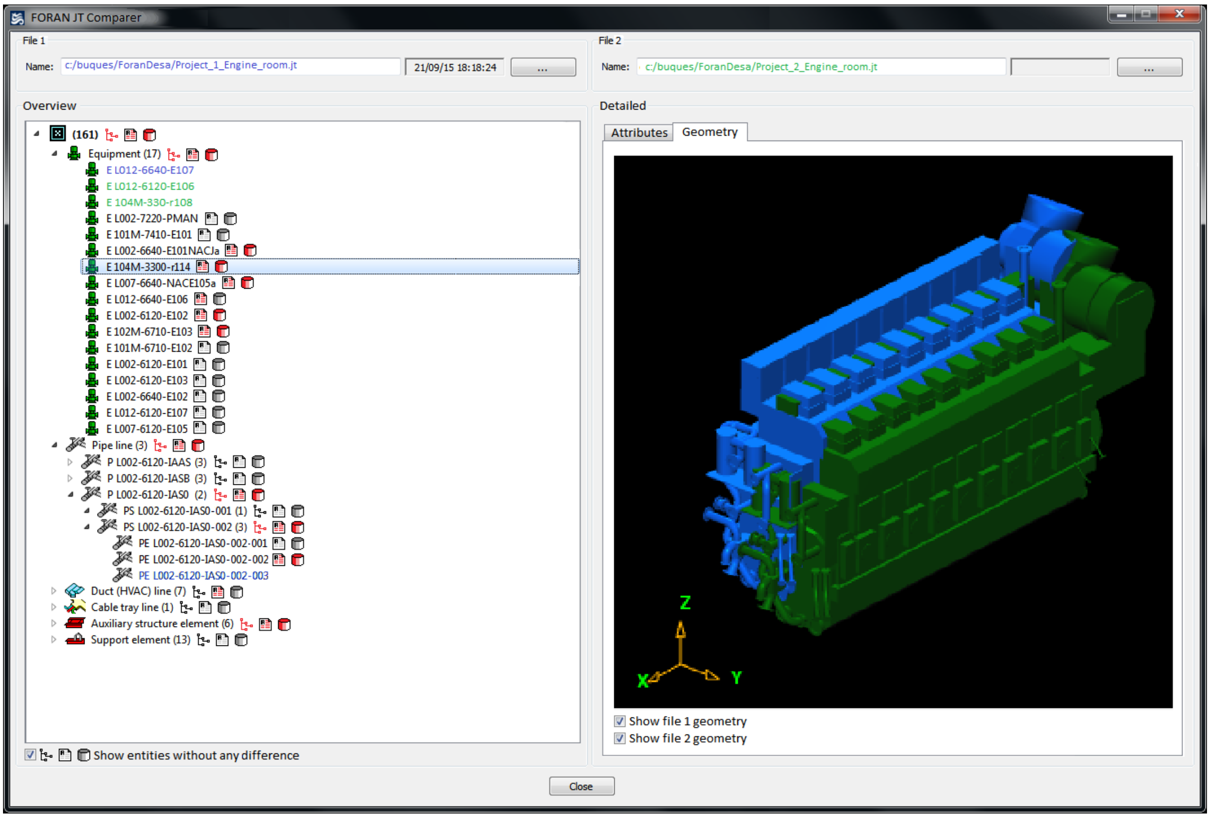
The following actions could not be directly done from this tool:

- Remove ship unit applicability from a range, because this means the entity removal from those ship units. If this operation is required, it will have to be done in two steps: 1- Divide the applicability range and 2- Remove the entity.
- Extend item applicability to other units, because it means the entity creation in those ship units and this common usage tool does not have the necessary information required to create an entity in FORAN, as the specific entity Manager is the only FORAN tool that knows the necessary info to create the entity.

In addition, a specific tool is available in FCM module to allow accessing the items applicability data and the multiple edition of their values. Applicability change ranges can only be performed by users with the FORAN Applicability Manager role. When applying those changes, it is important to ensure that this operation is required to fulfil an expected design change and that it is done by the appropriate and authorized users. For performing an applicability cutback operation, it is not required to previously unlock the involved FORAN items.

5. Comparison tools

Current solution also incorporates tools to visualize the differences between entities existing in more than one ship in the series, but that belong to different applicability ranges. These comparison tools are capable of showing visual differences (e.g. different position and orientation) as well as metadata ones (e.g. attribute values). These tools allow a quick analysis on these differences, as shown in the following images.



File 1 Name: c:/buques/ForanDesa/Project_1_Engine_room.jt 21/09/15 18:18:24

File 2 Name: c:/buques/ForanDesa/Project_2_Engine_room.jt

- (161)
  - Equipment (17)
    - E L012-6640-E107
    - E L012-6120-E106
    - E 104M-330-r108
    - E L002-7220-PMAN
    - E 101M-7410-E101
    - E L002-6640-E101NACJa
    - E 104M-3300-r114
    - E L007-6640-NACE105a
    - E L012-6640-E106
    - E L002-6120-E102
    - E 102M-6710-E103
    - E 101M-6710-E102
    - E L002-6120-E101
    - E L002-6120-E103
    - E L002-6640-E102
    - E L012-6120-E107
    - E L007-6120-E105
  - Pipe line (3)
    - P L002-6120-IAAS (3)
    - P L002-6120-IASB (3)
    - P L002-6120-IAS0 (2)
      - PS L002-6120-IAS0-001 (1)
      - PS L002-6120-IAS0-002 (3)
        - PE L002-6120-IAS0-002-001
        - PE L002-6120-IAS0-002-002
        - PE L002-6120-IAS0-002-003
  - Duct (HVAC) line (7)
  - Cable tray line (1)
  - Auxiliary structure element (6)
  - Support element (13)

☑ Show entities without any difference

☑ Show file 1 geometry
☑ Show file 2 geometry

Fig.12: Comparison between ships in the series

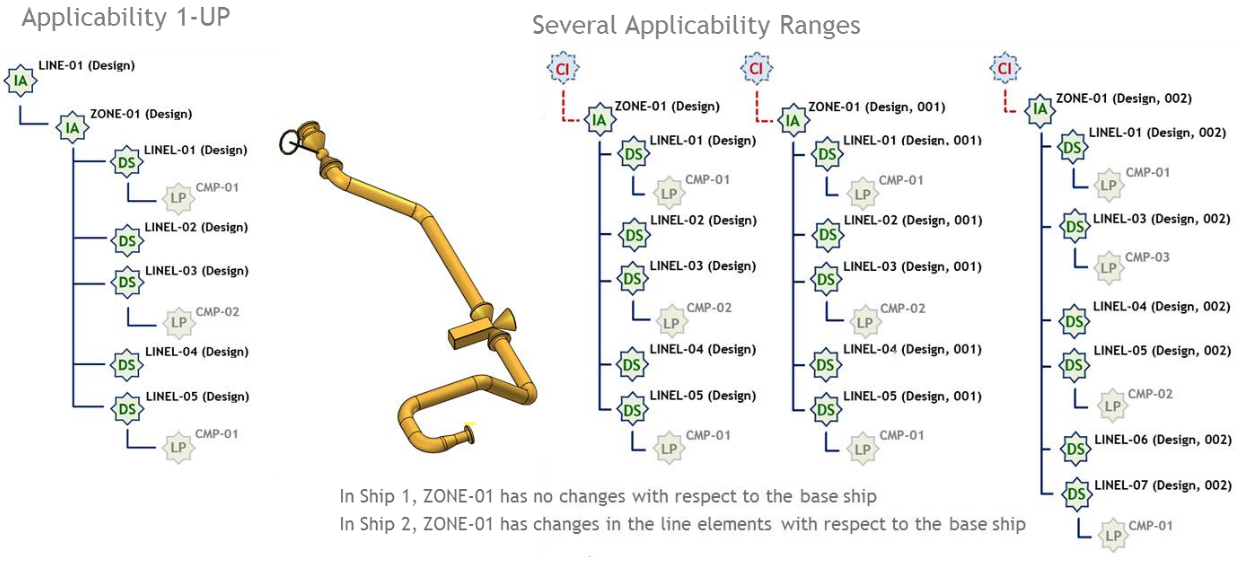
6. Implementing Ship Series Applicability with PLM Integration

According to the PLM integration used, PLM system can take advantage of the CAD Ship Series Applicability usage. Publishing data to PLM that includes applicability ranges will be reflected in PLM published data that will support that applicability data. Normally, PLM systems can support applicability in different ways. The following are just a few of them:

- <u>Effectivity by Serial Number reflected in Item Version</u>. Different applicability ranges are reflected in different item versions so that each version is valid, effective or applicable to a range of ship numbers in the series. For example, if an item has two applicability ranges ([1-2] and [3-UP]), then at least two item versions will exist so that, for example, version A will be applicable to ships #1 and #2 and version B will be applicable to ships #3, #4 and all others up. The PLM system will then dynamically select the appropriate version to handle when PLM user indicates a particular ship number in the series to handle with.
- <u>Effectivity by Serial Number reflected in Item-to-Item relationship</u>. Different applicability ranges are associated to the link object in the product structure context. So, the different data among ships in the series are explicit in the corresponding hierarchical links. So, the system will activate or disable certain hierarchical links according to the ship number we are handling with. This method allows more flexibility than the previous one, but has the disadvantage of not having all applicability data directly contained in the item, so it is necessary to move in a product structure context to be capable of handling applicability data.

- Usage of Alternate BOM Product Views. A totally different approach. Each item will have a particular Alternate BOM view for each ship in the series. So, this means information that is identical in more than one ship will be duplicated. Then, when navigating in PLM through the product structure for a particular ship in the series, the PLM product structure navigator will show the corresponding Alternate BOM views for the particular ship.

The CAD system handles the applicability data in the same way, regardless the method used in PLM system to represent them. Accordingly, it is responsibility of the particular CAD-PLM integration plug-in to handle applicability data from CAD in such a way that the applicability data published into PLM is structured in the desired way. For example, the following figure shows a particular case in which a pipe and its elements are deployed in the case of an Alternate BOM implementation in PLM:



In Ship 1, ZONE-01 has no changes with respect to the base ship

In Ship 2, ZONE-01 has changes in the line elements with respect to the base ship

Fig.13: Sample Applicability deployment in PLM system in the case of using Alternate BOM

7. Conclusions

This paper presents a solution for the applicability of a shipbuilding specific CAD System (FORAN) with an advanced PLM System in a Naval Shipbuilding environment. The described integration presents several important advantages:

- Takes profit of the experience and results of previous integration of FORAN with different PLM Systems.
- Incorporates the most outstanding requirements for the CAD – PLM integration coming from some relevant European shipbuilding companies, designing and manufacturing surface ships and submarines.
- Improves predictability by providing a single point of truth for the whole organization.
- The design of the integration has been done with the objective of limiting the degree of coupling between the CAD and the PLM, with several important aims in mind:
  - To reduce to a minimum the impact of the integration on the performance of both systems (the CAD and the PLM).
  - To produce a scalable solution capable of working with hundreds of designers in the CAD Engineering side and with thousands of PLM users in the whole shipbuilding organization.
- It would allow the PLM to take benefit of all the vessel information handled by the CAD from the early stages of the design.

The described integration is now under implementation for several important European Naval Shipbuilder.

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Ontology Based Integration of Ship Inspection Data

Marianne Hagaseth, SINTEF OCEAN, Trondheim/Norway, marianne.hagaseth@sintef.no
Ulrike Moser, DNV GL, Hamburg/Germany, ulrike.moser@dnvgl.com

Abstract

This paper describes how ontology based integration of heterogeneous ship data can be done to provide risk models with consistent and up-to-date information, including ship particulars, inspection results and AIS data. The purpose of the risk based inspection models is to calculate the overall risk for each ship from a set of ships to select the one most relevant for inspection. The paper presents the methodology to generate this ontology, an example ontology used in the SAFEPEC Tool to fetch parameter values used by the various risk models, and the architecture of the Data Integration Module that uses this ontology.

1. Introduction

1.1. Ontologies

An ontology formally represents the “knowledge” about a domain in a structured and computer-readable way, *Gruber (1993)*. With the introduction and standardization of technologies like RDF[1], RDF Schema and OWL[2] (Ontology Web Language), the possibilities of using ontologies in the field of data integration and semantic web increased significantly, *Allemang and Hendler (2008)*. Due to these standards, the formal description of a domain by ontologies became executable. A digital object (identified by an URI[3]) has associated metadata represented by RDF. In RDF, information is represented as a triplet containing a subject, a predicate and an object. A set of such triples is called a RDF graph. These RDF statements make use of concepts described by an OWL ontology. The digital objects can thus be classified by using this OWL ontology. The classification is supported by additionally inferred RDF statements arising from the logic inside the OWL ontology, that is, the relationships (object properties and data properties) and sub-classing defined in the OWL ontology. The inferencing is done by components called OWL reasoners. By applying further ontologies to the digital objects, they are classified and described with respect to these other ontologies. This means that several ontologies can be linked to other related domains, Section 3.2.3. The OWL Ontology can be queried using SPARQL[4], Section 2.2.

1.2. Challenges in Data Integration

Data integration is the task of combining different sources of data together to produce useful business information, *Underdahl (2014)*. In practise, these data sources may include legacy mainframe databases, relational databases, desktop applications, social media comments, blog postings, data fetched through web services, machine sensor data and so on. The various data sources are typically heterogeneous, both when it comes to the structure and the semantics, *Wache (2001)*. In addition, they are distributed, and thus may be physically stored in different places. The interoperability problem between the different heterogeneous data sources includes both structural and semantic heterogeneity between the data sources. Structural heterogeneity means that the different sources has structured their data in different data models. The difference can also be in how the physical representation of the data is done, for instance in relational tables, xml files, web posts etc. Also, the data can be on different level of structuration, that is, structured (e.g. relational databases), semi-structured (e.g. CSV, XML, JSON documents, NoSQL databases) or unstructured (eg. text and multi-media content, e-mails, web pages). Semantic heterogeneity means that the information content and the meaning of the data in the

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[1] RDF: standard representation for semantic data from W3C.
[2] OWL: standard ontology language from the World Wide Web Consortium (W3C).
[3] URI: Uniform Resource Identifier.
[4] SPARQL: standard query language for semantic data from the W3C.

different sources, varies. Three different causes for semantic heterogeneity is, *Goh (1997)*:

- Information items that looks similar are in fact different, for instance due to differences in the context of the systems.
- Different reference systems are used to measure a value, for instance for currency or weight.
- Naming conflicts: Same name is used for different meanings, or different names are used to mean the same.

To achieve semantic interoperability between the data sources, the meaning of the information that is exchanged, has to be described and understood. One way to do this is to use ontologies to describe the semantics of the common concepts of several data sources. This is part of ontology based data integration.

1.3. Challenges in Ship Inspection

Ship inspections are conducted by several different stakeholders, for instance port state authorities, classification societies, ship owners, ship managers and ship operators. Each of these stakeholders produce large amounts of data (findings, monitoring) as a result of the various inspections performed. However, today this data is kept locally and there is no way to collect information related to the same ship to improve the quality of the ship inspections. This means that several stakeholders may also collect the same information about the same ship. Another possible improvement of ship inspection is to use risk-based inspection methods to identify potential degradation and threats to the ship and to assess the failure probabilities and consequences, instead of condition based methods. To be able to do this, information from several different types of inspections must be collected and used as input to the risk model calculations. For a risk based inspection tool to take advantage of information collected by several stakeholders, up-to-date ship information, condition data and accident statistics must be collected from several data sources to be able to assess the probability of failure and the consequence of failure. However, access to several of these data are restricted. The different owners of the data both have confidentiality issues and economic interests of restricting the access to their data. In this work, we use information from IHS Maritime World Register of Ships, IHS Maritime World Casualty Statistics, Port State Control (PSC) data, Class data and Automatic Identification System (AIS data). Integrating individual inspection results for a specific ship into the risk models will make the result more reliable when assessing this ship. Without inspection results, the risk is calculated only based on the performance of the reference fleet characterized by the ship particulars.

1.4. The SAFEPEC Risk Based Inspection Models

Risk-based inspection of ships uses risk calculations to optimize the inspection in terms of inspection date, scope and the technique to use, *Kim et al. (2017)*, http://safepec.eu/. It is a decision-making technique for planning inspections based on the risk. It is a formal approach to develop optimized inspections. The potential benefit of doing *risk-based* ship inspections is the possibility to reduce lifecycle costs needed due to complying with maritime regulations, without reducing the safety. It is used to handle the probability and consequences of failures to avoid unreasonable risks, *Hamann et al. (2016)*. The main objective for the risk-based inspection model that is developed in the SAFEPEC project is to decide which ship to select for inspection from a group of ships, *Hamann et al. (2016)*. This is in contrast with detailed models developed to describe the detailed risks for the various part of a single ship. This means that the risk-based model will not go into details on the structure of each ship, but will instead work at a coarser level. Relevant input data to this risk model is historical data about non-conformities, information about deficiencies detected by port state control and class inspections, near miss cases and accidents in addition to administrational information about each ship. The risk calculation in SAFEPEC is done according to the following formulae[5], meaning that both the cause, the vulnerability and the consequence is taken into account during the computation:

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[5] Ca is the Cause, F is the Failure mode and Co is the Consequence.

$$Risk = \sum_i P(Ca_i) \sum_j P(F_j|Ca_i) \sum_k U(Co_k)\, P(Co_k|F_j)$$

Fig.1 shows more details about the SAFEPEC risk models. It also shows that even if the models do the calculations at a high level (ship level), inspection and monitoring results can be added to give evidence to the values that are otherwise estimated. With available inspection results of the individual ship, the reliability of the calculated risks increases.

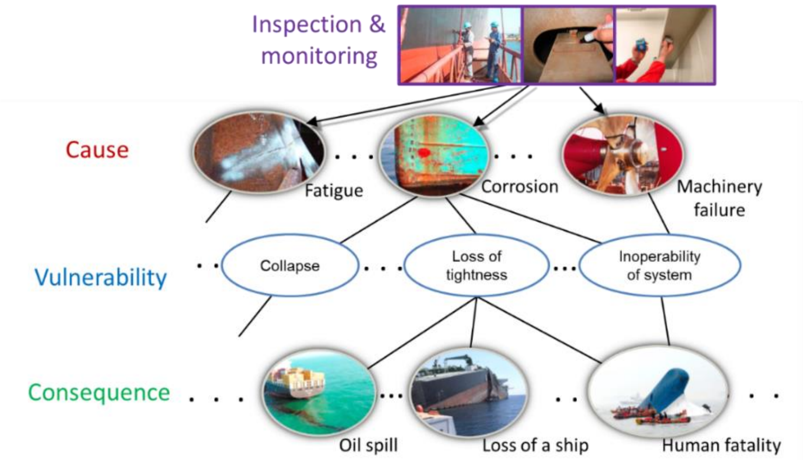


Fig.1: SAFEPEC: Risk Updated with Inspection Data, *Kim et al. (2017)*

The risk-based ship inspection model developed in the SAFEPEC project is quantitative in that it calculates a numerical risk value for each ship in the set of ships that are compared. However, this approach is data-intensive and computational-intensive. This is why a Data Integration Module (DIM) was introduced to the SAFEPEC Tool, Section 1.5: To combine data in different formats and different data sources into a common data structure and to make the data easily available to the risk models. This will also reduce the computational efforts needed, since the data sources are carefully selected and processed with respect to the needed high level risk evaluation of a single ship.

In the SAFEPEC Tool, mathematical representations are chosen to prepare the risk model and all of its sub-models and sub-sub-models covering for instance corrosion cause, coating cause or bending capacity vulnerability. Different approaches used to model the relevant aspects include

- Bayesian networks (BN) (e.g. for the causes originating from corrosion and fatigue)
- Fault Trees (FT) (e.g. for causes originating from life-saving appliances)
- Response surfaces (e.g. for ultimate moment capacity of a ships mid-section used by the vulnerability model)

A BN is a graphical inference technique used to express the causal relationships among variables. BNs are used either to predict the probability of unknown variables or to update the probability of known variables given the certain state of other variables (evidence) through the process of probability propagation or reasoning. The reasoning is based on Bayes' theorem. Due to this ability, BNs have provided a promising framework for system safety analysis and risk management, *Khakzad et al. (2011)*. The top event usually represents a major accident causing safety hazards or economic loss. While the top event is placed at the top of the tree, the tree is constructed downwards, dissecting the system for further detail until the primary events leading to the top event are known. Primary events are considered binary (with two states) and statistically independent. Fault tree analysis (FTA) is a top down failure analysis where the system state is analysed using Boolean logic by combining several lower-level events. FTA describes the relationship between the faults, subsystems and redundant safety design elements by creating a logic diagram of the overall system. The relationships between events are represented by gates, usually AND-gates and OR-gates.

All these models and sub-models have the purpose to quantify risk contributions. Each contribution can be quite complex and worth an own (sub-)model such as causes or the corrosion cause. But it can also be small with respect to the overall target and thus only be represented by a BN node, e.g. the quality of the maintenance regime, or even only some mathematical equation. Each model or sub-model depends on other sub-models.

1.5. DIM: Integration of Data Source for Ship Inspection

The DIM uses ontological data integration to provide external data to the Risk Module in the SAFEPEC Tool, both to Bayesian Network (BN) models and to Fault Tree (FT) graphs. Fig.2 gives an overview of the Data Integration Module (DIM) which simplifies the data access for the various risk models. The DIM was designed to fulfil the following main objectives, *Moser and Hagaseth (2016)*:

[1] **Hiding complexity**: The task of evaluating the risk and providing the input data to the risk models are clearly separated, Fig.3. The risk module is responsible for the risk based inspection calculations and the DIM for fetching data from the various external data sources and presenting this data to the various risk models in the Risk Module. The DIM has to be able to use the vocabulary of its target domain, that is, the unified risk models. By fulfilling this requirement, the complexity of the actual data sources is completely hidden from the risk models.

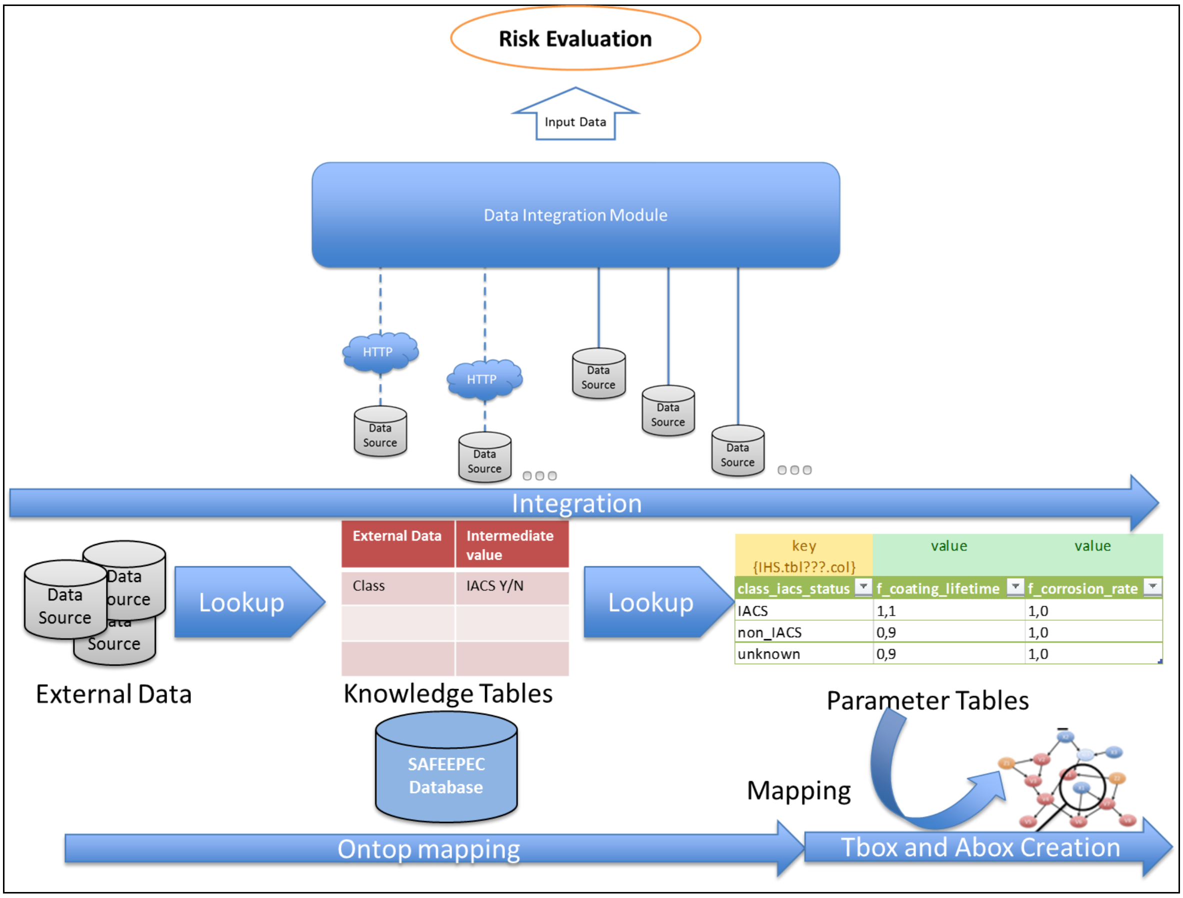


Fig.2: DIM Overview

[2] **Ensuring consistency**: For the risk models, it is crucial to execute on valid input data. It is the responsibility of the DIM to ensure that input data to the risk models is consistent with respect to the one vocabulary and that the interpretation of queries is handled unambiguously.

[3] **Ensuring up-to-date results**: Since the external data sources to be integrated by the DIM are under constant change (e.g. the PSC database is continuously updated with new inspection and

detention data, IHS Ship Register updates with respect to flag, class or owner changes), the Risk Module should do the computations based on up-to-date information. Thus, the DIM has to be designed to allow live access to data sources which are subject to external data changes.
[4] **New data sources**: The risk models can start to use new data sources with no changes in the risk model implementation as long as the parameter tables remain the same.

The lower part of Fig.2 shows the mapping between the external data sources and the parameter tables containing the parameters and values used by the leaf nodes in the risk models. Parameter tables are implemented in the ontology, and they describe the mapping from the external data items to the parameters needed for a certain BN node or FT node to support setting evidence on that node. Parameter tables are described in Section 3.1.1. Knowledge tables are added in those cases where the data sources do not contain the values that can directly be used in the mapping, see Section 3.2.1.

1.6. SAFEPEC - Risk Based Inspection Tool

Fig.3 gives an overview of the SAFEPEC Tool that is being developed in the SAFEPEC Project, *Hamann et al. (2016)*. The risk calculations start with computation of probability of cause which is then used as input to the Vulnerability model where the probability of failure is calculated. In addition, the consequences of failure are computed and used as input to the risk analysis calculations. The Inspection Module can be used to set evidence to increase the correctness of the cause module. Interaction with the end user is done through a GUI as shown to the left in Fig.3. GUI makes the end user able to select one or more ships for inspection.

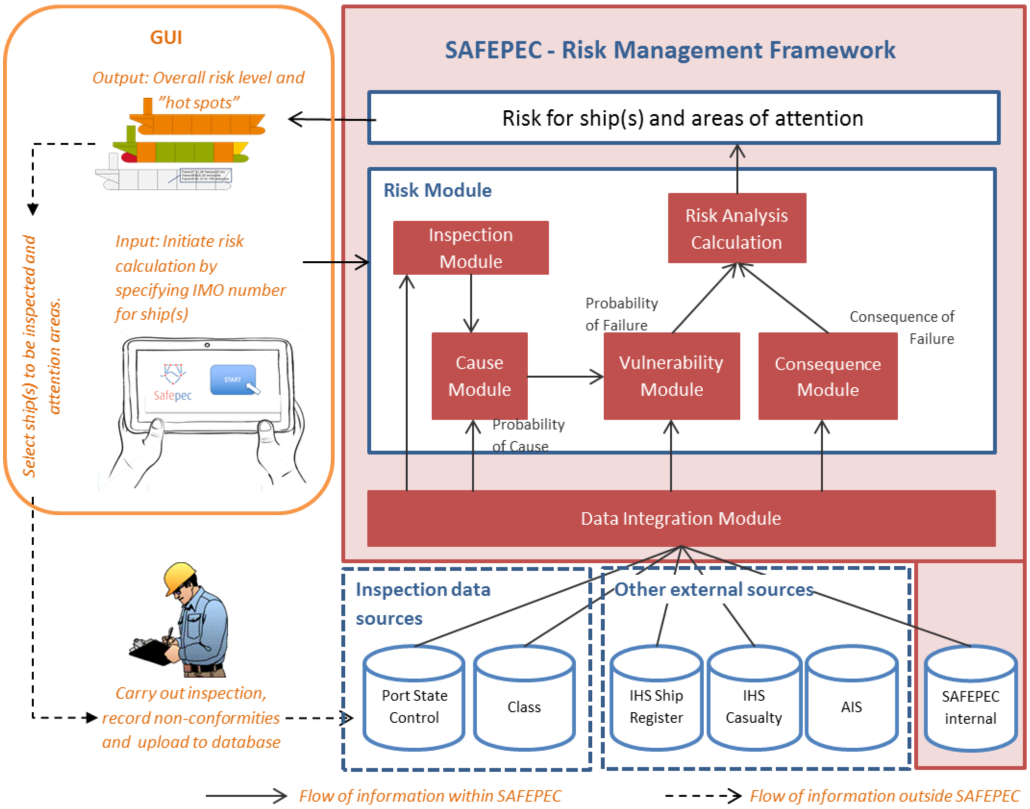


Fig.3: SAFEPEC Tool Overview, *Hamann et al. (2016)*

The steps in using this tool is as follows:

1) Initiate the risk calculation by entering the ship(s) unique ID (IMO number). This can be a list of ships to be compared or just one ship to be benchmarked against a fleet average.
2) Start the calculation: The risk level for each ship is calculated.

3) The result is presented to the user: The risk level for different ships are compared or benchmarking is done towards a fleet average.
4) The ship to be inspected is selected and the areas of concern are noted by the inspector.
5) The inspection is conducted on board and the inspection data is reported in the actual databases and then fed back to the SAFEPEC Tool through the external databases accessed by the DIM.

2. Ontology Design Principles

In this section, we describe the methodology used to create the ontology to implement the integration of heterogeneous data sources containing ship information and ship inspection results, and to present these external data to several risk models in a unified way. The methodology describes how to set up a system to fetch data values from several heterogeneous data sources used by a statistical model as a black box. The different data sources are not visible to the statistical models (Bayesian Networks or Fault Trees); they only have links from the various parameter tables for each node to the external data values needed to do the statistical evaluations.

2.1. Ontologies as Data Integration

The usage of ontologies to define the common semantics of several heterogeneous data sources can basically be done by three different organizations of the ontologies, *Wache (2001)*:

- Single ontology approach where one common, global ontology is defined to describe the shared vocabulary for the domain. All information sources relate to this global ontology. The objects in each data source is related to the global domain model, and these relationships clearly defines the semantic of the source objects and the corresponding objects in the global ontology. The global ontology can also be a combination of several specialized ontologies, especially when the domain is complex. This approach can be applied if all the data sources have a very similar view of the domain.
- Multiple ontologies: Each data source is described by its own ontology, with no common, global ontology defined. This means that no common vocabulary exists, which implies that integration becomes difficult. It is then difficult to compare the different source ontologies.
- Hybrid approaches: This is a combination of the two previous approaches, where each local data source has its own local ontology in addition to a global vocabulary (only the common terms) or a global ontology (also including the relations between terms).

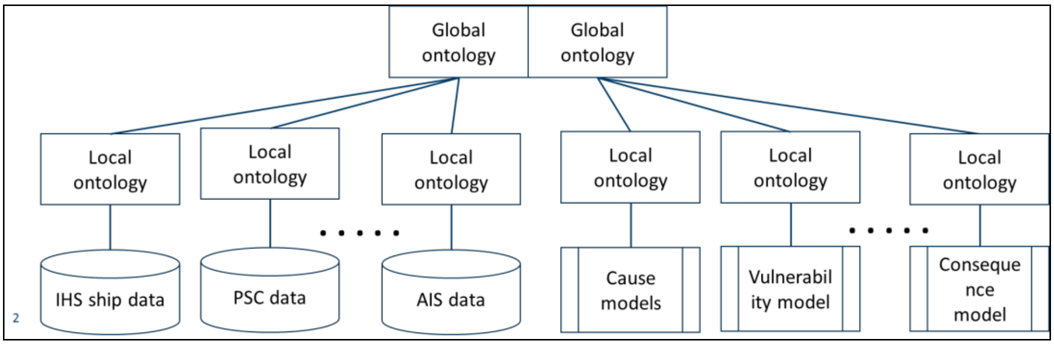


Fig.4: SAFEPEC Ontology Overview

We used the hybrid approach with one local ontology for each data sources and one local ontology for each risk model in addition to a common, global ontology, Fig.4. The global ontology consists of two parts, one describing the high level concepts for the external data sources and one describing the high level concepts that are common for the different risk models. This is further described in Section 3.2.1. The links between the global and local ontologies are ensured by having the classes of the local ontologies as subclasses of the classes in the global ontology.

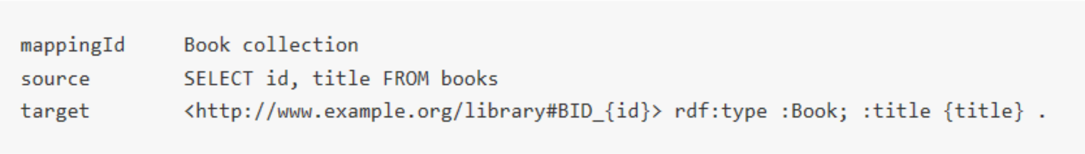
The reason why this approach is chosen can be summarized as follows:

- The data sources used by risk based inspection models are heterogeneous both when it comes to content, structure and the level of abstraction.
- New data sources can be added by just describing the local ontology. Data items already used by the risk inspection models can be replaced by values from the new data source with no changes in the risk models or in the global ontology. If a data item from a new data source that are not previously defined are to be used by a risk inspection model, the local ontology for this risk inspection model also has to be updated.
- We still have the advantages of having a common, global ontology: The different local ontologies can be compared, and queries can be performed on top of the set of both local and global ontologies as a whole.

One disadvantage with having a global ontology on top of local ontologies is that the local ontologies must be written from scratch based on the information needed by the various risk inspection models.

2.2. Ontologies as a Query Model

In this work, we use the global ontology as the basis for performing queries to all the integrated data sources. The modelling concepts described in the ontology are expressed in an OWL ontology, which is a formal language making it possible to execute and reason over the ontology. In addition, meta data is represented using RDF, meaning that SPARQL can be used to query the ontology. In order to ensure consistency of the data, the ontology is designed such that SPARQL queries can be constructed around class restrictions (TBox assertions), that is, the 'is of class'-relation is used to identify the individs of a class. The mapping tool -ontop- is used to populate the ontology with individs (Abox) based on the link between the results of querying the external data sources and the correct classes of the ontology *Muro (2013)*. -Ontop- is a tool that supports the mapping from relational tables to ontologies, as shown in Fig.5.



```
mappingId     Book collection
source        SELECT id, title FROM books
target        <http://www.example.org/library#BID_{id}> rdf:type :Book; :title {title} .
```

Fig.5: Example mapping in –ontop-

The example shows how the id and title columns of a relational table about books are translated to two RDF statements:

1. A newly constructed URI for the new individual with the value for id as its suffix is of type `Book`, i.e. is an individual of class `Book`.
2. This new individual has a data property `:title` with the value asserted to the value of title from the relational database.

The -ontop- mapping statements have one `source` part consisting of a SQL SELECT query possibly with JOINS, GROUP, MIN, MAX, etc. and a `target` part consisting of RDF statements that defines how the result of the SQL query is mapped to the ontology. The reasoner that is used by -ontop- is Quest. It is able to answer SPARQL 1.0 queries and supports OWL 2 QL inference.

Because of this –ontop- mapping, the ABox (individs) only exists virtually at query runtime. We have made it a design principle to use the class restrictions (at the TBox level) to assert that the individuals are related to the classes by an object property assertion 'is of class'. This will ensure consistent classification of the external data. This further means that the responsibility for this consistency is clearly located inside the OWL ontology, *Horridge (2011)*. Further, it implies that we do not need to ensure correct classification and consistency at the individ level through the -ontop- mappings, but instead inside the OWL ontology.

2.3. Ontologies as Data Mapping

This section describes how the ontologies defined in this work is related to the rest of the system that it is part of. This mapping consists of three parts:

- The mappings between the ontologies and the information they describe
- The mappings between different ontologies in the system.
- Mappings to other ontologies.

2.3.1. The mappings between the ontologies and the information they describe

In our system, the mappings between the ontologies and the information they describe, that is, the external data sources, is done by defining the mapping between simple data items in the external data sources and the local ontology. These mappings are implemented by –ontop-, and an outline of the mapping is shown in Fig.2 and also described in Section 2.2.

2.3.2. The mappings between different ontologies in the system.

The global ontology contains of two parts, one representing the statistical models (left side in Fig-10) and the other representing the information fetched from the external data sources (right side in Fig-10). The mapping between the two parts is done by defining the class `para-meter_definition` that links the parameters used in the risk models with the data items needed to set evidence to these parameters.

2.3.3. The mappings to other ontologies

The ontology is defined in a SAFEPEC namespace (http://data.safepec.eu/2016/bn/0.3) only referring to established RDF and OWL standards or widely accepted ontologies like FOAF (Friend of a Friend) or SKOS (Simple Knowledge Organization System). In this way, it will be independent from developments of other ontologies. To provide the link to other ontologies like BFO (Basic Formal Ontology), IAO (Information Artifact Ontology) or domain specific ontologies in e-Navigation, e-Maritime and e-Compliance and thus to add the knowledge encapsulated by the SAFEPEC ontology to the semantic world, there are additional RDF statements using SKOS terms added to the ontology.

3. Ontology Based Data Integration – Methodology and Results

This section describes the methodology used to set up the link between the parameter values needed to evaluate nodes in statistical models (for instance BN models and Fault Tree models). The result of applying the methodology is a global and local ontology defining the mapping from the parameter values used when setting evidence on the risk model nodes to a set of external data sources. The methodology consists of the following steps: Requirement Specification, Ontology Building and Ontology Verification and Validation. This section also describes the ontology used by the Data Integration Module (DIM) to integrate data from various sources containing inspection results and ship data.

3.1. Requirement Specification

During the requirement specification, the following tasks have been completed

1. Identify the purpose and scope of the data integration including specialization, intended use, scenarios and set of terms (characteristics and granularity)

2. Use Cases
3. Competency questions

3.1.1. Purpose and Scope

Two different scenarios are relevant for the DIM. The first scenario is the runtime scenario for the risk management framework. To execute the risk module for a specific ship or group of ships, the risk models have to be adjusted to the characteristics of the respective ship. This adjustment of the risk models happens by setting the risk model parameters to ship specific values. The parameter values are maintained inside the SAFEPEC database. From here, they are queried by keys specific to the risk (sub-)model. The values to the keys are ship specific properties to be obtained from external data sources like IHS Ship Register, Port State Control inspections and other sources. The second scenario is a development scenario. This affects the setup of the risk model parameters. These *parameter tables* represent quantifications of expert judgement. The parameter values result from heuristic approaches and are evaluated manually by the domain experts. The heuristics are based on statistical values (e.g. mean values, standard deviation, parameters in contribution functions) gained from available ship data, i.e. AIS, Port State Control etc., *Graziano et al. (2015)*. Since the statistical data are quite stable over time, for SAFEPEC the parameter values are stored with model parameter tables in the SAFEPEC database and only updated from time to time, and not through the DIM.

3.1.2. Use Cases

The following is a summary of each of the use cases in the risk assessment scenario:

- Get Ship Specific Attributes values: In order to evaluate some details during the risk assessment, some values of ship attributes (main particulars) are required. Additionally, the user interface needs to display some ship specific attributes as background information to the user.
- Get Ship Specific Model Parameters: The system must be able to populate the risk model with the parameters and applying them to the given ship. This corresponds to a specialization of the risk model to the properties of the respective ship.
- Get Evidence Data: With the probability approaches (e.g. Bayesian networks, fault trees) used by the risk models, there may be nodes in which the state for a specific ship is known (or evident). The goal of this use case is to identify whether there are probability variables to which the state is known for the given ship and the value for this state.

3.1.3. Competency Questions

The ontology is developed using Competency questions needed by the use cases defined for the risk models applications. The competency questions are formulated in natural language to check whether the ontology contains enough information to answer these questions, *Noy and McGuinness (2002)*. By doing so, every used term (either object or action) is checked for consistent use inside the set of questions. An illustration of the risk assessment scenario is shown in Fig.6. The figure shows the four main steps to be taken in order to turn a ship's IMO number and a sub-model identifier to the valid sub-model parameter set for a specific ship. The four steps are:

(1) Identify dependency on data integration definitions: This means to identify the sub-model in the overall sub-model hierarchy of the risk assessment model and traverse down to the data integration definitions the sub-model depends on. Traversing the sub-model hierarchy can take more than one step.
(2) Identify ship data items in the scope of data integration definitions: From the type of data integration definition it has to be resolved which types of data items of a ship are required to query the model parameters from the SAFEPEC database.
(3) Query ship data item values for the ship with IMO number: With this information about the required data item types, the values have to be obtained by means of the external data sources.

(4) Get model parameters by ship data item value(s): The ship specific data item values are used to get the model parameters from the SAFEPEC database.

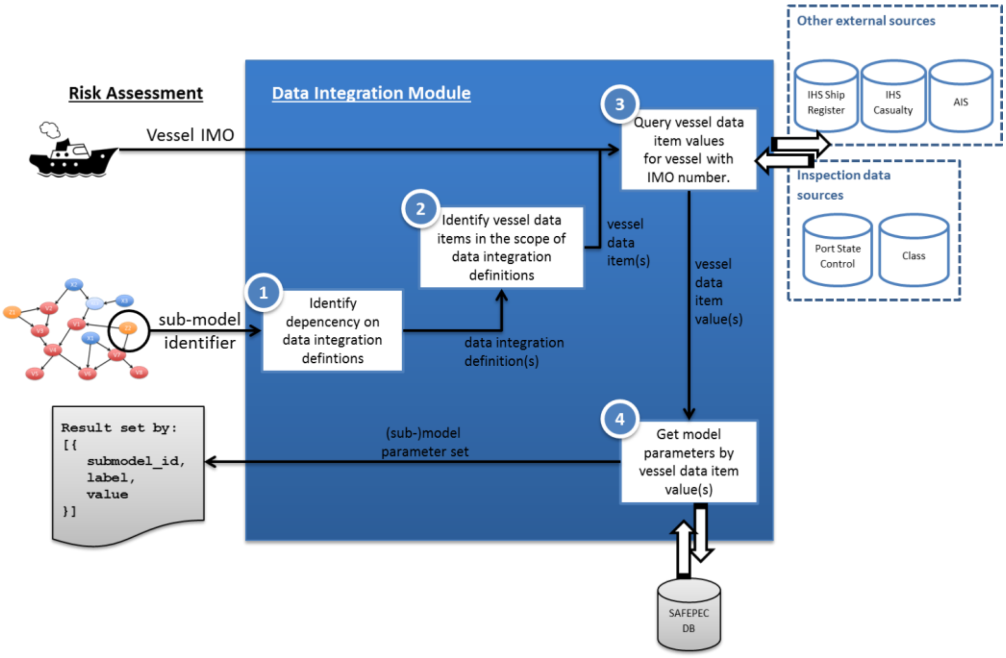


Fig.6: Illustration of the risk assessment scenario

3.2. Ontology Building

3.2.1. Knowledge acquisition

To be able to set up the local ontologies for each of the risk models, details about the knowledge tables and parameter tables were collected from the risk model designers. Fig.7 shows some examples of Parameter tables that are used in the mapping from the external data sources to the nodes in the Bayesian Network for the Corrosion Cause model, *Moser and Hagaseth (2016)*. Here, the scaling factor for corrosion is given for different parameters of a ship (country of yard, building class, flag etc.). For some of the parameters, the values are not directly found in the external data set, for instance whether the building class of the ship is member of IACS or not. Only the actual class society is available. This means that a knowledge table is used to do the lookup from the external data item (the class society) to the IACS membership status, see also Fig.2.

Country of yard	China	Europe	Japan	S-Korea	Other/unknown
	0.67	1.06	1.17	1.11	0.67
Building class	IACS	Non-IACS	unknown		
	1	0.9	0.9		
Flag	White	Grey	black	unknown	
	1.1	1	0.9	0.9	
No of owner changes	0	1-2	>2	unknown	
	1.2	1	0.9	0.9	
Av sailing time between ports	>=3 days	<3 days	unknown		
	1.2	1	1		

Fig.7: Example of Parameter Tables (example values)

Also, to be able to set up the local ontology for each of the risk models, the following must be known, Fig. **8**, *Moser and Hagaseth (2016)*:

- the structure of the model (the relations between each node),
- the name of the nodes,

- the leaf node in the risk models and which parameter table(s) they link to.

The dependencies between (sub-)models can be drawn as a hierarchical graph for the complete risk assessment model, Fig. **8**. Each relevant sub-model can be identified by a node and describes its dependencies. The lowest level nodes in the model dependency hierarchy (e.g. owner, flag) are further called leaf models. The leaf models are input parameters like owner, flag, or class to the higher level (sub-)models. They are no mathematical models like the other (sub-)models but factors quantifying the impact of a named concept (e.g. flag, class or owner) on the dependent sub-models. The quantifications of these impact factors (or model parameters alternatively) are prepared by risk model developers based on domain knowledge and statistical values. They are stored in the SAFEPEC database. The quantification of a leaf node is not constant for all ships but depends on some characteristic values for instance PSC flag rating or IACS membership status. These characteristic values are some concepts, definitions or groupings that provide the link between the actual data available from the real data source and the value required by the leaf-model. For the risk assessment scenario, it is the responsibility of the data integration module to provide the correct values at the leaf models by data integration definitions. In order to illustrate the model or abstractions behind the data integration definitions, the class node from Fig. **8** is shown as an example.

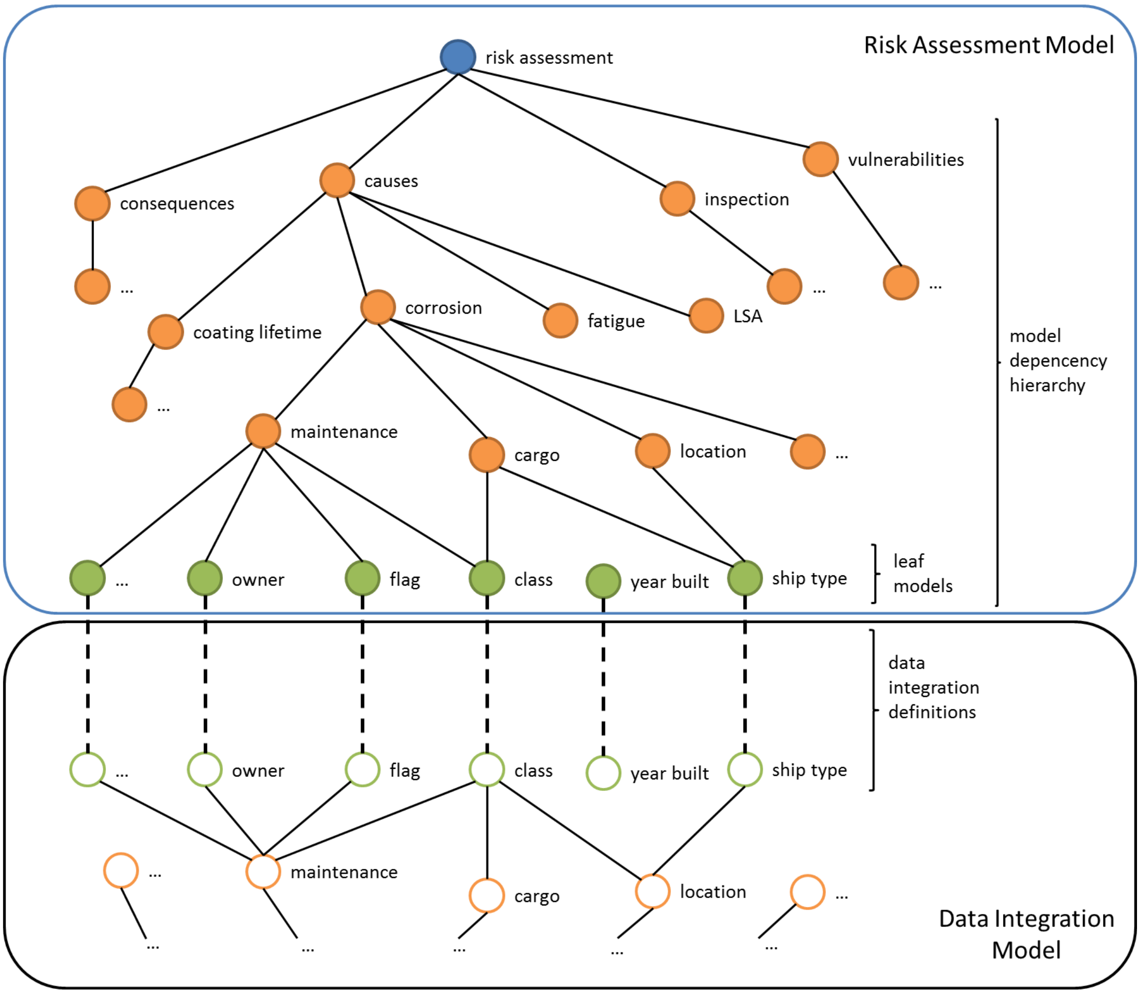
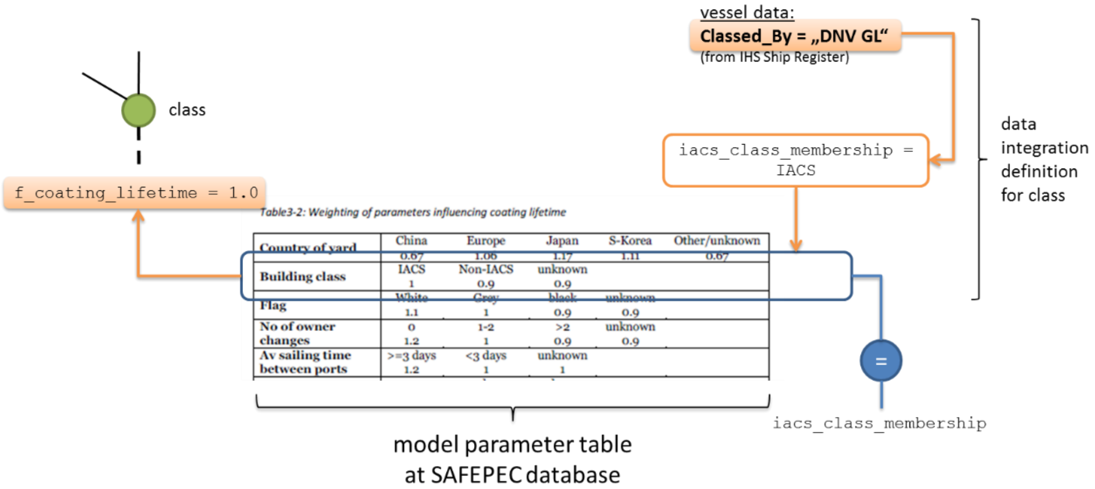


Fig. 8: Simplified hierarchy scheme of sub-models and leaf-models assembling to the risk model

Fig.9 demonstrates that the impact factor class depends on the IACS membership status of the ships classification society. However, this value cannot be directly read from the data sources. Here, only a string value identifying the ships classification society is provided. The gap between the actual ship data and the impact factor (or model input parameter more generally) is closed by the data integration definition. This usually involves one or more artificial higher value concepts like the IACS membership status which must be identified from the risk model descriptions and put into a formal concept. As the DIM will be able to identify all data integration definitions that resolve dependencies of a (sub)-model, the respective sub-models and dependencies have to be setup. This approach can be easily taken to higher levels of the model dependency hierarchy. The data integration model is hence mirroring the model dependency hierarchy of the risk assessment model as far as necessary to resolve the dependencies between the hierarchy nodes.



Country of yard	China 0.67	Europe 1.06	Japan 1.17	S-Korea 1.11	Other/unknown 0.67
Building class	IACS 1	Non-IACS 0.9	unknown 0.9		
Flag	White 1.1	Grey 1	black 0.9	unknown 0.9	
No of owner changes	0 1.2	1-2 1	>2 0.9	unknown 0.9	
Av sailing time between ports	>=3 days 1.2	<3 days 1	unknown 1		

Fig.9: Data integration definition to resolve the quantification of a class node using the abstract concept “`iacs_class_membership`”

3.2.2. Structuring of the domain knowledge in a conceptual model

Fig-10 shows the UML of the global ontology that supports the data integration.

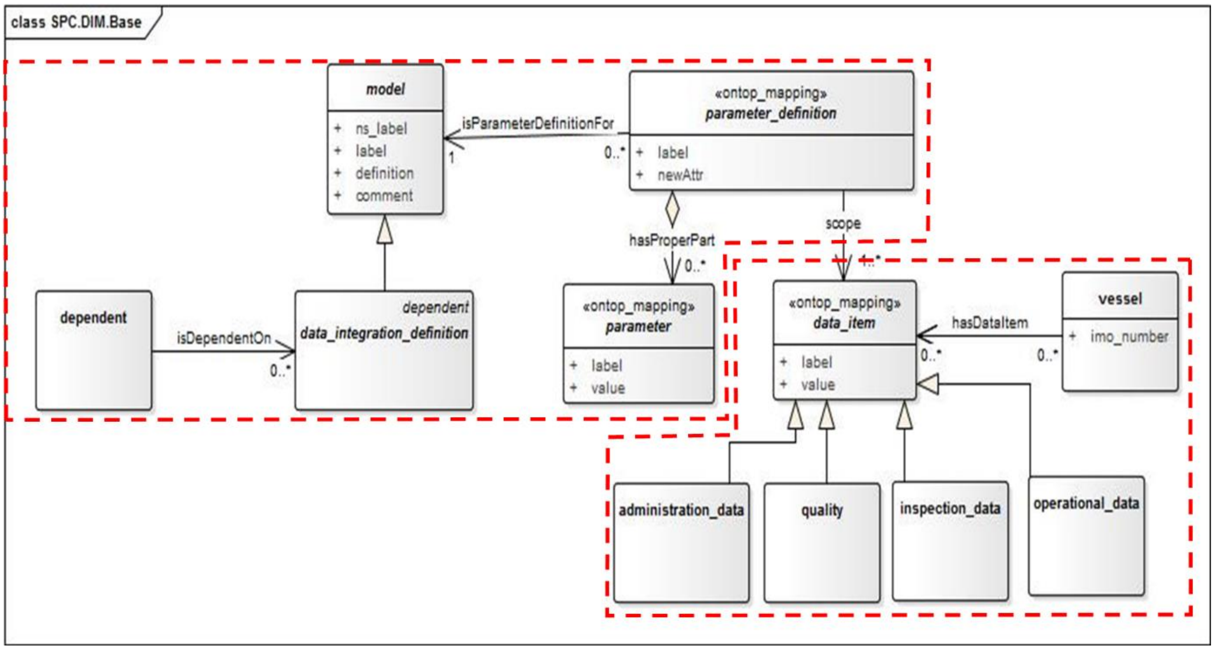


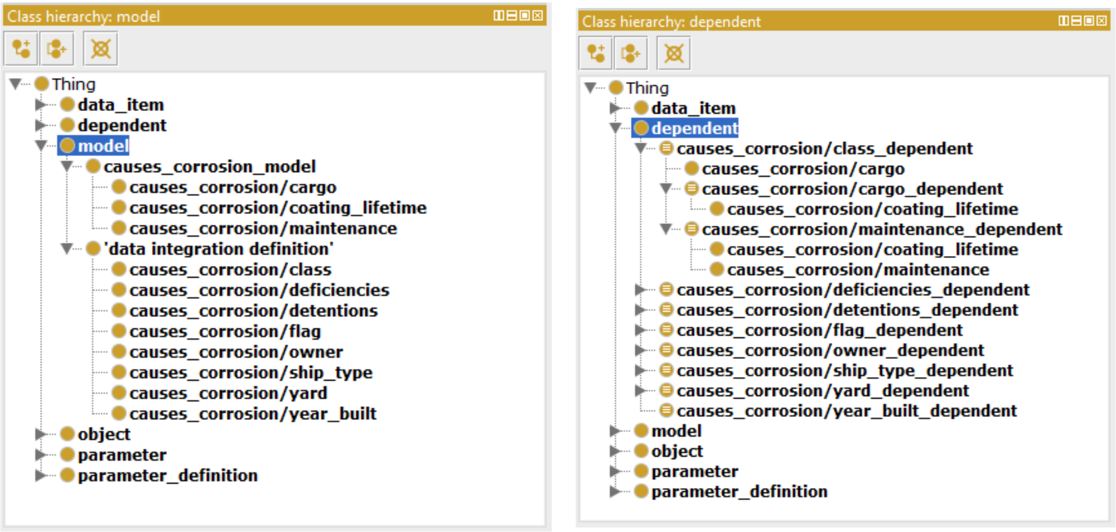
Fig-10: SAFEPEC Basic UML Diagram

The ontology consists of the following parts:

- The classes *model*, *dependent* and *data_integration_definition* represents the structure of the risk models.
- The classes *data_item*, *quality*, *administration_data*, *operational_data*, *inspection_data* and *vessel* represents the items fetched from the external data sources.

- The classes *parameter_definition* and *parameter* represents the mapping between the risk model and the external data items.

Fig.11 shows part of a local ontology for the corrosion cause model. The purpose of the *model* class hierarchy is to establish unique resource identifiers (URIs) to each sub-model of the risk models. The model sub-classes are arranged into a sub-class hierarchy for better overview and maintainability.



Class hierarchy: model

- Thing
  - data_item
  - dependent
  - model
    - causes_corrosion_model
      - causes_corrosion/cargo
      - causes_corrosion/coating_lifetime
      - causes_corrosion/maintenance
    - 'data integration definition'
      - causes_corrosion/class
      - causes_corrosion/deficiencies
      - causes_corrosion/detentions
      - causes_corrosion/flag
      - causes_corrosion/owner
      - causes_corrosion/ship_type
      - causes_corrosion/yard
      - causes_corrosion/year_built
  - object
  - parameter
  - parameter_definition

Class hierarchy: dependent

- Thing
  - data_item
  - dependent
    - causes_corrosion/class_dependent
      - causes_corrosion/cargo
    - causes_corrosion/cargo_dependent
      - causes_corrosion/coating_lifetime
    - causes_corrosion/maintenance_dependent
      - causes_corrosion/coating_lifetime
      - causes_corrosion/maintenance
    - causes_corrosion/deficiencies_dependent
    - causes_corrosion/detentions_dependent
    - causes_corrosion/flag_dependent
    - causes_corrosion/owner_dependent
    - causes_corrosion/ship_type_dependent
    - causes_corrosion/yard_dependent
    - causes_corrosion/year_built_dependent
  - model
  - object
  - parameter
  - parameter_definition

Fig.11: Example class hierarchy of class *model and dependent*

The *data_integration_definition* class represents the parent class to all models that are data integration definitions. The risk model and its sub-models establish an internal dependency hierarchy. These dependencies are represented as sub-classes of *dependent* in the ontology, Fig.11.

3.2.3. Integrating existing ontologies

The ontology defined here can be linked to other relevant ontologies, for instance SKOS (Simple Knowledge Organization System) to represent thesauri, classification schemes, taxonomies, subject-headings and other structured information, BFO (Basic Formal Ontology) to support information retrieval, analysis and integration, among others. Also, the ontology can be linked to domain specific ontologies, for instance the maritime ontology defined in the e-Compliance project that was developed to be able to structure the meaning extracted from maritime regulation texts, *Hagaseth et al. (2016)*. This was done to be able to query the regulations at a detailed level, down to separate sentences. Most of the work focused on describing the applicability of each sentence in the regulation text to a certain ship type with certain ship particulars. The relation between the two ontologies can be described by making the classes subclasses of *SKOS:concept* and then use the *SKOS:related* property to link the two ontologies. This can be done to relate the *vessel* class in SAFEPEC to the *ship* class in e-Compliance. One advantage of doing this is the possibility to query the maritime regulations for text that is applicable to exactly the ship in question. Based on the ship particulars, the set of regulation text that is applicable to this ship can be found.

3.3. Ontology Verification and Validation

The verification of the ontology is done by running the competency questions defined and also by using the VQS tool to visualize the ontology, *Soylu et al. (2016, 2017).*

4. DIM Architecture

Fig.11 gives the component view of the DIM prototype. The *SPARQL Manager* handles all external calls. Based on the ontology, it prepares a valid SPARQL query and passes it to the Mapping

Manager. The returned result set also forms the result set for the call and is transformed to the expected format, e.g. JSON.

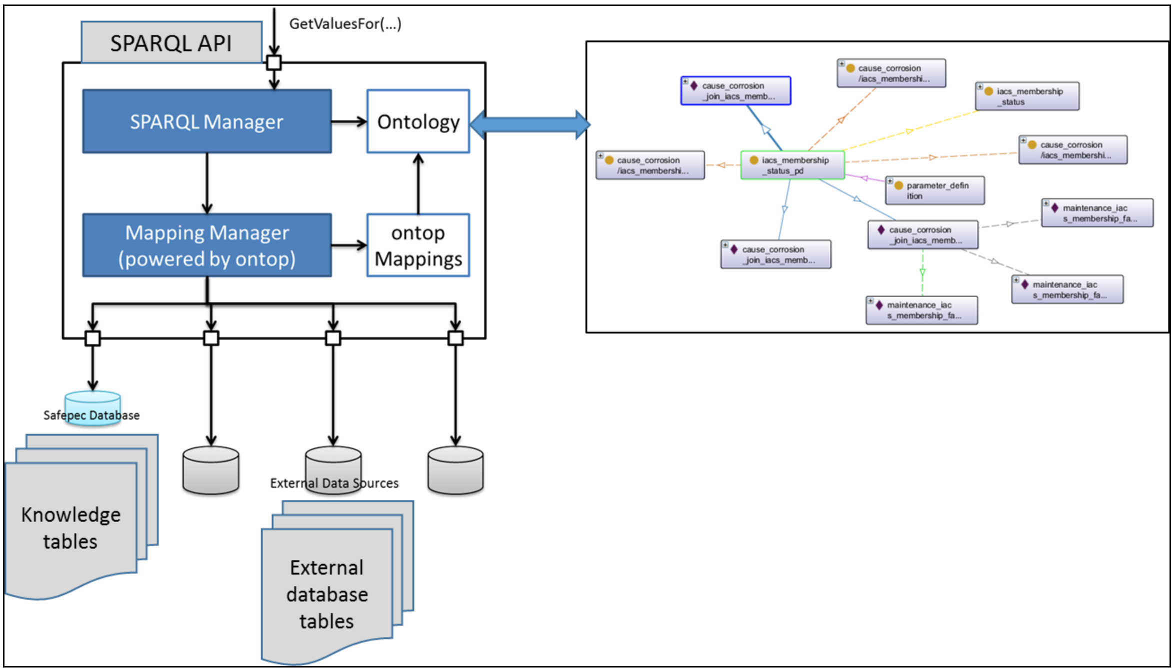


Fig.12: Component view of the DIM

The *Ontology* component contains the data integration definitions, that is, the Ontology stores the knowledge by which it is possible to resolve the sub-models to the data integration definitions that the sub-model depends on. Additionally, the Ontology encodes by which aggregation of ship data the correct values can be found at the SAFEPEC database. The *Mapping Manager* encapsulates -ontop- and is responsible for executing the SQL queries. The -*ontop*- *mappings* define how the individs are constructed from the results of the SQL queries.

5. Conclusion and Further Work

The Data Integration Module (DIM) described here provides ship specific technical data and risk model parameters to the SAFEPEC risk module for risk evaluation. Although using heterogeneous data sources, consistency and validity of the data are ensured by the DIM. The DIM utilizes ontology-based data integration. In contrast to a standard approach to data integration, the use of an OWL ontology implies representing the meaning of the data concepts by a formal language. The implementation effort can then be limited to provide a framework that ensures ontology-based data access. Here, we use -ontop- to implement the mappings from the external data sources and to the integration ontology. Based on the requirements analysis the global ontology for providing data to the risk models was developed. Since the ontology is written in OWL, it is open for extensions needed by each of the risk models. Additionally, the ontology is open for establishing references to existing ontologies. However, using –ontop- means that the external data must be available in relational databases or converted to relational databases, or alternatively using virtual databases. The main task is to set up the local ontology for each risk model, both the structure of the graph and the parameter tables and knowledge tables. Further work would be to implement the mapping from this ontology to other ontologies related to the maritime transport domain.

Acknowledgements

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Preparing for a Digital Future –
Experiences and Implications from a Maritime Domain Perspective

André Keane, Ulstein International, Ulsteinvik/Norway, andre.keane@ulstein.com
Per Olaf Brett, Ulstein International, Ulsteinvik/Norway, per.olaf.brett@ulstein.com
Ali Ebrahimi, Ulstein International, Ulsteinvik/Norway, ali.ebrahimi@ulstein.com
Henrique M. Gaspar, NTNU, Aalesund/Norway, henrique.gaspar@ntnu.no
Jose Jorge Garcia Agis, NTNU, Trondheim/Norway, jose.agis@ntnu.no

Abstract

The re-emergence and subsequently increased credibility of big data analytics to support and enhance effective decision-making in recent years, comes largely because of significantly increased available computing power, which has consequently caused a dramatic spur in the generation of new applications encroaching upon the normalcy of business processes and models. Maritime industries are often attributed with an elaborate complexity, which often protrudes the difficulties of state-of-the-art technology adaptations and implementations that have not been developed natively within the industry. As such, there is a clear need for a modern, systemic, and methodological approach so that more traditionally inclined industries not only can utilize such digital enhancements, but embrace it to further contribute towards previously incomprehensible applications and provide enhanced sustainability including but not limited to higher productivity and new business opportunities. This paper examines the empirical and implicational facets of embracing digital technologies in the maritime domain from a Big Data Analytics handling perspective. It presents an introduction on the emergence of digital technology, discusses the challenge of integrating such innovations into the traditional maritime business and presents a few examples from Ulstein digital experiences.

1. Extended Systems of Systems Boundaries and its Effect on Traditional Maritime Business

With over 90% of the world trade being carried by ships, the maritime industry is, more than ever, an integral part of the process of globalization, which makes it strongly dependent of the world behaviour. As such, the industry is influenced by factors such as economy, trade, production, consumption, politics, financing, and technology that drive the demand and supply of manufactured goods, raw materials, and shipping services, *Stopford (2009).*

Companies operating in the maritime business are challenged by much more extended and somehow *liquid* system of systems boundaries, a VUCA world. Volatility, complexity, uncertainty, and ambiguity (VUCA) coexist in many industries, *Bennet and Lemoine (2014)*, maritime being one of them. VUCA aspects characterize the technical and managerial development of firms, limiting innovation, and challenging the implementation of new technologies, *Corsi and Akhunov (2000)*. Fuel prices, market supply or demand are volatile variables. They are influenced by a diverse list of factors that makes them unpredictable. Although we know they are continuously changing, it is very difficult or impossible to predict their exact behaviour. Volatility covers the expected but unpredictable. Fuel price is one of the volatile factors with stronger influence in the maritime industries. Uncertainty, contrary to volatility, refers to changes that are not expected. New regulations, new market entrants (products, services, or business models) or natural disasters are typical examples of uncertainties affecting the maritime industry. Both, volatility, and uncertainty can be assessed by simulation of future scenarios, *Schoemaker and van der Haijden (1992)*, which improves the agility of the company in reacting towards unpredictable or unexpected changes. Data availability, storage capacity and increasing capability are key drivers in mitigating future uncertainty, and the emergence of Big Data Analytics and Artificial Intelligence (AI) bring with them capabilities that will undoubtedly further our understanding the technology is matured.

The complexity of the maritime industry and its corresponding decision-making processes are a cause of the large variety of operations, operational environments, and multitude of stakeholders. This complexity at industrial level influences directly on the degree of complexity of the systems operating in it, such as the fleet, the ship, and its subsystems, *Gaspar et al. (2012)*. If we define complexity as the amount of relevant information to properly define a system, how then to be precise and establish a boundary for properly enough? Such reflexions in the industry foster ambiguity. Typically, the latter relates to the lack of data, comprehension, and a clear idea about cause-effect relationship. How will the market react to a new disruptive product? Will these extra functionalities or capacities add value to the customer? How much more information is necessary to increase precision and reduce uncertainty? Experimentation, simulation, and data analysis can solve this problem. One example is the use of statistics and multivariate data analysis to estimate vessel performances, *Ebrahimi et al. (2015)*. Virtual prototyping brings the possibility of simulating changes during design or operational phases before their real implementation. It gives the opportunity of testing before experiencing, which reduces the probability of errors, and furthermore improving efficiency, safety, and environmental friendliness. It is important to approach design in the conceptual phase from different perspectives: This is to differentiate among different solutions, to have better understanding of consequence for input change, to measure Goodness of Fit between initial product expectations and final as built performance yields, to have more meaningful benchmarking with market competitors, to make better and more robust decision-making in vessel design, and to support the development of effective sales arguments.

Counter to other comparable industries such as aerospace or automotive, the maritime industry constitutes a cost-driven business model, *McCartan et al. (2014)*. The implementation of innovation and new technologies will be challenged by cost as the only benchmark, since maritime companies in general act capitalistically, *Borch and Solesvik (2016)*. This view acts in direct contradiction to innovations and new technologies, labelling many shipping companies as “deeply conservative”, *Glave et al. (2014)*. Considering these premises and the difficulties of connecting technological developments to growth in revenue, technical development in shipping, has historically been moved to second division play, *Dijkshoorn (1977)*. Other factors such as human, regulatory, and financial, challenge the introduction of new technologies and innovative features in the maritime industry as well.

Considering the potential benefits and the challenges for its implementation, *Norden et al. (2013)* suggest changes in the business concept as a way towards the digital future. A switch from a product-based business concept, typically focused on costs, towards the more service-oriented approach, which focuses on recurring revenue and overall system performance over its life time. Such change, would open the door to innovations and new technology that may increase the revenue making capability of the design solution at a required but justifiable higher initial investment, and potentially reduce lifecycle costs and increase overall performance yields. Leading companies such as GE, IBM, Rolls-Royce, or Siemens are all looking for how such “servitization” concept should be applied in their respective industries, *Ahamed et al. (2013)*.

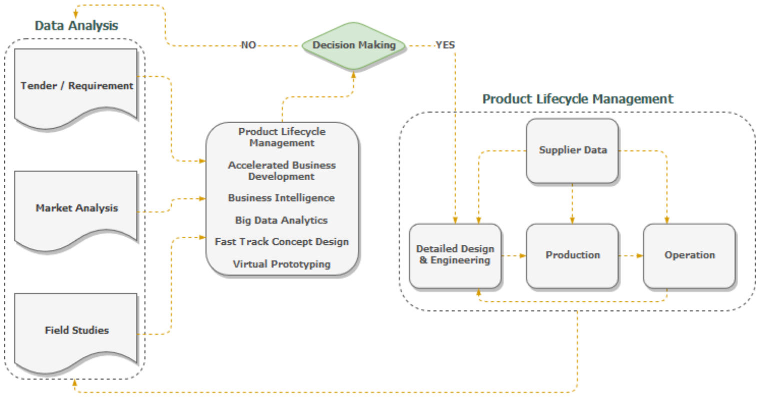


Fig.1: Ulstein Value Creation Process in Vessel Design

The different steps of the Ulstein value creation process, digitalization, and automation of processes are continually being applied to reduce time and required resources, while at simultaneously enhancing robustness of the decisions and actions that are being made. Fig.1 illustrates the process within a product lifecycle context for ships. This is a new product development process where different business intelligence approaches, tools and techniques are applied to improve overall system effectiveness. The exploration of these phenomenon and recent related developments of the maritime industry are reviewed by this paper.

2. The Integration Challenge

2.1. PLM as an Umbrella

Products within the maritime domain not only must comply with a vast set of requirements governed by national and international politics, rules and regulations, and vested stakeholder interests, but a high performing asset also demands exceeding capabilities within aspects such as the commercial, technical, and operational, *Ulstein and Brett (2009)*. Such multi-faceted criteria as input to product development requires a robust product development suite to supplement the human capability and to stay competitive as a product supplier. Product lifecycle management (PLM) was introduced in the 1990s to better manage information and expand the scope of computer aided tools throughout all phases of a product's lifecycle, which from a manufacturer's standpoint is comprised of imagination, definition, realisation, support, and retirement, *Lee et al. (2008)*. Such an approach enhances the overall effectiveness of vessel design, *Ulstein and Brett (2015)*.

PLM is the business activity of managing a product from first idea to final retirement – cradle to grave, *Stark (2015)*, which furthermore can be viewed as an approach to integrate information, people, processes, and business systems, *Lee et al. (2008)*. Realising such an approach in practice, not only encompasses an immense amount and variety of data in terms of volume, veracity, and compatibility, but also requires interfaces to enable an efficient two-way communication channel for information exchange among relevant stakeholders. Adding to the consideration an inherent complexity within ship design, manufacturing, and operation, the challenge of integration is an intractable one.

Lee et al. (2008) argue that PLM originates from two main domains: The first being enterprise management, which further consists of subdomains such as enterprise resource planning (ERP), customer relationship management (CRM), and supply chain management (SCM); and the second sourced from product information management. The latter largely pertains to computer aided design and manufacturing, and product data management tools that have become imperative in the process of product development, *Sharma et al. (2012)*.

Taking a ship as a product-example from the maritime domain, the lifecycle phases pertaining to product definition and generation in a PLM context serve to provide a complete product definition in terms of both performance evaluation and input documentation for subsequent production activity. Each module in the core product data model is composed of multidimensional sources of information in terms of formatting, frequency, and compatibility to name a few, which, in turn, clearly exemplifies the extent of the integration challenge to systematically manage the product's lifecycle. From a shipbuilding perspective, *Morais et al. (2011)* further elaborate regarding some of the main challenges of technology adoption within the industry.

2.2. PLM as Basis for Emergent Technology

As increased competition among vendors thrive, an increase in demand drives complexity in modern engineering design, which furthermore protrudes the nuanced and frail trade-off between technical, operational performance, and commercial viability, *Sharma et al. (2012)*. For a product in development to meet or exceed customer expectations and simultaneously adhere to regulation, coordinate cross-functional workloads, and deliver on budget, it would follow that through an increase in design complexity, the resulting information produced to manage and govern the product's total lifecycle would increase proportionally. Mitigating potential model inconsistencies in the flow and management of product information over the lifespan is stated as one of the major concerns and keys to a successful PLM implementation, *Thimm et al. (2006)*. Minimising the probability of inconsistency in such an information model can be obtained through meticulous data decomposition, tracking, and gathering, ensuring a high degree of fidelity, level of detail, and perspective.

Kessler and Bierly (2002) claim that a fast-paced innovation strategy is increasingly successful if context is predictable. It is well documented that a well-executed PLM implementation leads to availability of quantifiable product information for purposes of knowledge decomposition and analytical insight, increased quality assurance and compliance, collaboration and communication, which all contribute to a transparency increase in context, which again would facilitate an intensified agile product development, *Stark (2015), Lee et al. (2008).*

In recent years, the term Industry 4.0 has emerged as a central topic of discussion, aiming to accentuate the current paradigmatic transition in technology towards increased use of cyber-physical systems, as compared to the previous three editions of the industrial revolution, which in short consist of water- and steam powered mechanical manufacturing, electrical mass production and labour division, and the digital revolution from the 1960s to the 1990s, as Industry 1.0, Industry 2.0, and Industry 3.0, respectively, *Devezas et al. (2017)*. Albeit with a slight manufacturing focus, Industry 4.0 does convey a central point, namely that digital and physical processes, technology, *Schmidt et al. (2015)*, and products continue to further intertwine, and as such will fundamentally change the inner workings of supply chains, business models, and processes the like, *Berger (2014).*

2.3. Can Diverse Data Have Compatible Taxonomy?

As previously introduced, vessel design, engineering and fabrication follow traditional approaches and the application of conventional marine systems design theory, methods, and analytical tools, comparatively can be characterized the same way. Current ship design, engineering and fabrication approaches are fragmented, discontinuous, time consuming, and laborious the way they normally are carried out. Rationalization of business and work processes (e.g., modularization, parameterization, and other design automation techniques) have so far, only to little extent been tested out and implemented. The main cause of these distances to more modern approaches is the lack of standards, common practices, and diversity of taxonomies that a ship can have.

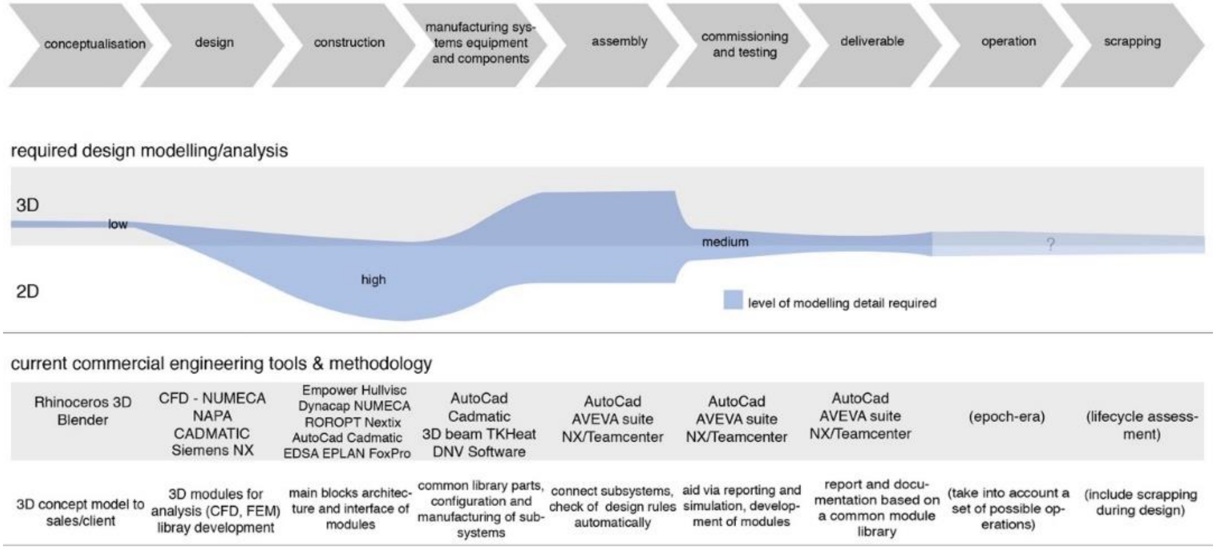


Fig.2: Relevant information related to activities in the ship design value-chain with example of current commercial tools, *Gaspar (2017)*

The ship design value chain is divided in multiple phases and gates, and many actors are involved, Fig.**2**. Traditions and approaches vary from designer to designer, from country to country, and from yard to yard. Only to a limited extent are novel and state of the art knowledge and technology (ICT–tools) in use to streamline and improve the efficiency of such work processes, and actor interfaces.

Moreover, highly detailed 3D concepts are presented to the client prior to a signed contract despite much of the engineering being remodelled in 2D, and few attempts to operate in 3D during the assembly phase. This excessive re-modelling, blocks innovation and consumes unnecessary time. The cause can mainly be attributed to the difference in boundary definition and placement for the parts and systems of the ship between phases.

Hierarchization was once considered the solution for such lack of standard: it handles the complexity on different layers and systems, such as the SFI group system in the 1970s, *Manchinu and McConnel (1977)*. Unfortunately, it also constrains the understanding of the system by a specific set of rules, which may not work in a different context. A mapping between such stiff hierarchy and other more pragmatic taxonomies is then necessary. The cumbersome task of handling multiple taxonomies and diverse tags attributed to each part/system is now promised to be handled by modern PLM systems.

3. Emergent Technologies in the Maritime Industry

3.1. From PLM to Everything Else

PLM systems promise to keep control of products' digital data structuring, using dedicated (and expensive) software for improving the management and collaboration of the team throughout the product development process. If modern PLM systems deliver on the promise of handling the aforementioned challenges of multi-taxonomy/disciplinarily issues, it is reasonable to assume that we can start to use PLM as a foundation towards handling and storing diverse data, and furthermore develop other emergent technologies.

The drawbacks of a decision to go completely via PLM are, however, well known. It is vital to understand how complicated and time consuming the implementation of a PLM project might become depending on the company requirements. Often maritime companies consider PLM system as too time and resource consuming before bringing benefits, and tend to avoid it or postpone its implementation. Another drawback is the failures of previous implementation attempts, *Levisauskaite (2016)*. PLM systems have been promising implementation miracles for years. Many ship design companies faced difficulties in the past, including Ulstein, when managing the large scale of data using 10-20 year old PLM systems, and such a poor experience is clearly reflected when introduced to more modern and agile software.

3.2. Cloud Computing and the Internet of Things

To circumvent sizeable capital expenditures and other typical challenges of on premise computing solutions, such as required space and maintenance for hardware, or need for competency in conjunction with advanced configuration, Cloud-computing has emerged as a viable solution. Aimed at providing much of the same solution scope, and at greater convenience, such systems have become highly scalable and personalised to the extent that many companies have chosen to outsource large, or all, parts of in-house IT infrastructure in favour of cloud services, *Willcocks and Lacity (2016)*. Complementarily, there has been a similar development in the adoption of Internet of Things (IoT), defined as "a set of interconnected things (humans, tags, sensors, and so on) over the Internet, which have the ability to measure, communicate and act all over the world," *Díaz et al. (2016)*. Whereby Cloud computing has virtually unlimited capabilities in terms of storage and processing power, IoT infrastructure comparatively lacks the same features. As such, the inherent complementarity that enables IoT to be abstracted from its limitations, and Cloud computing to fruition, has led to the Cloud of Things, *Aazam et al. (2014)*. Leveraging the combined strengths of these technologies has become a priority for many solution providers, *Díaz et al. (2016)*, https://news.microsoft.com/2016/07/11/ge-and-microsoft-partner-to-bring-predix-to-azure-accelerating-digital-transformation-for-industrial-customers/, and has certainly also minimized the barrier of entry for parties still considering whether to pursue such technology in their organisation. The application of practical IoT use has been demonstrated in a vast set of use-cases, such as the structural health of buildings, waste management systems, traffic congestion monitoring, energy consumption monitoring, smart lighting, building automation, nursing home patient monitoring, eating disorder mitigation, and indoor navigation for the blind, to name some, *Zanella et al. (2014), Al-Fuqaha et al. (2015)*. In the maritime domain, there have also been several publicized initiatives spurred on by larger industry actors, e.g. Hyundai Heavy Industries, *MarEx (2016), Wärtsilä (2016),* and DNV GL, *Späth (2017).*

3.3. Simulation and Virtual Prototyping

The rapid development of computational power and the need of robust, quantitative metrics have progressively incentivized the implementation of simulation and virtual prototyping in the maritime industries. Starting in academic environments as a way to generate knowledge, *Haddara and Xu (1998),* and expanding lately to rule development, *Glen (2001)*, training purposes, *Pawlowski (1996),* conceptual design, *Chaves and Gaspar (2016), Erikstad et al. (2015),* construction, *Karpowicz and Simone (1987)*, and operational management, *Ludvigsen et al. (2016).*

In general, the ship design environment has been the one using the most simulation and virtual prototyping within the maritime industry. The lack of information at early concept design stages, together with influence on final performance of decisions taken at this stage – up to 80% of the costs are fixed in the concept design, *Erikstad (2007)* – spurred the need of understanding the consequences and implications of decisions in technical, operational, and commercial performances, *Ulstein and Brett (2015)*. Specific, single-attribute simulation tools could not solve this complexity problem, therefore holistic, multi-attribute simulation tools have been the core focus of recent research. Concept design workbenches developed both by universities and industry, pursue the acceleration of the concept design development process and to increase the potential number of alternatives being evaluated during consideration of changing contextual factors. These workbenches approach the concept design development from an alternative perspective. Rather than focusing purely on design parameters their approach embraces the selection of functional requirements, and which mission the vessel is intended for, as a premise to design a better vessel: “it is only when having the correct set of requirements that we can decide upon the correct vessel”, *Gaspar et al. (2016).*

VISTA (Virtual sea trial by simulating complex marine operations) is a simulation-based workbench to assess operability performance of a design, *Erikstad et al. (2015).* Its goal is to shorten the time spent in concept development and make it more efficient, by creating a template to configure alternative designs and measure their performance. Notwithstanding, as a state-of-the-art simulation tool for ship design, VISTA does lack a commercial perspective. *Chaves and Gaspar (2016)* present a similar approach based on open-source web-based applications. As an alternative application, *Li et al. (2016)* assess the value of implementing virtual prototyping to support the planning phase of offshore operations though simulation of vessel’s manoeuvrability.

3.4. Big Data

Following the emergence of Industry 4.0, the prevalence of digitization, and the ensuing deluge of information and knowledge that has surfaced because of it, the topic of Big Data has been at the centre of many discussions in terms of defining what it is, and how it can be done. In that respect, *De Mauro et al. (2015)* after a thorough review, suggest an entailing characterization of volume, velocity, and variety in terms of the what, and “… specific Technology and Analytical Methods for its transformation into Value” as to the how. The definition leaves little to interpretation in terms of compositional criteria, but it does leave the innate content of said criteria still as a topic under development and one to be further explored. More specifically, the technology used to gather, process, store, and distribute various sources of data, as well as the methodology with which said data is transformed into insight and subsequent value creation, are the components in need of attention and development to achieve the end goal of spurring economic value. It is generally agreed that as the volume of data keeps growing, opportunities for new discoveries increase thereafter, *Manovich (2011).* It is also anticipated to facilitate and create substantial shifts in a range of different disciplines, bringing disruptive innovations into play and potentially revamping how research is conducted, *Kitchin (2014).* Nevertheless, organizations are still facing significant challenges in understanding the guiding principles and value proposition during early stage adoption, *Wamba et al. (2015).* A main cited contributor is the multidisciplinary knowledge required across topics such as statistics, programming, and other domain (industry) specific fields, to effectively understand the business challenge at hand, and envisage the necessary solution scope that will provide an economic surplus upon completion, *Dumbill et al. (2013).*

Considering prevalent Big Data technology, Hadoop was one of the first commonly available frameworks developed for distributed storage and processing of Big Data. Since its inception in 2003, it arguably has emancipated utilization of big data analytics (BDA), as it could be run by computer clusters based on cheap commodity hardware. Over time, many competing, as well as complementary, systems have been developed, many of which have been adopted by the Apache foundation to ensure operational maintenance and further development, e.g. Apache Pig, Apache Hive, Apache Spark. The latter has for several applications become a contender to be reckoned with, even though the two are not mutually exclusive and can work together in some fashions, *Gu and Li (2013)*. There are an untold number of other technological solutions not mentioned herein, as a complete overview is beyond the purpose and scope of this paper.

When considering methods and techniques of approach, implementing, and governing Big Data initiatives, there are many options to consider. Prominent techniques used in the context of analysis and prediction include data mining, clustering, regression, classification, association analysis, anomaly detection, neural networks, generic algorithms, multivariate statistical analysis, optimization, heuristic search, *Chen et al. (2012).*

As has been briefly touched upon in this paper, there are many variations of which to choose from when evaluating technologies and methodologies for Big Data analytics (BDA). Notwithstanding, the most impactful challenge lies in the implementation and embracement of BDA as a core part of the firm's business model as a quote from *Henke et al. (2016)* states: "the real power of analytics-enabled insights comes when they become so fully embedded in the culture that their predictions and prescriptions drive a company's strategy and operations and reshape how the organization delivers on them." These initiatives are often easy to deprioritize as leadership is often focused on performance and the bottom line based on individual projects or cases, whereas pivoting towards a more holistic perspective, and aggregating each incremental gain, might depict a much larger benefit. Uncovering this value in the early stages of BDA initiatives is paramount to gain traction and acceptance.

BDA in practice emanates from many fields and sectors, ranges from economic and business activities to public administration, and from national security to scientific research, *Chen and Zhang (2014).* State-of-the-art applications and use-cases are copiously being developed, including behaviour prediction, healthcare analysis, content recommendation, and traffic forecasting, *Lv et al. (2017).* In maritime, much of the focus has currently resided with geospatial analysis, *Adland and Jia (2016),* logistics optimization, *Xu et al. (2015),* and condition based monitoring, *Wang et al. (2015).* Additionally, the Japan Ship Technology Research Association has been reported to invest a substantial amount of funding into a vast BDA system designed to analyse yard workers' behavioural patterns by gathering and analysing imagery, radio-frequency identification tags, and physical force gathered from smartphone accelerometers, *Wainright (2016).*

3.5. Artificial Intelligence

The first reported work referencing artificial intelligence (AI) emerged in 1943 and touched upon knowledge of basic physiology and functions of neurons in the brain; the formal analysis of proportional logic; and Turing's theory of computation, *Russel and Norvig (1995).* Both applications and research have come a long way since then, and to portray how it currently can be utilized some explanations are in order. The most prominent interrelationship between fields within AI research normally depict a hierarchical structure showing AI at the top, Machine Learning (ML) in the middle, and Deep Learning (DL) as the newest addition, http://blog.algorithmia.com/ai-why-deep-learning-matters/. Whereas the term AI is commonly accepted as a machines capability of mimicking human intelligence, ML refers to algorithms that allow computers to learn behaviours by generalizing from data, and DL a representation-learning method with multiple levels of representation based on artificial neural networks (ANN), *Bravo et al. (2014).*

Using ANNs to emulate how the brain functions, in conjunction with higher levels of representation, enables the machine to identify features that have not been designed by human engineers, they are learned, *LeCun et al. (2015).* Combined with the increased availability of high performance parallel computing via the cloud, this methodology has become increasingly present in consumer products, such as language translation, image context recognition, or purchasing recommendations. Recently, Google created a novel approach using DL to replace large parts of their existing language translation service, Johnson et al. (2016). Whereas most translation systems only work on a single pair of languages, this method could handle multiple pairs despite not having been directly trained to do so. As such, based on discovered patterns, the machine essentially created a new language that could translate via an intermediary.

Within a maritime domain, the use of DL yields little results in terms of academic research literature. Identified examples have shown application regarding image processing for ship detection, *Tang et al. (2015),* and the response or load prediction of offshore floating structures, *Mazaheri (2006), Uddin et al. (2012), Maslin (2017).*

4. Preparing for the Future – Ulstein Experiences

4.1. Decision Making in Ulstein

It is important to approach vessel design in the conceptual phase from different perspectives: i) To differentiate among different solutions; ii) to have better understanding of consequence for any small input change; iii) to measure goodness of fit between final product and requirements; iv) to have more meaningful benchmarking with market competitors; v) to make better and more robust decision-making in vessel design; and vi) to support the development of effective sales arguments of - what is a better vessel. Furthermore, Ulstein appreciates that proper and effective decision making should be based on the fact that ship design is a multi-variable-based decision making process, and big data oriented to secure proper balancing of new vessel designs with appropriate trad-off among requirements to resolve the inherent complexity of ship design. It is essential that the decision-making model can demonstrate, separate and distinguish among the effects of design parameters (main dimensions, power, mission attributes, machinery, etc.) on final vessel design performance yield, *Ebrahimi et al. (2015).* The Ulstein approach typically, integrates both multi criteria evolutionary problems with multiple objective optimization problems to come up with the better solution. Ulstein applies complementary methods for benchmarking of ship designs: i) Ranking based vessel design including indices developed based on vessel missions, scoring by indices, and ranking by statistics. Ulstein also apply Hierarchical multivariate based vessel design benchmarking according to smarter, safer, and greener performance perspectives by i) hierarchical factor categorization, ii) metric attribution of design factor causal map matrices and iii) hierarchical comparative based ranking.

4.2. Data Integration in Practice

As has been highlighted previously the challenge of creating a centralized, organized, and maintained single version of the truth, is a formidable yet increasingly surmountable task. Facilitated by new storage and processing technologies such as Apache Hadoop and Microsoft Azure, NoSQL, or T-SQL, and combined with modern processes of transformation, augmentation, and automation using languages such as R, M (Power Query), Python, and PowerShell, Ulstein has initiated the creation of an integrated ecosystem of information – the Ulstein Big Data Repository. Currently, the scope has largely covered domains such as finance, market intelligence, and resource management much because of the transaction based nature of residing information. Moving forward, the product and all aspects pertaining to vessels and ship designs lifecycle will increasingly become a focal point, seeing as, in an ideal state, the product is at the heart of all business activities. This drives the further development, integration, and extension of PLM.

4.3. PLM as an Implementation

Implementation of modern PLM is a key success factor for modernization of the Ulstein processes and methods in novel ship design. Ulstein experience is based on key implementations and testing of modern established commercial software tools (e.g. Autodesk, Siemens), in conjunction with internal proprietary knowledge. As an example, testing and implementation of the non-conventional 4GD framework in ship design has been performed as a comparison to the conventional structuring approach *Levisauskaite (2016).* Several design and change cases were evaluated and analysed, emphasizing challenges in ship design like exchange, remodelling, alternatives, and reuse across vessels. The method is described in detail in *Levisauskaite et al. (2017),* and proved to be a powerful tool for this research to verify whether the 4GD improves the exchange and facilitates the 3D re-use.

The mentioned case study showed that the 4GD approach requires different thinking on the assemblies and designing process as the components and features are distinct from a traditional assembly approach. Due to the absence of assembly constraints together with flat assembly structure in 4GD, the positioning of the parts becomes straightforward, and changes are accomplished smoothly. These features influence the exchange of parts which are non-restrictive and a fluent process in comparison to the traditional assembly approach. Additionally, the effectiveness in 4GD proved to be an efficient solution for alternative vessels or various ship configurations across the vessel family. It supports the designers towards avoiding remodelling, and instead reuses 3D models of previous products. In ship design, it is a powerful tool that is innovative, cost effective, and time saving *Levisauskaite (2016).*

However, this implementation only scratched the surface of the 4GD framework from an entry level point of view. 4GD is a highly-advanced approach to work and organise design data, which requires advanced competence within programming, configuration and working with Teamcenter and Siemens NX to gain sufficient benefit. Moreover, it requires well established needs and requirements to efficiently employ and integrate 4GD into business processes. The installation and configuration must be well set and customized. To verify whether 4GD is a beneficial approach for continuous improvement in shipbuilding, it must be implemented and tested in maritime business and products. Ulstein has plans to proceed along this experimental line of implementation initiatives.

4.4. Accelerated Business Development

Ulstein has over the years introduced and implemented an Accelerated Business Development methodology (ABD) to enhance and strengthen our capability to effectively solicit relevant stakeholders´ expectations and desires when it comes to the realization of ship designs and new building projects, *Ulstein and Brett (2009).*

The core elements of the ABD approach, which aims to better guide ship designers, yards, cargo, and ship owners in realizing a business opportunity within intermodal transport or offshore field development work whereby ship design is utilized to achieve a competitive advantage. The approach advocates that a new or improved solution system, where the ship plays a significant role, shall fulfil the needs and expectations of all the involved stakeholders in the best possible way through the multi-attribute decision making ABD-approach. This approach makes it possible to follow the complex and normally fragmented processes of business development related to maritime transport, offshore oil & gas field, and the pertinent ship design in a systemic and explicit way.

Traditionally, the big data oriented logistics-based requirements of a transport or offshore field system have been included in the ship conceptualization and design often, in a non-structured and non-scientific way. Knowledge about logistics is spread over many actors and subjects being involved in realizing the transport system at hand where the ship design solutions are integral parts of the operation of such systems, but seldom an integral part of the business development process. The actors in such processes are ship operators, brokers, investors, designers, consultants, and companies managing transport chains. None of these parties isolated have the full picture and specific knowledge on assessing a ship's technical and operational performance in a broader business context. Traditions and specialization over many years among actors in the overall realization value chain is to blame. Historically, separate documents like outline, contract and/or building specifications and drawings have constituted the communicational instrument among the players in the overall decision-making process. Owners' specifications are typically formulated based mainly on their experience in ship operations. Expanding on what is or has been the experiences of the past is more typical than what it is we really need. Yards or designers, on the other hand, typically optimize a vessel with respect to preferred engineering criteria, such as installed engine power, speed, or lane meters and frequently their own production facilities. If more specific and complimentary technical, operational, and commercial project information is necessary, typically ad-hoc inquiry sessions are held with different information sources. More often than is admitted, solutions developed along these lines are presented as best practice and state-of-the-art, without really meeting preferred requirements as to applying a sound set of rationales and scientific reasoning. The ABD approach counteracts these discrepancies and inefficiencies and secures a holistic management of complex data such as metric, film/video, sensor signals and the like.

Ulstein has carried out more than 25 such ABD processes on own development projects and with customers. Comprehensive data analytics processes have been carried as complimentary fact finding following such ABD approaches.

4.4.1. Business Intelligence and Market Analysis

The “Ulstein Business Intelligence Methodology” is intended to create, map and organize the necessary resources and tasks that streamline the process from an initial BI need to final BI product. The preconceived idea of an Ulstein methodology was originally sketched as shown in Fig.3. The ensuing process of refining this model was performed together with experienced domain experts from external companies. The methodology is designed purposefully to be iterated upon, such that during or after each case specific feedback or experiences should be continuously integrated, adjusted and updated. In Ulstein marketing research and analytics support executive, marketing, sales, and product development managers with more effective direction setting and in complex every day and strategic decision making support.

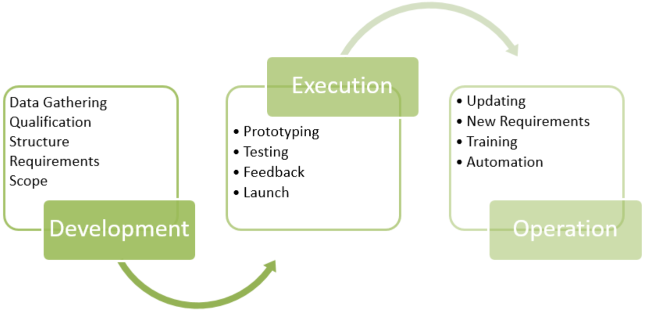


Fig.3: Methodology Sketch (left) and Market Information Data Model (right)

Ulstein International is today the main proprietor of market information, and as such actively subscribes to various sources consisting of news subscriptions, PDF reports, and databases to name a few. The databases constitute a driving portion of the performed market analysis, and traditionally would have to be individually cleaned, modified, and processed before any analysis would occur – a task that could extend up to several hours without difficulty. The task of the project was to automate the manual processing, and integrate the best attributes from each database into one central version of the truth that is always up to date. An overview of the model is illustrated in Fig.3.

4.4.2. Field Studies and Big Data Analytics

As a slight divergence from the most common interpretation of Big Data, field studies are a well-known method for the acquisition of operational data and the facilitation of detailed, holistic, and accurate information that typically is contained as tacit knowledge. They play an important role in acquiring contextual, systems-oriented, and human-centered knowledge from on-site operations and during execution generate an extensive amount of data. Sources of information include video, audio, pictures, interviews, physiological monitoring, notes, diagrams, and models in addition to the plethora of both on-board systems and provided third party sources such as the integrated automation system (IAS), automation systems for winches and cranes, dynamic positioning system, accelerometers, cargo load calculator, route planner, weather forecasts, radar imagery, task plans, operation logs, and so on. Aggregated, these sources can generate upward of a terabyte of data per day in countless formats, and as such counts significantly towards the data integration and big data analytics challenge as presented previously in the paper. In cooperation with various research institutions, Ulstein has developed methodology to handle the various challenges such an approach entails, and are in the process of creating a corresponding infrastructure to convert the data into knowledge.

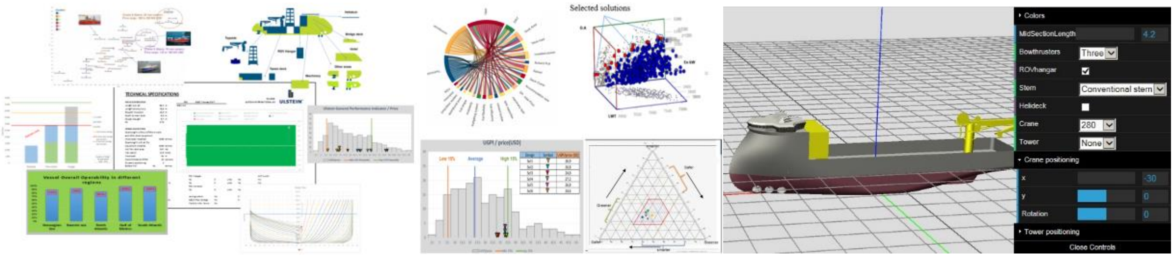
As one of the initial use-cases analysis of AIS (Automatic Identification System) information containing data for nearly 6000 vessels, was performed. Gathering such data for integration and analysis improved existing knowledge of design performance, that traditionally had been extracted from theoretical models and simulations. Additionally, it provided an opportunity to compare aspects of operational features, such as service speed and operating draft with design draft and speed, respectively. Containing 24 days of on-site operation, the vessel data was processed and stored in the repository and then analysed. Despite the relatively short period of evaluation, it showed that offshore vessels typically operate 30% below designed service speed and 20% below design draft during most commercial operations. This significant discrepancy between utilized and available capacities is an indication for further investigation, development, and eventual design target resetting. This type of analysis provides new opportunities for verifying actual performance including variation in motions, fuel consumption due to respective weather conditions.

4.4.3. Fast Track Vessel Concept Design Analysis (FTCDA)

Companies operating in the design of maritime units are challenged by the need of incorporating flexibility, innovation, speed, and agility to their business model, *Ulstein and Brett (2009)*. The conventional concept design development process, based on work processes relating to the traditional design spiral for vessels has proven to be non-effective when it comes to ensuring very short customer response time and robustness of the results. It is too time consuming and resource demanding, and drastically limits the number of alternatives to potentially be evaluated for goodness of fit.

In response to this, Ulstein has developed a Fast-Track Concept Design Analysis tool (FTCDA). This simulation tool combines multivariate statistics, network resources and design knowledge/expertise to accelerate effective decision making in vessel concept design. The FTCDA is an integration tool which gathers different modules of the conceptual design process in a unified digital platform. A holistic approach, combining technical, commercial, and operational perspectives, ensures a more balanced and robust design solution. The overall concept design development is benchmarked with peer vessel alternatives, including existing vessels. Hence, the concept design is validated and potential points of improvement can be identified and rectified to improve the overall performance of vessel design solutions proposed.

This comprehensive approach requires a multi-disciplinary design platform, combining the different aspects of maritime systems. Technical analyses such as stability, structural strength, and calm and waves propulsion resistance. Hydrodynamic aspects such as seakeeping and operability, combined with the evaluation of capacities and capabilities give the operational perspective. The feasibility analysis of the configured solution, is assessed simultaneously in the tool, including the commercial perspective. Newbuilding price and operational expenses are then contrasted with the potential revenue capability and costs of the design solution. This fast-track evaluation of design performance enables designers and decision makers to better perceive the implications and consequences of individual design changes such as: main dimensions, mission equipment, operational environment, crew nationality, material, or build country.



MidSectionLength 4.2
Bowthrusters Three
ROVhangar ☑
Stem Conventional stern
Helideck ☐
Crane 280
Tower None
x -30
y 0
Rotation 0

Fig.4: Collage of example results from Ulstein's FTCDA tool (left) and 3D configurator (right)

The implementation of FTCDA in early design phases has demonstrated three principal advantages: more robust decisions, higher quality of vessel design solutions - due to the availability of additional information at an early stage of the concept design process of the problem at hand. Other achievements include a significant reduction of response time and committed resources, and the capability of evaluating (visually and analytically) multiple design solutions. In addition, it brings the possibility of performing sensitivity analyses of cost, capacities, and capabilities towards specific design parameters. Parallel use of the FTCDA, ABD and other Big Data Analytics tools allow us to validate and verify promising solutions very quickly. This again, has dramatically reduced the response time with customers.

4.4.4. Virtual Configuration and Prototyping

FTCDA can also be combined with modern virtual prototyping technology to deliver fast and real-time 3D parametric concepts. A simplistic version of the Ulstein 3D configurator is presented in Fig.4. It consists of pre-defined modules that are combined in a web-like environment using JavaScript and WebGL. It provides real-time 3D modules based on pre-defined choices such as modules, main dimensions, and style preferences. It can also be combined with the FTCDA to deliver a full 2D/3D analytical package during early and exploratory stages of design.

5. Conclusion

The Ulstein experience of approaching and using Big Data Analytics at larger scale has already proven its worth. Higher productivity in ship design and more robust and higher performance of ship design solutions are evident. Close to hundreds of recent case studies have exemplified lead time gains and performance yields of vessel design solutions being developed. Expertise-based design of ships relies on the domain knowledge and experience of the naval architects. Their capability and capacity to also utilize and maximise the use of big data analytics and artificial intelligence have demonstrated value and appropriateness in handling the maritime industry's challenges represented by a continual influx of volatility, uncertainty, complexity, and ambiguity, as described in Chapter 1. Such approaches having been reviewed, discussed, and critically scrutinised in this paper, opens three potential strengths to companies operating in the maritime industry:

- Flexibility: The usability of the resources outside the portfolio of services and products provided by a company is limited. Typically, when entering in a new segment, even within the same discipline, requires training and in many cases the acquisition of new or additional expertise. The same happens when going beyond conventional solutions, where traditional design principles may not apply
- Agility: The need of acquiring new knowledge or expertise is a time-consuming activity, that may limit the response time of companies to new market demands, making them less competitive
- Robustness: Decision-making under high degree of uncertainty exists because of lack of data and/or the misinterpretation of them. More and qualified (verified and validated) data reduces uncertainty and leads to a more effective decision-making process.

Ulstein has undertaken a substantial digitalisation effort in recent years and developed and implemented a set of new internally manufactured Big Data Analytics based tools and knowledge repositories to enhance its ship design activity. It is envisaged that this effort is only a good start in exploring the benefits and potential of Big Data Analytics and digitalisation of business and work processes. The continuation of improvement activities will encompass, but not be restricted to such expansions such as online web-based vessel configuration, algorithmic intelligence supported naval architecture and vessel engineering work, and artificial intelligence based tools' expansions. Continual improvement work along these strategic avenues and steadily inclusion of new internally and externally developed analytics tools are bound to happen, thus accelerating the effectiveness of Ulstein doings.

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A Vessel Weather Routing Scheduler to Minimize the Voyage Time

Natalie Cariaga Costa Rodrigues, UFRJ, Rio de Janeiro/Brazil, nataliecariaga@poli.ufrj.br
Rodrigo Uchoa Simões, UFRJ, Rio de Janeiro/Brazil, rodrigo.usimoes@poli.ufrj.br
Luiz Antônio Vaz Pinto, UFRJ, Rio de Janeiro/Brazil, vaz@oceanica.ufrj.br
Luiz Felipe Assis, UFRJ, Rio de Janeiro/Brazil, felipe@peno.coppe.ufrj.br
Jean-David Caprace, UFRJ, Rio de Janeiro/Brazil, jdcaprace@oceanica.ufrj.br

Abstract

Maintaining the efficiency and sustainability in sea transportation is essential to ensure cost competitiveness of ship operations. The constant need to maximize profit motivates further developments and improvements in voyage optimization and weather routing systems. Indeed, these technologies may lead to a significant reduction of voyage time, fuel consumption and emissions. This paper presents a weather routing scheduler based on Dijkstra's algorithm. The model seeks the route that minimize the voyage time considering the forecast of wave specific height and wave direction at sea. Therefore, the optimal route is obtained by considering both voluntary and involuntary sailing speed reduction. Validation of the model is performed comparing the results to standard routes. The results demonstrate that the developments may lead to significant voyage time reduction. Future developments to consider fuel consumption and emissions for ship constant speed are planned.

1. Introduction

It is well known that ship routing is a procedure to determine an optimal route for ocean voyages based on weather forecasts, characteristics of a particular ship and sea conditions. The principles of ship performance analysis, considering the problem of a routing algorithm for optimizing trajectory and the advance in marine weather forecasting, has allowed the navigation industry to reduce voyage time, fuel consumption and minimizing cargo and hull damages. Agencies of routing services based on weather forecasts show results of structural damage reduction by 73%, an 80% in the voyage time, and damage to cargo reduction by 87% *Chen (2002)*.

This optimization problem has received attention of many researchers in past years, such as the calculus of variations *Bijlsma (1975)* that aims to minimize or maximize functions, expressed as integrals, in order to find extremals. The optimization is achieved through variation of the parameters that control the trajectory, for example time or velocity. The isochrone method proposed by *James (1957)* is a practical deterministic method for calculating the minimum time route. The optimization is determined by varying ship headings while assuming constant engine power. The isopone method of *Spaans (1995)*, finds the optimal track by defining planes of equal fuel consumption (energy fronts) instead of time fronts. In addition to above mentioned algorithms, recently there have been significant advances in the modified isochrone method, *Lin et. al. (2013)* which has applied a 3D model that considers the variation of sea conditions during voyage and avoids land. There is also the augmented Lagrange multiplier *Tsujimoto (2006)*, the genetic algorithm *Bekker (2006)* and the Dijkstra algorithm of *Takashima (2009)* that will be used for this paper and discussed later.

This paper describes a ship weather routing scheduler for determining optimal route, taken as the minimum time route, based on Dijkstra's algorithm. In the routing algorithm are established weight functions based on forecast of wave specific height and wave direction at sea, voluntary and involuntary speed reductions. All possible routes will be taken into account and the algorithm must calculate the one of minimum weight, obtaining de optimal track.

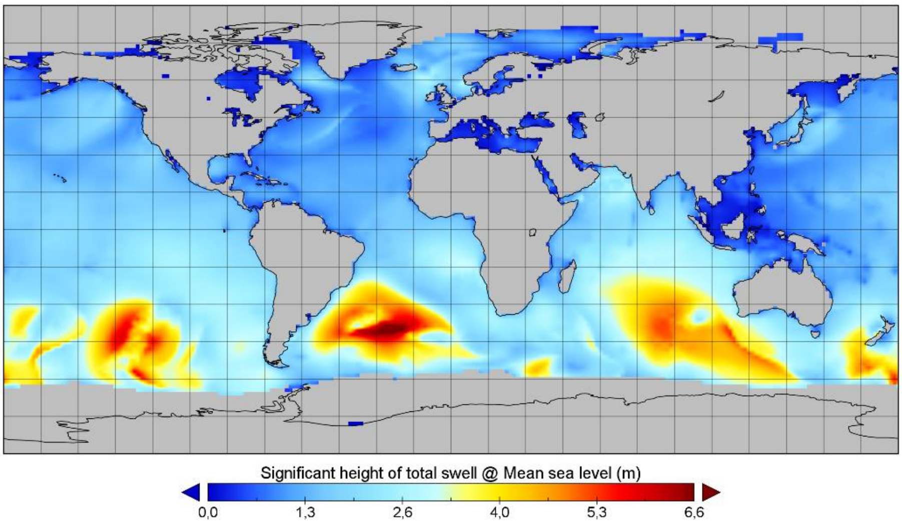
The reliability of the optimal route derived from the ship weather routing scheduler is based on the following parameters: the accuracy of weather forecasted data and the estimated ship behaviour in such ocean wave conditions.

2. Methodology

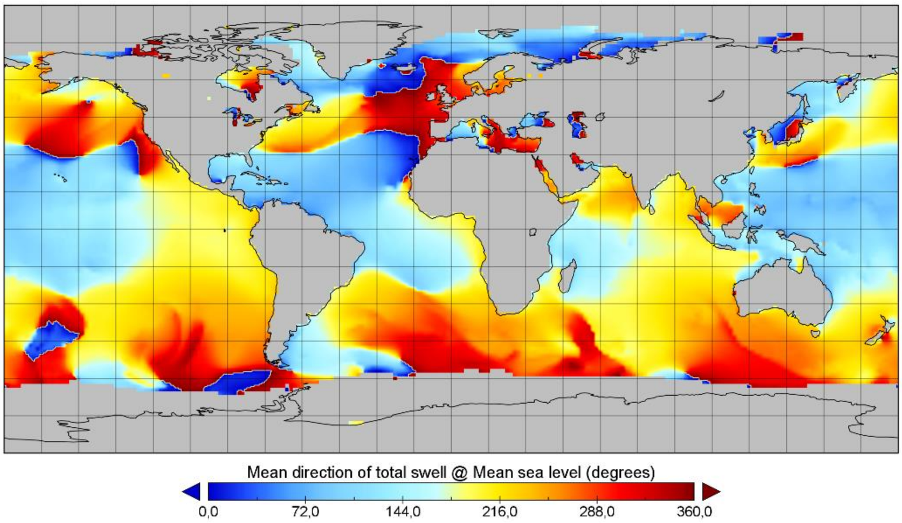
2.1. Weather forecasting

Finding the optimum route involves the development of an algorithm that regards the relevant parameters of the voyage, such as, weather forecast. Significant advance in quality of wave data have been made over the past few years, forecasting models of sea conditions are available and produce reliable data. In this paper, to evaluate the vessel behaviour, the parameters used as input data are wave direction and wave specific height.

The data from such wave models is obtained over a 1° x 1° grid created by latitude and longitude lines. An example of wave height and direction generated from European Centre for Medium-Range Weather Forecasts (ECMWF) for July 20^{st} 2010 is shown in Fig.1.



(a) Significant height of total swell combined with waves at mean sea level in meter



(b) Mean direction of total swell at mean sea level in degrees

Fig.1: Wave data extracted from ECMWF for January 1st 2010

2.2. Speed reduction

The resistance of a ship at a given speed is the force required to tow the ship as that speed in smooth water, assuming no interference from the towing ship *Harvald (1992).* According to *Sen and Padhy*

(2015), the total resistance in still water is given by $R_T = R_{SW}$, but in the presence of waves, wind and current the total resistance must consider the presence of each one of these events. The sum of the resistance due to waves, wind and current is known as additional resistance, given by equation (I). So, the total resistance is given by the sum of still water resistance and additional resistance (II).

$$R_{ADD} = R_{AW} + R_W + R_C \qquad \text{(I)}$$
$$R_T = R_{SW} + R_{ADD} \qquad \text{(II)}$$

The additional resistance can be represented either by an increase in the required power to maintain the speed, or by a speed reduction for a given constant power. In order to simplify the calculations, the speed reduction regards only the presence of waves, in other words, only the wave additional resistance parcel will be considered. The additional resistance will be represented by a speed reduction, and it will be considered both voluntary and involuntary speed loss. The voluntary speed reduction is intentional and ordered by the ship's captain during adverse sea conditions, aiming the safety of the crew, cargo and vessel. The involuntary speed loss is not intentional and it is due to an increase in resistance as result of the presence of waves.

In rough seas, the vessel's bow and stern emerges from the water surface and subsequently submerges re-entering the water, the action produces large forces for short time durations. These impact loads with high-pressure peaks, known as slamming, can cause vibratory motion of the entire ship and severe structural damages. For this study, we are interested in the impact loads such as bow flare and bottom slamming. In order to calculate the voluntary speed reduction it will be considered a standard speed profile formulated by *ABS (2011)*. This profile is applied based on the significant wave height and relates the speed reduction with the occurrence of slamming, as shown in Table I.

Table I: Standard speed profile for slamming load prediction

Significant Wave Height	Speed
	Bottom/Bowflare Slamming
$0 < H_S \leq 6$ m (19.7 ft)	100% V_d
6 m (19.7 ft) $< H_S \leq 9.0$ m (29.5 ft)	75% V_d
9.0 m (29.5 ft) $< H_S \leq 12.0$ m (39.4 ft)	50% V_d
12.0 m (39.4 ft) $< H_S$	25% V_d

For the involuntary velocity, reduction it will be applied the method proposed by *Townsin et. al. (1984)*. Townsin determined a procedure to calculate a percentage of speed loss due to the presence of waves, from statistical data. The involuntary speed reduction percentage is defined in equation III.

$$V_{\text{inv. reduction}}(\%) = \mu \frac{(a \times BN) + (BN^b)}{d\left(\nabla^{\frac{2}{3}}\right)} \qquad \text{(III)}$$

Where, μ is a coefficient responsible to consider the directions of waves, given in equation IV. The coefficients, a, b e d vary for each condition to consider the different types of ships, ∇ is the volume of the ship in m³ and the BN is the Beaufort number, *Beaufort (1805)*, that associates wind speeds and wave heights ranges with the sea state as shown in Table II.

The wave directions and significant heights obtained by the weather forecasting model are arranged according to a grid divided in latitude and longitude lines, in other words, for each point of the grid it will have a specific wave direction and significant height. This means that, considering these values and calculating the voluntary and involuntary speed losses, for each one of the grid points, the total speed reduction $V_{i,j}$ can be calculated and it is given by the sum of involuntary and voluntary reductions presented in equation IV.

$$V_{i,j} = V_{\text{inv. reduction}} + V_{\text{vol. reduction}} \qquad \text{(IV)}$$

Table II: Beaufort scale

Beaufort Number	Description	Wind (m/s)	Wind (kn)	Wave Height (m)
0	Calm	< 0.3	< 1	0
1	Light air	0.3 to 1.5	1 to 3	0.0 to 0.2
2	Light breeze	1.6 to 3.3	4 to 6	0.3 to 0.5
3	Gentle breeze	3.4 to 5.4	7 to 10	0.6 to 1.0
4	Moderate breeze	5.5 to 7.9	11 to 16	1.1 to 2.0
5	Fresh breeze	8.0 to 10.7	17 to 21	2.1 to 3.0
6	Strong breeze	10.8 to 13.8	22 to 27	3.1 to 4.0
7	Moderate gale,	13.9 to 17.1	28 to 33	4.1 to 5.5
8	Fresh gale	17.2 to 20.7	34 to 40	5.6 to 7.0
9	Strong/Severe gale	20.8 to 24.4	41 to 47	7.1 to 9.0
10	Storm	24.5 to 28.4	48 to 55	9.1 to 11.5
11	Violent storm	28.5 to 32.6	56 to 63	11.6 to 14.0
12	Hurricaneforce	> 32.7	> 64	> 14

2.3. Route optimization

2.3.1 Dijkstra’s algortihm

Dijkstra’s algorithm is used for finding the shortest paths between nodes in a graph. The algorithm exists in many variants. The original variant finds the shortest paths between two nodes, but a more common variant fixes a single node as the source and finds de optimal track from the source to all the other nodes in the graph, producing a shortest-path tree among all the possible routes in the graph.

According to *Fan and Shi (2010)*, among the available algorithms this one is the most classical and mature for obtaining the optimal route. With the advent of computing power and suitable digitalization of the open sea area, this algorithm is practical for the problem and easy to implement. In this paper, it will be used for finding the optimal route for minimum time travel between the origin node and a single destination node.

As defines *Zhu et. al. (2016)*, consider a directed diagraph G = (V, E), with n vertexes and e real valued weights sides. Where V is a collection of initial vertexes, E is a set of real valuated weights sides and S is a set of vertexes which have found the minimum time travel route from the starting vertex to themselves. In the diagraph the track from the vertex v_0 to the vertex v_n is a sequence of vertexes v_0, v_1,, v_2,…, v_n. V-S is a set of vertexes that have not found the optimum route between the origin and themselves. The steps for Dijkstra’s algorithm are:

1) Use the weighted adjacency matrix arcs to represent the directed graph and arcs(s,i) is the weight from the node s to i. Suppose S equals $\{V_s\}$ and V_s is the origin point. Suppose dist[i] equals the minimum time track from node V_s to node V_i.
$$\mathrm{dist[i]} = \begin{cases} 0, & \mathrm{i = s;} \\ \mathrm{arcs(s,i)} & \mathrm{i \neq s,} < \mathrm{V_s, V_i} > \in \mathrm{E;} \\ \infty & \mathrm{i \neq s,} < \mathrm{V_s, V_i} > \notin \mathrm{E;} \end{cases}$$
2) V_j is the end of the next optimum path. Select the node V_j by:
$\mathrm{dist[j]} = \min\{\mathrm{dist[k]} \mid \mathrm{V_k} \in \mathrm{V - S}\}, \mathrm{S = S} \cup \{\mathrm{V_j}\}$
3) If $\mathrm{dist[j]} + \mathrm{arcs(j,k)} < \mathrm{dist[k]}$, then:
$\mathrm{dist[k]} = \mathrm{dist[j]} + \mathrm{arcs(j,k)}, (\forall\ \mathrm{V_k} \in \mathrm{V - S})$
4) Repeat step 2 and 3 until S = V.

In a scheme formulated below, this algorithm can be clearly understood. The scheme is given by a graph of vertexes *s*, *u*, *x* and *v*. In this example, the aim is find the optimum track, the minimum total weight path starting from the vertex *s*, to the node *v*. Firstly, a temporary weight value should be assigned to each node of the mesh, for the origin this value is zero and for the other nodes is infinity.

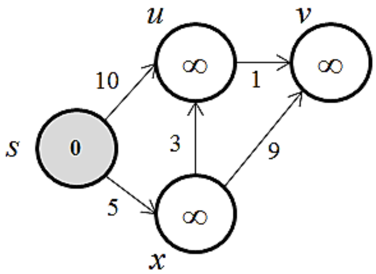


Fig.3: Illustration of Dijkstras's first step example

Table III: Dijkstras's first step example

Vertex	Visited?	Distance	Predecessor
s	Yes	0	-
u	-	-	-
v	-	-	-
x	-	-	-

Then, it is necessary to define the initial node as the current node and mark the remaining nodes as unvisited, creating a set of unvisited nodes. Next, the adjacent vertexes, in this case *u* and *x*, have not been visited yet. The node *s* is then at a 10 unit of weight in relation to the start node *u* and at a 5 unit of weight in relation to *u*.

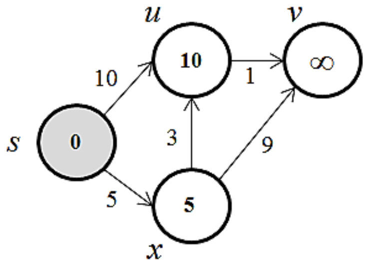


Fig.4: Illustration of Dijkstras's second step example

Table IV: Dijkstras's second step example

Vertex	Visited?	Distance	Predecessor
s	Yes	0	-
u	No	10	s
v	No	-	-
x	No	5	s

The node that has de minimum time value in relation to *s* is the node *x*, so the first vertex to visit is the *x*. For vertex *u*, it will be adopted a new temporary weight equal to 8, since the new value is smaller. In other words, at each step that the algorithm gives, the provisional weight of the unvisited nodes is changed if the new temporary weight is less than the previous weight. Note that as the path progresses, the predecessors are also being registered, as there is a need to store the predecessor in order to find the final path.

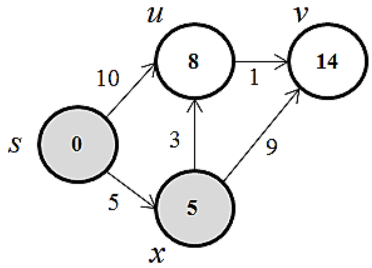


Fig.5: Illustration of Dijkstras's third step example

Table V: Dijkstras's third step example

Vertex	Visited?	Distance	Predecessor
s	Yes	0	-
u	No	8	x
v	No	14	x
x	Yes	5	s

The next node to visit is *u*. Analysing the node we can notice that there is a path to the node *v*, with weight 1, so the temporary values are updated again, because the algorithm has found a shortest path to the destination vertex *v*. The next step is to visit the *v* vertex, and then the algorithm finds the track: *s*-*x*-*u*-*v*, which has a minimum time track.

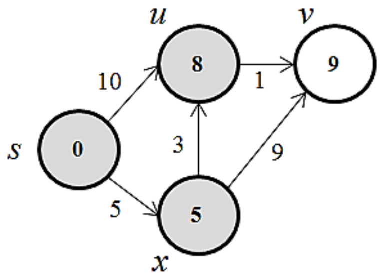


Fig.6: Illustration of Dijkstras's third step example

Table VI: Dijkstras's third step example

Vertex	Visited?	Distance	Predecessor
s	Yes	0	-
u	Yes	8	x
v	No	9	u
x	Yes	5	s

2.3.2 Weight Function

A direct weighted graph is a digraph that has each one of the vertexes attached to a weight value. As discussed in the example above, Dijkstra's algorithm will calculate the minimum time route for a given origin and destination by considering all the possible paths and comparing the possible weights. The Fig.7 shows an example of a weighted graph, where the nodes are represented by the vertexes in the interceptions of latitude and longitude lines.

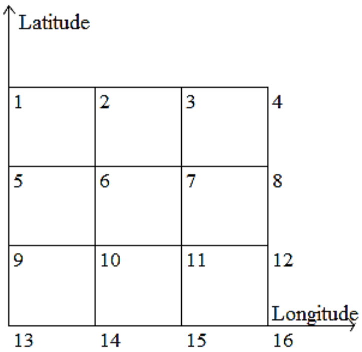


Fig. 7: Illustration of direct weighted graph

The weight function is the objective function that has to be optimized, since the faster track needs to be found. With the total speed reduction $V_{i,j}$ calculated (sum of voluntary and involuntary losses) it is possible to determine the weights $e_{i,j}$, since the distance $L_{i,j}$ crossed from the start point to de destination is calculated. $L_{i,j}$ is obtained by transforming the distance covered in degrees between two latitude and longitude points in meters, for each point of the mesh. For distances in kilometres between two points (x_1,y_1) and (x_2,y_2), the equation V can be used.

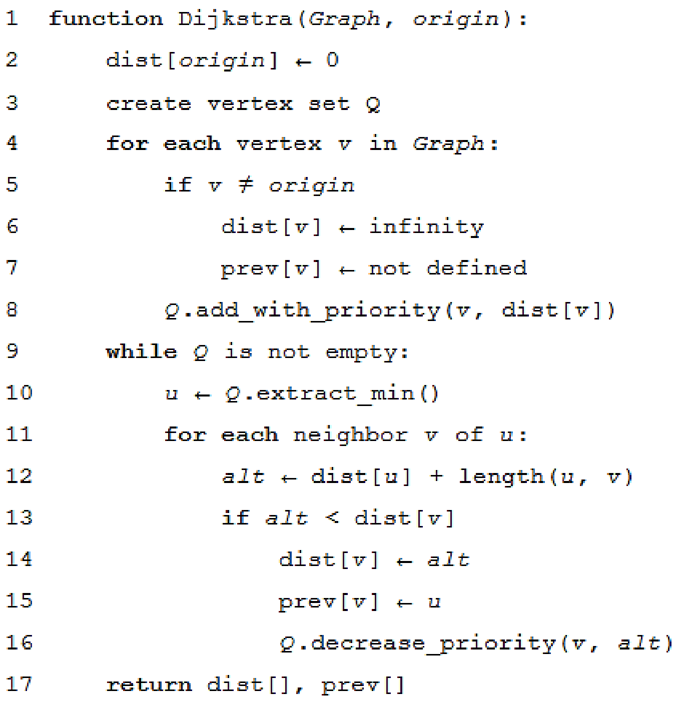
$$L_{i,j} = \mathrm{acos}\big(\sin(x_1) * \mathrm{SIN}(x_2) + \mathrm{COS}(x_1) * \mathrm{COS}(x_2) * \mathrm{COS}(y_2 - y_1)\big)\ 6371 \qquad \text{(V)}$$

So, the weight function $e_{i,j}$ is given by the ratio of the speed and the crossed distance between each point (i, j) of the grid. By optimizing the objective function, the algorithm finds the minimum sum of weights, in other words, minimum voyage time.

$$e_{i,j} = t_{i,j} = \frac{L_{i,j}}{V_{i,j}}$$

2.3.2 Routing optimization algorithm

In order to apply the Dijkstra's algorithm in the ship routing problem, a code has been developed. The route scheduler uses this algorithm to determine the minimum voyage time, and the pseudocode is shown in Fig.3.



```
function Dijkstra(Graph, origin):
    dist[origin] ← 0
    create vertex set Q
    for each vertex v in Graph:
        if v ≠ origin
            dist[v] ← infinity
            prev[v] ← not defined
        Q.add_with_priority(v, dist[v])
    while Q is not empty:
        u ← Q.extract_min()
        for each neighbor v of u:
            alt ← dist[u] + length(u, v)
            if alt < dist[v]
                dist[v] ← alt
                prev[v] ← u
                Q.decrease_priority(v, alt)
    return dist[], prev[]
```

Fig.3: Dijkstra's pseudocode

Another algorithm was developed with the intent of track the path calculated by the Dijkstra's algorithm. An *S* list is created and a variable *u* is associated with the destination node of the route. The next step is given by a decision using the predecessor *u* as the criteria, if there is no predecessor means that the first node of the path was found, otherwise, node *u* is added to the *S* list. Then, the node *u* is visited and a new *u* is assigned with the current node's predecessor, coming back to the decision point again, as illustrated by the below flowchart. The process is repeated until the predecessor attribute of the node is empty, in other words, it reached the origin node.

This research area has many specifications and several weather routing services providers. The complexity of each system varies according to its purpose. In the case of this study, some considerations are made in order to simplify the routing scheduler. Considering all the factors of influence in weather forecast, climate is undeniably a complex system and is subjected to variation. In order to consider the possible climate change, the weather data is updated once a day taking as reference the half-day time. This way, if the ship is going in a certain direction and a storm arises in its route it will be possible to avoid the storm.

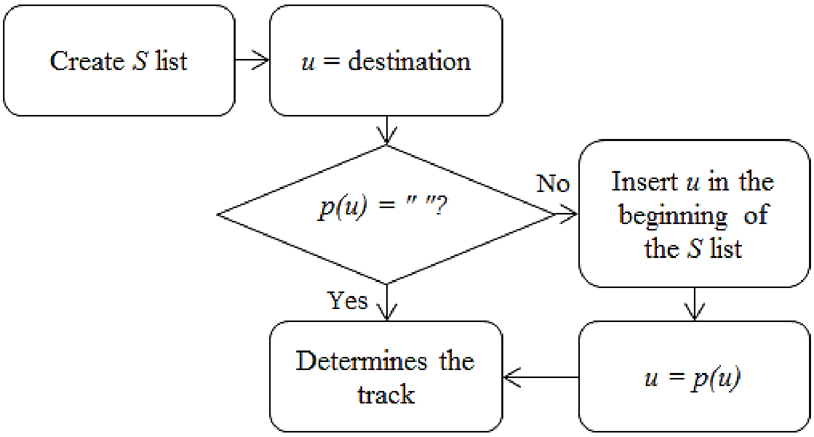


Fig. 4: Track algorithm

Another important feature to be highlighted is the soft waypoint routing scheduler. A waypoint is a term used to refer to an intermediate point on a route, a stopping point or point at which course is changed. So, it is possible to select points in the path, besides the final destination, for which the algorithm will provide the optimized voyage time between the origin and that middle point.

3. Results and Discussions

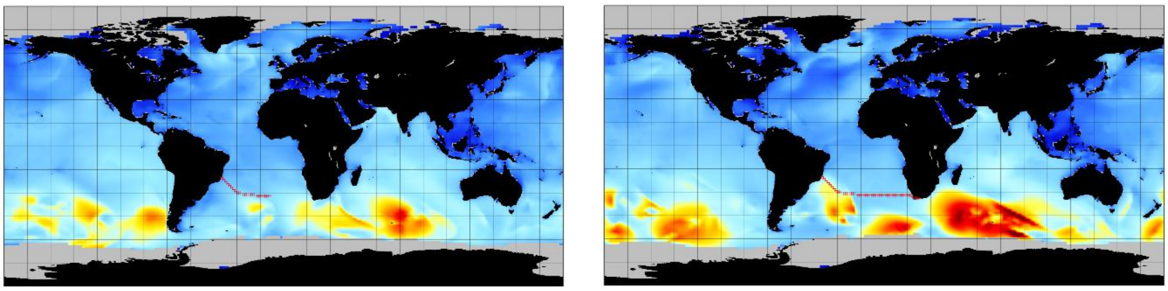
In order to validate the capability of the proposed method, a simulation was carried out. For the simulation, the departing point is Tubarão, Espírito Santo in Brazil (-20.29°, 40.00º) and the destination is Zhanjiang, Guangdong province in China (21.22º, 110.42º). During the voyage, two soft waypoints will be considered: South Africa (-35.15°, 19.73°) and Singapore (1.29°, 103.68º). Soft waypoints are introduced to give the general direction of the ship and assess correctly the angle between the true heading and the global swell. However, the ship is not constraint to pass by these waypoints. The selected ship for the study is an Ultra Large Ore Carrier (ULOC) class *Valemax*, which the principal particulars are shown in Table V.

Table V: Principal particulars of the ship

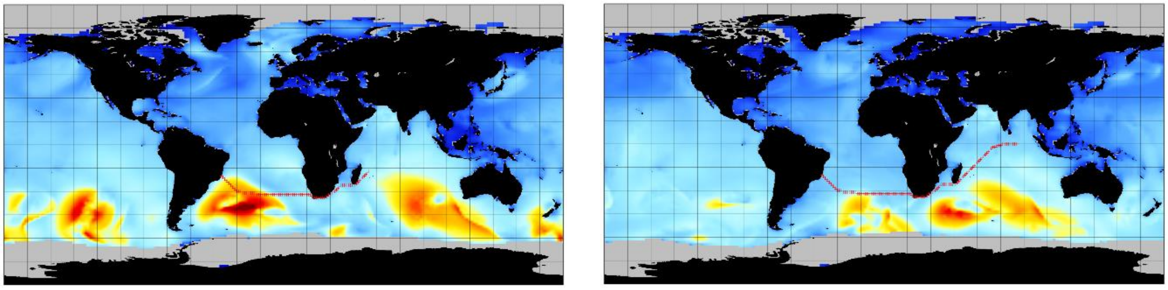
Length (m)	360
Breadth (m)	65
Draft (m)	23
Depth (m)	30
Sailing Speed (knots)	14
Volume (m^3)	454186

Fig.5 presents the results of the optimized route combined with the total significant height of swell at various moment of the journey. It observed that in the Atlantic Ocean the ship has not been in front of rough weather. However, when the ship arrived at the cap of good hope, he has been forced to slightly go north between South Affrica and Madagascar to avoid rough weather and therefore reduce the steaming total time. Once the ship passed the south of Madagascar the algorithm choose to go even more North for the same reasons. Once arrived in Indonesia it may be observed that weather is not any more affecting the route. Due to a problem of weather data low resolution (1° x 1° grid), the ship passed through Thailand instead of taking the Malacca channel. It can be solved simply by using a better resolution of the weather data; however, the computation time will be drastically penalized. Finally, the ship arrived in China after 34.76 days of navigation.

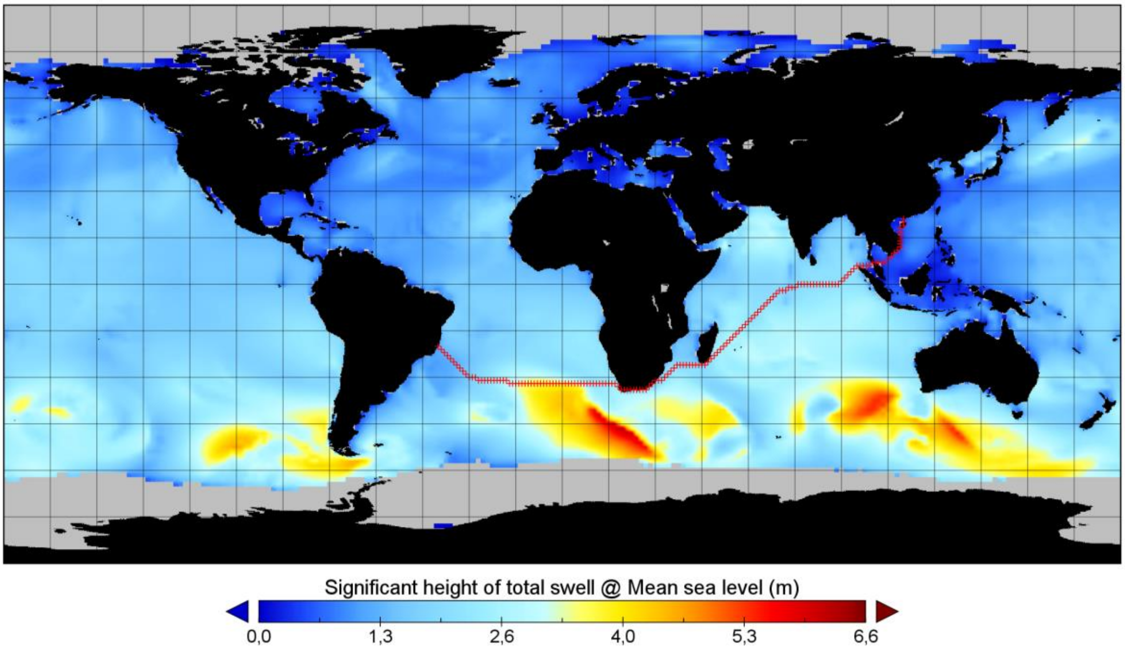
The developed algorithm gives a good insight on the weather routing optimization, however it still lacks critical points in order for it to be implemented in a working product. First, the methodology is computation intensive as it is based on grid search method. Second, the steaming time optimization objective have been implemented disregarding the full consumption or operational cost objective.



(a) 6.7days of navigation (b) 13.6 days of navigation



(c) 20.4 days of navigation (d) 27.1 days of navigation



(e) 34.7 days of navigation

Fig.5: Optimized route combined with the total height of swell

4. Conclusions

The route optimization problem has great commercial application and there are several companies that provide this service. Most of these companies do not offer much information, probably due to the commercial and competitive nature of this business. In the available literature, in-depth information about this optimization method is generally scarce, there are usually research publications that deal only in theoretical perspective and not applied to the navigation area. Thus, this study presents the basis for the ship routing problem elucidating the basic structure for the approach of an algorithm in the route optimization problem.

This research can be extended in many directions. Future developments to consider fuel consumption, operational costs and emissions for ship constant speed are planned. One of the limitations of this approach is that the speed reduction regards only the wave additional resistance parcel, so the influence of the wind and current should be considered in future improvements. Generally, in the wave data sites the weather forecast is updated every 3 hours. To reduce computation time, the algorithm updated weather data every 24 hours with a resolution of 1° x 1° grid. A suggestion for futures development is to reduce the updating time and increase the resolution of the grid, keeping in mind that the shorter this time is, the more accurate the results will be.

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Big Data Analysis of AIS Records to Provide Knowledge for Offshore Logistic Simulation

Maricruz A. F. Cepeda, COPPE, UFRJ, Rio de Janeiro/Brazil, maricruzcepeda@oceanica.ufrj.br
Rodrigo Uchoa Simões, PENO, UFRJ, Rio de Janeiro/Brazil, rodrigo.usimoes@poli.ufrj.br
João Vitor Marques de Oliveira Moita, PENO, UFRJ, Rio de Janeiro/Brazil, joaov@poli.ufrj.br
Luiz Felipe Assis, COPPE, UFRJ, Rio de Janeiro/Brazil, felipe@peno.coppe.ufrj.br
Luiz Antônio Vaz Pinto, COPPE, UFRJ, Rio de Janeiro/Brazil, vaz@oceanica.ufrj.br
Jean-David Caprace, COPPE, UFRJ, Rio de Janeiro/Brazil, jdcaprace@oceanica.ufrj.br

Abstract

Today, Big Data is getting popular in shipping where large amounts of information is collected to better understand and improve logistics, emissions, energy consumption and maintenance. In shipping, the Automatic Identification System (AIS) records millions of information of ships operations. However, to get the most of these big chunks of information specific technologies should be applied to process these data within an acceptable time. This paper presents a model to extract patterns from AIS records in the field of supply chain of offshore platforms. Here a solution using distributed processing framework based on Hadoop Hive queries (map/reduce) and Hadoop Distributed File Systems (HDFS) is developed. First, a short benchmark study is present to compare performance of Big Data technology in front of former technology. Second, results of the pattern extraction regarding navigational behaviour of Platform Supply Vessels are presented. Then, the new knowledge is introduce in a stochastic simulation to mimic the supply chain management of offshore platforms. The results shown that the proposed methodology is efficient to reproduce offshore logistic activities taking into account uncertainties related to operational matters, as well as weather uncertainties that affect the system. Moreover, big data technologies are greatly reducing time to extract pattern from considerable amount of data.

1. Introduction

1.1. Contextualization

Offshore Oil and Gas (O&G) industry is one of the most important industries in the world with a direct impact on the worldwide economies. According to annual world energy statistics, it is stated that in 2014 approximately 55% of total energy consumed in the world has been produced from oil and natural gas, *IEA (2016)*. World oil demand grew more strongly in 2015 (+1.8 million barrels per day (mb/d)), *UK (2016)*. The profitability of O&G development activity depends on both the prices realized by producers and the cost and productivity of present and newly developed wells. Prices, costs, and field's productivity have all experienced significant changes over the past decade, *EIA (2016)*. The collapse of oil prices in late 2014 forces the offshore oil key players to reduce their logistics costs to recover competitiveness.

Most of Brazil oil reserves are nestled in offshore fields, a fact that has led the O&G activities to achieve increasing depths. The logistic of Brazilian pre-salt fields are challenging due to the considerable distance to coastline (~300 km).

Every day, 2.5 quintillion bytes of data are created. Datasets whose size is beyond the ability of typical database software tools to capture, store, manage and analyse. This is known as Big Data, *MGI (2012)*. Big data is present in key sectors as health care, public sector administration, global personal location data, retail, manufacturing, social personal and professional data, *Zicari (2014)*.

Big data have revolutionized the industry over the past several years. Companies across the various travel and transportation industry segments as airlines, airports, railways, freight logistics, hospitality and others have been handling large amounts of data for years. In addition, today's advanced analytics technologies and techniques enable organizations to extract insights from data with previously unachievable levels of sophistication, speed and accuracy, *IBM (2014).*

Today, Big Data is getting popular in shipping where large amounts of information is collected to better understand and improve logistics, emissions, energy consumption and maintenance.

Using satellite navigation and sensors, trucks, airplanes or ships can be tracked in real-time. In shipping, the Automatic Identification System (AIS), which is used for preventing collisions at sea and by vessel traffic services (VTS), records millions of information of ships operations, between vessels and between vessels and shore facilities. Historical AIS data is a valuable data source used for vessel traffic analyses, port calling information, risk assessment and accident investigation. It may also provide basement for decisions in offshore logistic.

1.2. Gap

Over the past few years, there has been a fundamental shift in data storage, management, and processing. Companies are storing more data from more sources in more formats than ever before. This is not just about being a “data package” but rather building products, features, and intelligence predicated on knowing more about this information, *Sammer (2012).*

Organizations discovers new ways to use data that was previously believed to be of little value, or far too expensive to keep, to better serve their clients. Sourcing and storing data is a part of the problem. Processing that data to produce information is fundamental to the daily operations of any industry, *Sammer (2012).*

However, to get the most of these big chunks of information specific technologies should be applied to process these data within an acceptable time and resources. In order to efficiently extract value from these data, the offshore oil key players need to find new tools and methods specialized for big data processing.

1.3. State of the art

To deal with this huge quantity of data, common solutions may not be any more efficient or too time consuming. Here a solution using distributed processing framework based on Hadoop Hive queries (map/reduce) and Hadoop Distributed File Systems (HDFS) is developed. Hadoop is a useful platform used in the last years where solutions have been developed for the industry with the use of big data.

In shipping industry, the use of big data is present in various studies. *Bons and Wirdum (2016)* describe how CoVadem introduces a big data solution that will add significant value to the inland shipping industry in Europe with a cooperatively sourced big data from over 50 vessels (over 55.000.000 measured values a day). It is used to provide effective key performance indicators (KPI’s) to judge actual performance and cater for the necessary metrics to analyse, interpret and decide upon improvement measures. With the right technical and organizational implementation a revolutionary basis is introduced that allows for effective, continuous and holistic improvement, *Bons and Wirdum (2016).*

Rødseth et al.(2016) present an overview of some of these issues and possible solutions about the constraints to the use of big data. New protocol standards may simplify the process of collecting and organizing the data, including in the e-navigation domain are reviewed. This paper references the external ship monitoring as AIS and VTS. It indicates that AIS receivers can provide very valuable data on ship movements due to ships will send AIS data quite frequently, normally minimum each 10 seconds. Data that is transmitted is position, speed, course, true heading and rate of turn. This automated ship reporting is a prioritized solution in the e-navigation strategic implementation plan, *IMO (2014),* so one may expect some developments in this area in the coming years, *Rødseth et al. (2016).*

Ramsden et al. (2016) use a Big Data solution to predicting fouling on an underwater hull because they consider that as a vital part of optimising the efficiency of a maritime vessel. They mash together multiple data streams for relevant vessel attributes, positional data, environmental data and fouling coating performance factor generated a dataset of over 3.5 Billon records, *Ramsden et al. (2016).*

The creation of realistic scenarios with simulation in maritime industry is important for training and for testing of the developed tools. These scenarios are verified and validated with the reality. In the shipping industry the use of simulation is present in various studies. *Korte et al. (2012)* present the project Safe Offshore Operations about offshore training simulations where the main idea consists of the development of an integrated operator assistance and information system based on a self-organising wireless computer and sensor network, and also prolong the time frames for offshore operations. The initial simulate scenarios and their verification shall be presented and discussed by the study, *Korte et al. (2012).*

Shyshou et al. (2010) proposed a simulation model for offshore anchor handling operations related to movement of offshore mobile units. The operations are performed by anchor handling tug supply (AHTS) vessels, which can be hired either on the long-term basis or from the spot market. The stochastic elements are weather conditions and spot-hire rates. The requirements on the weather conditions are similar to the methodology developed in this paper. However, the authors are using met-ocean data to assess theses distributions, *Shyshou et al. (2010).*

The work developed by *Aneichyk (2009)* covers the designing of a simulation model for offshore supply process with the aim of creating a tool to plan the operations and fleet size. Some uncertainty factors affecting the process are taken into account such as weather conditions, varying demand and delays. A discrete-event simulation (DES) model is developed in order to model those uncertainties with a stochastic approach. Results obtained show that simulation may be seen as an important tool to develop new strategies under varying conditions and improve the efficiency of the process dramatically. The authors stated that simulation has a promising future in offshore logistics field and the usage will increase in near future, *Aneichyk (2009).*

The novel approach to use AIS data to feed DES input is original and the problem has not been previously studied in that way.

1.4. Purpose

This paper presents a model to extract patterns from AIS records in the field of supply chain of offshore platforms. Big data technologies are greatly reducing time to extract pattern from considerable amount of data. Then, DES methodology is used to simulate the offshore logistics. The results shown that the proposed methodology is efficient to reproduce offshore logistic activities taking into account uncertainties related to operational matters, as well as weather uncertainties that affect the system.

2. Methodology

Apache Hadoop is a platform that provides pragmatic, cost-effective, scalable infrastructure for building many of the types of applications described earlier. It is an open source software that allows for the distributed processing of large data sets across clusters of computers using a simple programming model. It scales up from single servers to thousands of machines, each offering local computation and storage, *White (2009).*

The Hadoop library is using a filesystem called Hadoop Distributed Filesystem (HDFS). HDFS was built to support high throughput, streaming reads and writes of extremely large files. *Sammer (2012).* HDFS uses a scale-out model based on JBOD (“Just a bunch of disks”) to achieve large-scale storage. It uses replication of data to accomplish availability and high throughput.

Fig.1 presents the differences between the traditional architecture of a development program to process data, and a Hadoop platform. The traditional architecture have a Both Storage Area Networks (SAN) or a Network Attached Storage (NAS). SAN is a local network of multiple devices that operate on disk blocks while NAS is a single storage device that operates on data files. These SAN or NAS are connecting to a database with a bunch of applications connected to it and data is being constantly moved to where processing needs to happen. Such a model does not provide high performance at scale. What you really need is a distributed storage as well as processing platform such as Hadoop, where the functionality is run locally on the data, and the system scales linearly to extreme limits - even to geographically dispersed locations, Fig.1, *Srivas (2017)*.

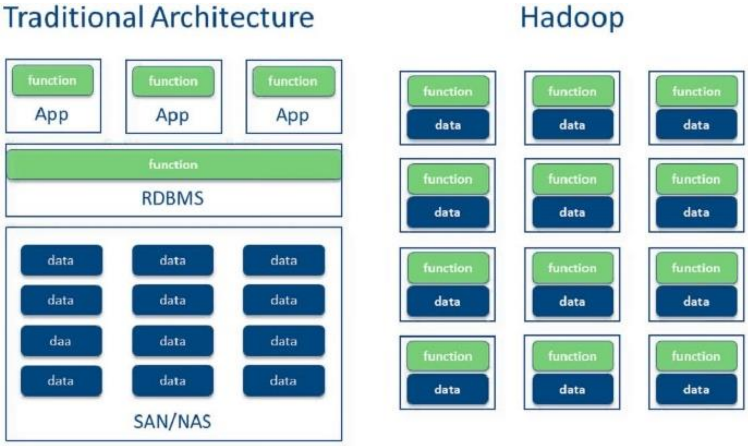


Fig.1: Differences between traditional and distributed architectures (Hadoop), *Srivas (2017)*

MapReduce is a particular programming model for data processing, it is suitable for non-iterative algorithms where nodes require little data exchange to proceed (non-iterative and independent), Fig.1. In MapReduce, developers write jobs that consist primarily of a map function and a reduce function, and the framework handles the gory details of parallelizing the work, scheduling parts of the job on worker machines, monitoring for and recovering from failures, and so forth, *Sammer (2012), Capriolo et al. (2012).*

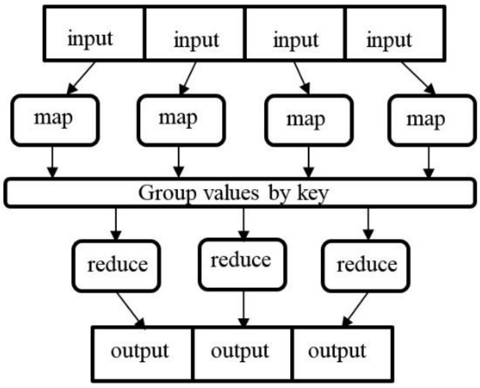


Fig.1: Map-reduce structure

Hadoop structure emerged as a cost-effective way of working with big data. MapReduce breaks up computation tasks into units that can be distributed around a cluster of commodity, server class hardware, thus providing cost-effective, horizontal scalability. Hive provides an SQL dialect, called Hive Query Language (abbreviated HiveQL or just HQL) for querying data stored in a Hadoop cluster similarly to traditional relational databases and the Structured Query Language (SQL), *Capriolo et al. (2012).* SQL knowledge is effective and reasonably intuitive model for organizing and using data. Mapping these familiar data operations to the low-level MapReduce Java API can be daunting, even for experienced Java developers. Hive does this work for you. It translates most queries to MapReduce jobs, thereby exploiting the scalability of Hadoop, while presenting a familiar SQL abstraction, *Capriolo et al. (2012).*

2.1. Benchmark on big data

2.1.1. Database

The benchmark has been performed using AIS messages database designed to store all the types of AIS messages, Fig.2. There is 196 different fields where the most important are MMSI, Channel, Message type, Navigation status, Rate Of Turn, Speed Over Ground, Longitude, Latitude, Course Over Ground, True Heading, Timestamp, Call sign, Name, Cargo type, Vessel dimensions, Estimated Time of Arrival, Maximum static draft, Destination, Data terminal ready, etc.

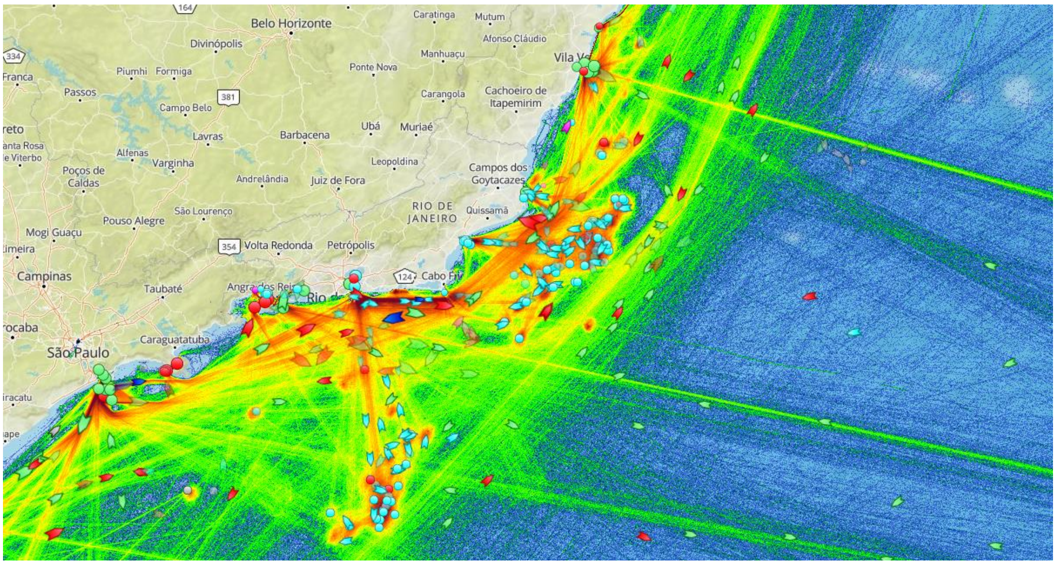


Fig.2: AIS data recorded during 2016 around Campos and Santos basin

The traditional architecture were designed using a Desktop Dell XPS 8700 Intel Core i7 with a HD of 2 TB and 16 GB of RAM. A SQL Microsoft server professional were install on the hardware mentioned in order to perform the SQL query that is the object of the benchmark. The distributed and scalable architecture were designed using 5 different nodes deployed with Cloudera. The Cloudera manager node were connected to 4 Cloudera agents that represent a total of HDFS of 7.2 TB.

Table I: Characteristics of the database included the numbers of records, volume of data, and process time in the traditional and distributed architecture.

ID	**Records**	**Data**	**Tradicional architecture**	**Distributed Architecture**		
	Number	*Volume*	*Seconds*	*#Mapper*	*#Reducer*	*Seconds*
1	1000	317 KB	< 1	1	1	25
2	10000	3.162 MB	< 1	1	1	28
3	100000	31.63 MB	1	1	1	28
4	1000000	312.76 MB	3	2	2	28
5	10000000	3.11 GB	11	12	13	29
6	25000000	7.62 GB	77	29	30	37

To make the comparison a simple SQL query has been developed to count how many AIS messages of each type are presented in the database: “`SELECT MESSAGE_ID, COUNT(MESSAGE_ID) FROM aismessages GROUP BY MESSAGE_ID;`”. This query has been executed on both traditional and distributed architecture considering various size of the database varying from 1000 to 25 million records. The result of the benchmark are presented in Table I and Fig.3. For the considered simple SQL query and small databases inferior to one million records the traditional architecture is more efficient that the distributed architecture. However, for bigger databases the distributed architecture is becoming more efficient. For the specific case of 25 million records, the distributed architecture took half time of the traditional architecture. Considering the amount of data to be treated in the second part of the paper, i.e. 100 million records (~30 GB), it has been decided to use the distributed architecture.

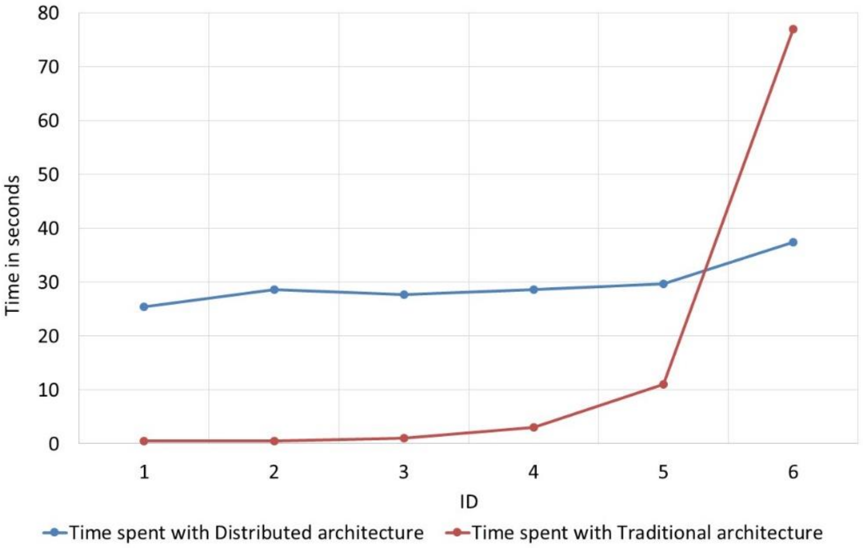


Fig.3: Differences in time spent between a traditional architecture and distributed architecture (Hadoop Hive)

3. Case of study

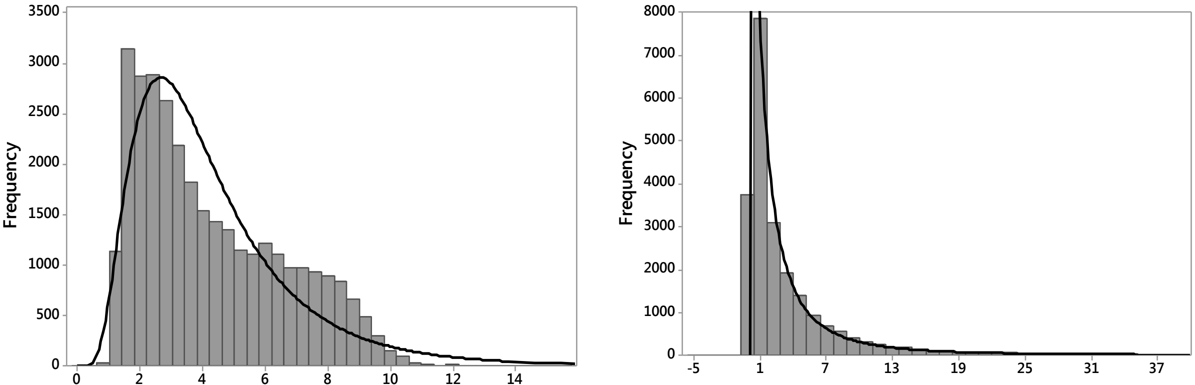
3.1 Extraction of the Statistical Distributions

The case study presented in this section focus on the Campos basin with latitude between 21° 49' 33.2414" S and 22° 40' 47.6969" S and longitude between 39° 42' 26.1104" W and 40° 43' 5.083" W. Several years of AIS data are available in Campos/Santos basin, but in this paper the emphasis is put on a database of 6 months from 1 April 2014 to 1 October 2014. We focused the study on the analysis of 90 platform supply vessels (PSVs) that are performing the supply of the platforms, FPSO’s and drilling ships in this region. Finally, these data represents about 100 million of AIS records.

Applying the methodology described in the previous section the histograms presented in Fig.4 have been extracted for the 90 PSVs. Table II gives number of tracks, mean and standard deviations for each behavior of the PSVs while Table III present the probability density functions that best fits the histograms presented in Fig.5.

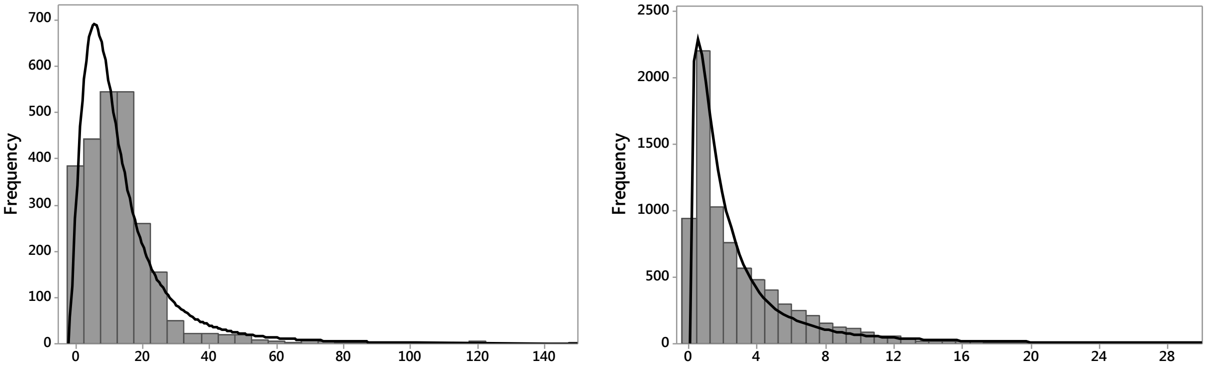
These data have been generated for any type of PSVs operated during the above-mentioned period. However, in a near future, it is planned to make the difference between various sizes of PSVs as well as to check the effect of weather seasonality on the statistical distributions. Similarly, the histogram related to the loading and unloading time at the logistic port corresponds to various terminals and the loading and unloading time at platform correspond to both production and drilling platforms.

It is interesting to note that the sailing velocity histogram seems to be decomposable into two different components. A first component for the small velocities around 2 knots and a second component for the highest velocities between 6 to 10 knots. This behavior could be explained by the fact that these ships has more than one operational profiles, e.g. PSVs operating close to the platforms are using a small velocity while in transit to port velocity is higher.



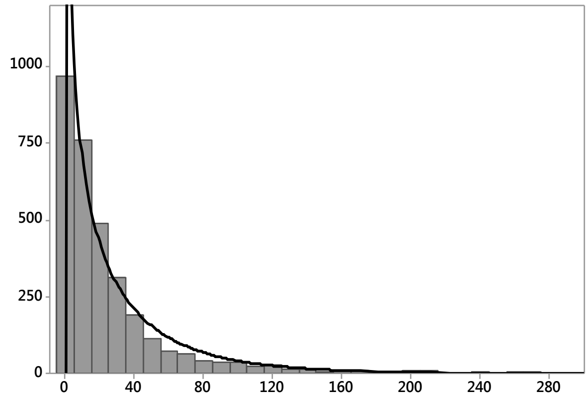
(a) Histogram of the sailing velocity in knots

(b) Histogram of the waiting/idle time at sea in hours



(c) Histogram of loading/unloading time at port in hours

(d) Histogram of the loading/unloading time at platform in hours



(e) Histogram of the mooring time at port in hours

Fig.4: Histograms of the 6 months operation of 90 PSVs in Campos and Santos basin

Table II: Extracted data from the AIS database

Behavior of the PSVs vessel	Unit	Number of Tracks	Number of tracks outliers	Mean	Standard Deviation
Sailing velocity	Knots	32 016 (43%)	39	4.34	2.31
Waiting/Idle time at sea	Hours	27 399 (36%)	0	3.75	7.76
Loading/Unloading time at port	Hours	3018 (4%)	5	16.09	33.53
Loading/Unloading time at platform	Hours	9064 (12%)	7	3.24	4.36
Mooring time	Hours	3798 (5%)	0	28.06	49.40

Table III: Best fitting statistical distributions

Behavior of the PSVs vessel	Unit	Type	Parameters
Sailing velocity	Knots	Log Normal	Location = 1.34; Scale = 0.54; Threshold = -0.067
Waiting/Idle time at sea	Hours	Log Normal	Location = 0.44; Scale = 1.33; Threshold = -0,0012
Loading/Unloading time at port	Hours	Log Logistic	Location = 2.51; Scale = 0.46; Threshold = -2,072
Loading/Unloading time at platform	Hours	Log Logistic	Location = 0.54; Scale = 0.72; Threshold = 0,016
Mooring time	Hours	Gamma	Shape = 0.58; Scale = 47.68; Threshold = 0,016

3.2 The Discrete-Event Simulation

To illustrate the concept presented in this paper, a case study based on the Brazilian Campos basin has been developed using discrete-event simulation (DES). The aim of the model is to assess alternative fleet size configurations taking into consideration uncertainty in weather conditions and unexpected delays. The configuration of the layout consist in one logistic port terminal (Macaé) containing 6 berths to load and unload the 23 PSVs considered in the simulation. Fig.6 presents the relative location of the 38 platforms organized in 19 clusters (group of platforms) as well as the port. The DES results are presented for 6 months of the operation of the PSV fleet.

Fig.5: Location of platforms and logistic port terminal (Macaé) considered in the DES. Color of the points represents the 19 clusters of the platforms

In the simulation, platforms are requiring supplies on a periodically base to the logistic port. That period has been defined as a constant in the simulation but differ with the type of the platform. Here the frequency has been chosen around twice a week, i.e., a platform requires a visit of a PSV twice a week. Then, the requests are organized by priority of the load and platform clusters. Depending of the availability of a berth in the terminal, a PSV available in the mooring area is called to be loaded in the port terminal. Finally, the PSV will sail to supply the platform cluster, deliver the load to each platform of the cluster, and then, sail back to the mooring area after the process. The process of PSV allocation and routing is repeated periodically until the end of the simulation.

The dimension, capacity and speed has been considered equal for all PSVs. Moreover, the route of the vessel has been considered straight lines. The statistical distribution of sailing velocity, waiting/idle time at sea, loading/unloading time at port and loading/unloading time at platform has been implemented in each relative process inside the DES while mooring time at port can be considered as the variable to be calibrated.

Fig.6 presents the overall traveled distance by all PSVs along 200 iterations for a period of six months. As the result is highly stochastic, testing the convergence of the output is required. Fig.7

presents the convergence of the overall travelled distance of all PSVs. It is observed that the accumulated mean value tends to converge roughly after 200 iterations, i.e. with a variation of less than 50 km per iteration.

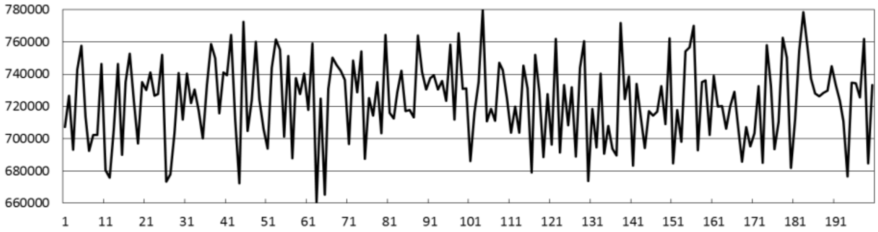


Fig.6: Simulated traveled distance of PSVs during 6 months of operation. Results of first 200 iterations.

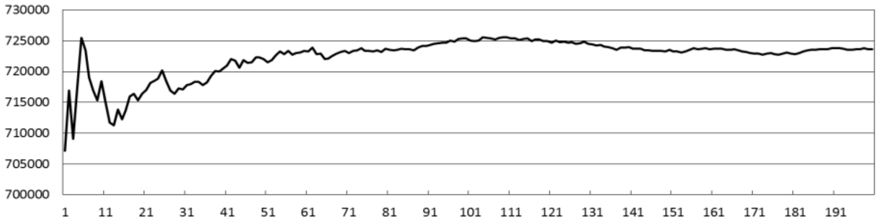
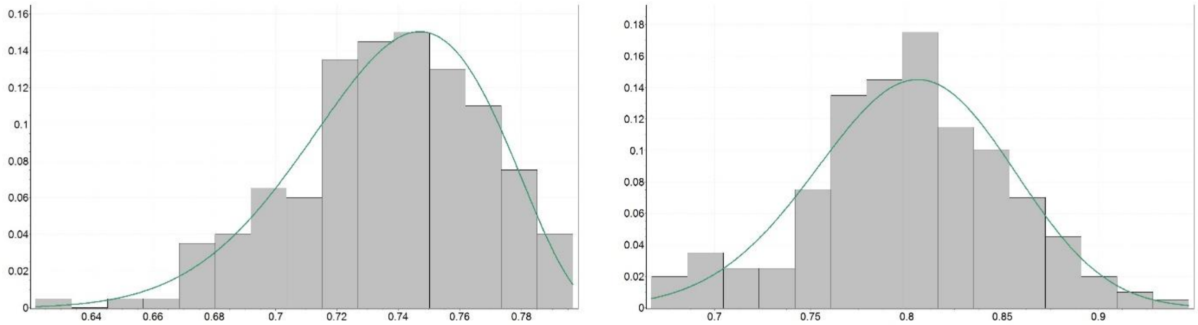


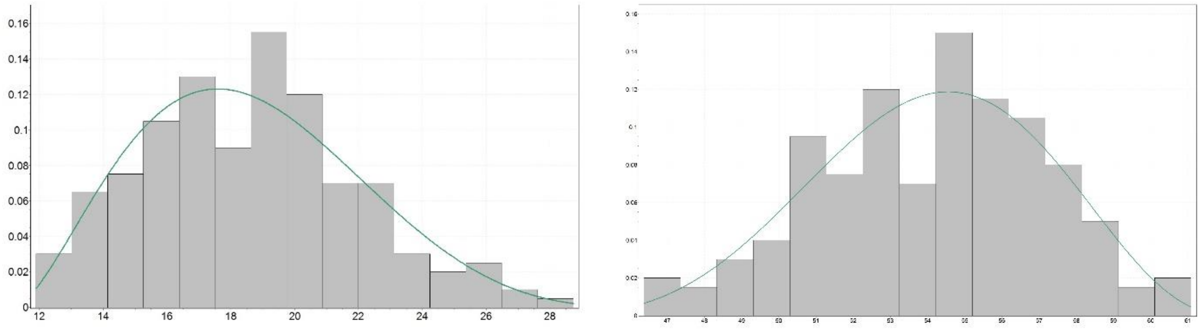
Fig.7: Convergence of the simulation after 200 iterations of the accumulated overall travelled distance measured in kilometers for 6 months of operation.

Any simulation required to be carefully validated. In this paper, the validation data were not presented for confidentiality reasons. However, following section shows typical preliminary results that can be obtained from the DES.



(a) Average utilization of the 23 PSVs in % (b) Average utilization of the 6 berths in %

Figure 8. Probability density function of the utilization of the resources considering 200 iterations and 6 months of operation



(a) Average mooring time per PSV in hours (b) Number of clusters supplied per PSV

Fig.9: Probability density function of typical outputs considering 200 iterations and 6 months of operation

Figure 8 shows respectively the probability density function of the average utilization of the 23 PSVs (mean 75%) and the average utilization of the 6 berths at the logistic terminal (mean 80%). These values indicate that for that configuration the logistic port is saturated. The average mooring time per PSV, Fig.9 (a), and the number of clusters visited per PSV, Fig.9 (b) are other typical results that can be generated. The mean value of the number of clusters supplied per PSV is around 55. That is cross checking the assumption on two visits of clusters per week for each PSV.

The actual DES model is limited to the study of the influence of the uncertainties due to weather downtimes and sea-going operation delays. However, in a near future, the model would be improved to included additional factor such as deck-load capacity, dry bulk capacity, load delivery delays, etc. Anyway, the presented methodology provides a novel approach to develop realistic simulation starting from the big data fed by AIS data. This represent the basic framework for fleet size decision making, scheduling optimization, cluster optimization, etc. To obtain better results it is recommended to use even bigger AIS database that cover at least 3 years to better mimic the weather uncertainness.

4. Conclusion and recommendations

The use of Big Data software technology such as Apache Hive in Hadoop makes it easy to read, write, and manage large datasets that reside in distributed storage using SQL. Moreover, it may drastically reduce the execution time of the query if enough nodes are used to process the data. This technology has been used here to extract pattern regarding navigational behaviour of Platform Supply Vessels. Then, the new knowledge was introduced in a stochastic simulation to mimic the supply chain management of offshore platforms. The results shown that the proposed methodology is efficient to reproduce offshore logistic activities taking into account uncertainties related to operational matters, as well as weather uncertainties that affect the system.

Acknowledgements

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The Extended Process-Centric Modeling Method for Logistics Simulation in Shipyards Considering Stock Areas

Byeongseop Kim, Seoul National University, Seoul/Korea, jjolla93@snu.ac.kr
Yong-Kuk Jeong, Seoul National University, Seoul/Korea, jake8967@snu.ac.kr
Seunghyeok Son, Seoul National University, Seoul/Korea, kalnal12@snu.ac.kr
Philippe Lee, Xinnos Co., Ltd., Seoul/Korea, philippe_lee@xinnos.com
Yonggil Lee, Korea Maritime and Ocean University, Busan/Korea, yaleyong@kmou.ac.kr
Jong Hun Woo, Korea Maritime and Ocean University, Busan/Korea, jonghun_woo@kmou.ac.kr

Abstract

Block logistic loads, such as those associated with transporters and stockers, are difficult to consider in the planning stage for a shipyard. This study was conducted to calculate the block logistics load in the planning stage using simulations and proposes an extended process-centric modeling method with the concept of a logistic token being added to the conventional process-centric simulation method used in the shipyard. The proposed method was validated first through a unit model and then with a logistics model of an actual shipyard that was constructed from the validated model. As a result of the simulation, usage result of stock area, transporter, and road for the plan was obtained.

1. Introduction

Ships are manufactured by a block construction, by assembling an intermediate product, usually in the form of blocks, and then constructing the ship as a finished product by mounting the blocks at the dock. After the assembly, blocks undergo processes such as outfitting, installation of pipe and electric devices, and painting. Blocks wait in the stock area if there is a period of time remaining between the processes before they can be mounted at the dock. Blocks are very large and heavy even though they are intermediate products, and they are transported one by one using a special facility called a transporter. Such transportation and stocking processes are referred to as block logistics in the shipyard.

Because the number of transporters and the space in the stock areas are limited, such logistic loads must be considered in the planning stage for smooth production. In most cases, however, logistics plans including transporter and stock area allocations are not set up in the planning stage and the block transportation department just provides such direction in the actual production stage. Because the loads of transporters and stock areas are not considered in the planning stage, even if the process equipment capacity is sufficient, processes can be delayed by logistic loads in the production stage, *Song and Kang (2009).*

In addition to the shipbuilding industry, logistical load issues within the plant are also experienced in the automobile, semiconductor, and aviation industries, and many studies have been conducted to calculate logistic loads using discrete-event system (DES) simulations. Most DES studies are based on resource-centric modeling, which is a method of modeling facilities and products flows along facilities. However, the resource-centric modeling method has a few problems when applied to shipyards, as shipyards do not produce mass production. First, products of shipyards don’t flow through a certain route, so modeling of route which is essential in resource-centric modeling is difficult. Second, it takes much time to model the resources of a plant because the shipbuilding plant has very large space and many facilities. Third, simulation results from the resource-centric model are not easy to analyze based on schedule, but most decisions in the production stage of a shipyard are based on the schedule made during production planning stage.

Due to these reasons, the DES simulation research of shipyards has focused on a process-centric modeling method instead of a resource-centric modeling method, *Lee et al. (2014)*. It has been demonstrated that the process-centric modeling method is more appropriate for shipyards and has been used in such cases as the validation of mid-term plans, *Jeong et al. (2015)*. However, the conventional process-centric modeling method has a limitation as it is difficult to express logistic loads between processes. In this study, therefore, an extended process-centric modeling method that has added the concept of a logistics token to the conventional method was proposed and applied to actual shipyard logistics.

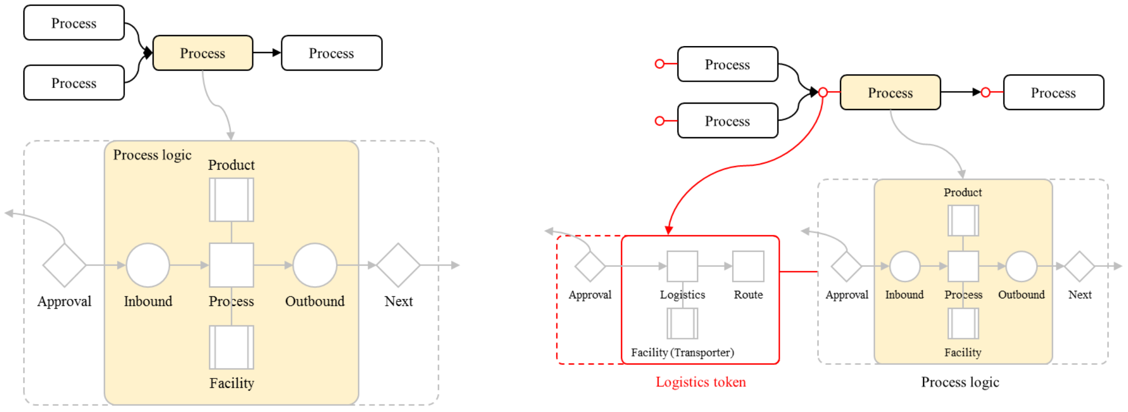
The application of logistics simulation in this paper consisted of two steps: a step for constructing and validating a unit logistics model test and a step for extending unit systems to build a logistics model of an actual shipyard including. The objective of the validation of simulation is to analyze the correctness and suitability of the model; correct validation can guarantee the credibility of the model, *Rabe et al. (2008)*. However, it is very difficult to confirm accurate modeling (especially process logic) because the model of an actual shipyard consists of numerous products, processes, and facilities. In this study, therefore, the process logic was validated by confirming that the desired simulation result can be produced through a virtual model. Furthermore, a logistics simulation model of an actual shipyard was constructed and the logistic loads for an actual production plan were determined.

2. Process-centric modeling method for logistics simulation in shipyards

2.1. Process-centric modeling method

The production system in the manufacturing industry can be divided into flow shop, job shop, and project shop depending on the characteristics of the facilities and manufactured products. The flow shop refers to a production system in which facilities and workers work at predefined locations and products move according to the pre-designed flow. Flow shops are used in highly automated production systems such as those in the automobile industry. If the manufactured products are large and difficult to move as in the aircraft manufacturing and construction industries, the job shop production system, in which the products are fixed, is applied. In a flow shop production system, the locations of facilities are rarely changed once they are fixed. Therefore, it is more advantageous to modeling around the facilities when constructing a simulation model. Most commercial simulation software applications targeting the manufacturing industry apply the resource-centric modeling method.

However, the production system of the shipbuilding industry, which is the subject of this paper, has characteristics that are similar to those of a job shop. The products manufactured in shipyards do not have a constant route inside the shipyard. Thus, when modeling a shipbuilding process in a shipyard, it is more advantageous to perform modeling centered on processes with products and facilities set as process constraints. A process-centric modeling method expressing this process has been proposed and represented the relationships between previous and next processes as a network. Each process was designed with detailed logics (approval, inbound, process, and outbound) and constraints (product, and facility) as shown in Fig. 1(a).



(a) Basic process-centric modeling method and detailed logic items

(b) Process-centric modeling method for logistics simulation

Fig.1: Process-centric modeling method and detailed logic items

2.2. Extended process-centric modeling method using logistics token

The conventional process-centric modeling method was useful in a simulation to validate the production plan of a shipyard, but has limitations in representing the block logistics between processes. To improve these, the existing modeling method was extended as shown in Fig. 1(b) by defining logistics flow and adding a logistics token before each process to express the detailed logistics logic.

The shipbuilding process in a shipyard is a job shop production system as described above. However, products are moved using a transportation facility in the semi-finished product stage prior to the finished product. As an example, semi-finished products may wait in the stock area due to a schedule gap between processes. All these phenomena can be expressed in the logistics flow of the shipyard. In order to perform block logistics simulation, a logic item for expressing a logistics phenomenon must be added to the conventional process-centric modeling method. The logistics token includes detailed logic for approval, logistics, and route and can define the constraints of transportation facilities.

3. Validation of the extended process-centric simulation model

3.1. Problem definition

The process of executing logistics simulation is outlined in Fig. 2. When the simulation is started, the product is input to the first process of the process chain corresponding to the date of the plan data. This process is carried out during the cycle time that is defined in the plan and logistics activities are generated to continue to the next process after a process is completed. At this time, the logistics are carried out according to the process logic of the logistics token. A transporter that satisfies the transporter constraints is allocated from the idle transporters and finds the path to the next process according to the route logic. If there is a waiting time before the start of next logic, the block is moved to the stock area according to the logistics logic. Once the waiting time expires, the block is moved to the next process, which is carried out in the same manner. The simulation logs for the transporters, stock areas, roads, and processes are recorded during the logistics simulation and can be reviewed after the simulation is completed.

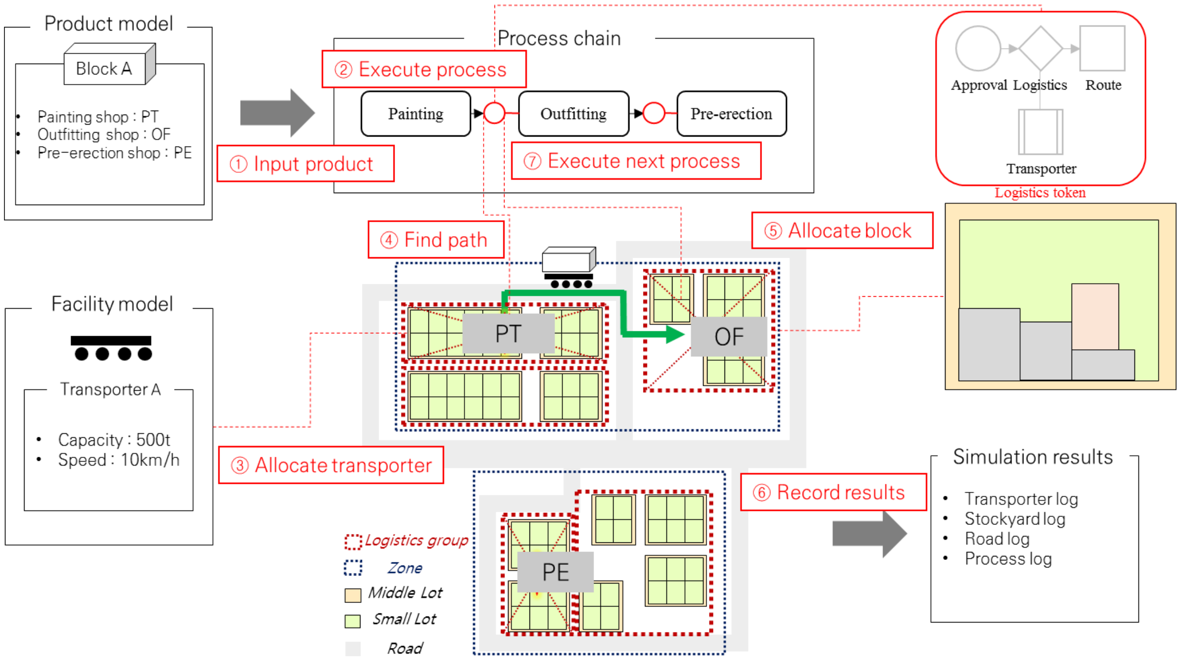


Fig.2: Logistics simulation execution process

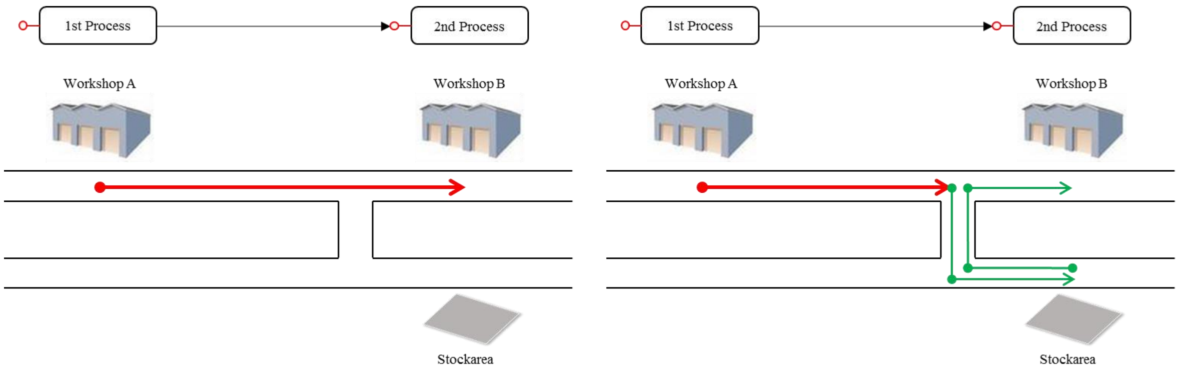
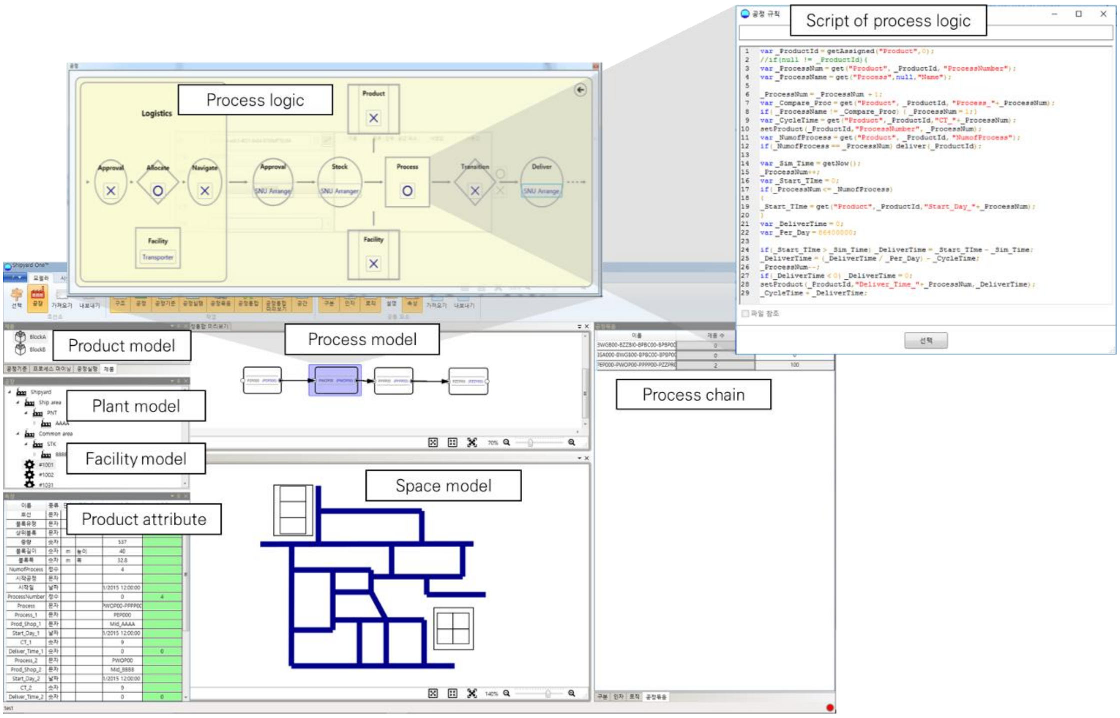


Fig.3: Factory Selection Logic

The workshop and stock area are created as part of the plant model that is mapped to spatial data. The plant selection logic is performed in the logistics step of the logistics token and determines stocking by comparing the simulation time and planned days. Fig. 3 shows a schematic of the routing path of blocks. When the difference between work time and planned days is less than one day, the block is immediately input to the workplace of the next process. If the block needs to be stocked, it is moved to and remains at the stock area until being moved to the workshop of the next process on the starting date of the next process.

The selection of a stock area can be considered as an important factor if stocking is required. The stock area selection logic in the simulation has the preferred stock area information for each workshop considering the logic of movements. During the selection of the stock area, the workshop of the next process checks the preferred stock area and stocks the blocks in the corresponding stock area.

The facility capacity must be considered for efficient use of transporters. This capacity refers to the maximum weight that can be transported. Transportation is impossible if the block weight is greater than the capacity. The simulation is designed to select a facility that has the smallest capacity among the facilities having a capacity greater than the block weight. The objective is to use the most efficient facility to minimize the fuel consumption, as fuel efficiency is lower when the facility weight is greater.



```
var _ProductId = getAssigned("Product",0);
//if(null != _ProductId){
var _ProcessNum = get("Product", _ProductId, "ProcessNumber");
var _ProcessName = get("Process",null,"Name");

_ProcessNum = _ProcessNum + 1;
var _Compare_Proc = get("Product", _ProductId, "Process_"+_ProcessNum);
if( _ProcessName != _Compare_Proc) { _ProcessNum = 1;}
var _CycleTime = get("Product",_ProductId,"CT_"+_ProcessNum);
setProduct(_ProductId,"ProcessNumber", _ProcessNum);
var _NumofProcess = get("Product", _ProductId, "NumofProcess");
if(_NumofProcess == _ProcessNum) deliver(_ProductId);

var _Sim_Time = getNow();
_ProcessNum++;
var _Start_TIme = 0;
if(_ProcessNum <= _NumofProcess)
{
_Start_TIme = get("Product",_ProductId,"Start_Day_"+_ProcessNum);
}
var _DeliverTime = 0;
var _Per_Day = 86400000;

if(_Start_TIme > _Sim_Time) _DeliverTime = _Start_TIme - _Sim_Time;
_DeliverTime = (_DeliverTime / _Per_Day) - _CycleTime;
_ProcessNum--;
if(_DeliverTime < 0) _DeliverTime = 0;
setProduct(_ProductId,"Deliver_Time_"+_ProcessNum,_DeliverTime);
_CycleTime = _DeliverTime;
```

Fig.4: Example of unit logistics simulation model

3.2. Description of unit logistics model

As shown in Fig.4, products, processes, facilities, process logic, and space should be modeled to run simulation. Processes were modeled based on production plan data, and process chains were created by connecting the processes passing by products in a network form. Each process was modeled by the extended process-centric modeling method so included the logistics token, process logic and constraints of product and facility.

Products were also modeled from production plan data, and had attributes such as the process list to be processed, the workshop where each process was performed, start time and cycle time of each process. Plants were hierarchically modeled according to the inclusion relation and had width and height as attributes. Facilities were modeled under plants so could be used only at the designated plant, and had the capacity and moving speed as attributes. Also note that unlike the resource-centric model, this model does not have the shape information of product or facility in 3D form.

Before constructing a logistics simulation model using actual shipyard data, a simple unit logistics model was composed to validate the process logic. The unit model had two zones, each containing a space that allows work and stocking, two products that pass four processes each, and two transporters. The process was carried out alternately in each zone, so a transporter was used when each process was completed.

3.3. Simulation results

The process result, transporter usage result, and stockyard usage result obtained by simulation using the unit model are summarized in Fig.5. The process result indicates the date each process starts and ends and the type of product used in the process. It also shows that the product was waiting at the stockyard when the preceding process was completed prior to the planned start date of the process. Also the stockyard usage result shows the same result. The transporter usage result shows that the transporter is used between the process and the process, and between the process and the stock. These results mean that the logistics logic and the facility constraint in the logistics token were reflected in the model as intended at the problem definition stage.

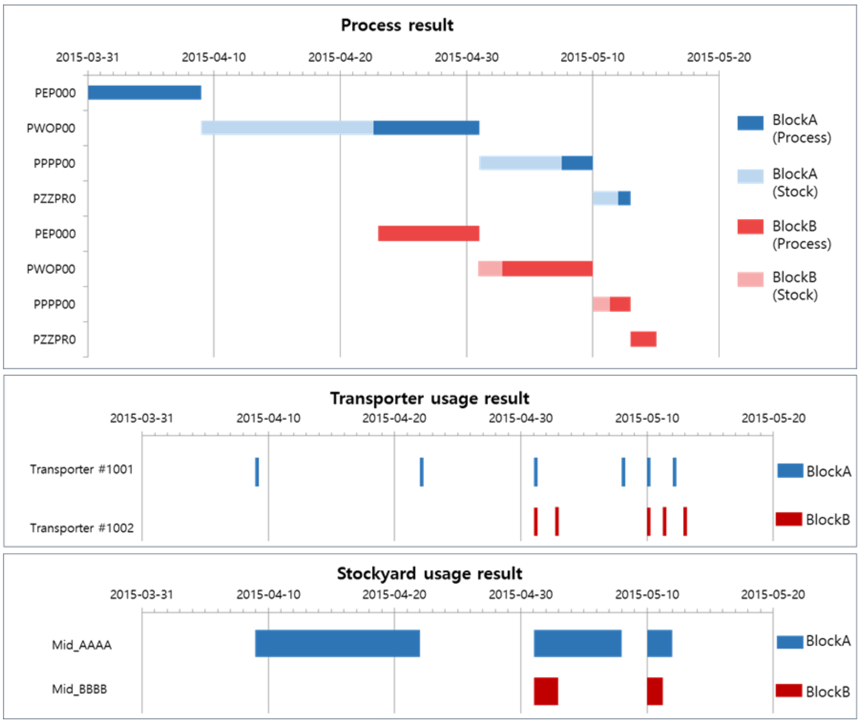


Fig.5: Simulation result of unit logistics simulation model

4. Implementation of the extended process-centric simulation model

A block logistics simulation model was constructed using actual shipyard data. Process information and product information were imported from the planning system, and spatial information was imported from the geographic information system (GIS) system. Process chain, product, and space model were created automatically in the simulation system from imported data. After that, the plant and equipment were manually modeled. In each process, the process logic and facility constraints of the unit model in the previous chapter were entered.

The simulation results are output as a table form; the structure of table depends on the main target (schedule, facility, plant or product) to be reviewed. Furthermore, the route path of a block is visualized in connection with the GIS model (Fig.6). The results of the simulation obtained are summarized as shown in the Fig.7. The usage rate of facilities is a ratio of the number of blocks each transporter carried. The usage rate of plants was obtained from the number of blocks that have been worked at each plant, and usage rate of roads were obtained from the number of blocks that have passed. A good analysis of the simulation log will provide meaningful results, as well as the ratio of use of these facilities and factories. Using the simulation log of this model, it is possible to obtain a variety of meaningful results not only the usage rate of facilities.

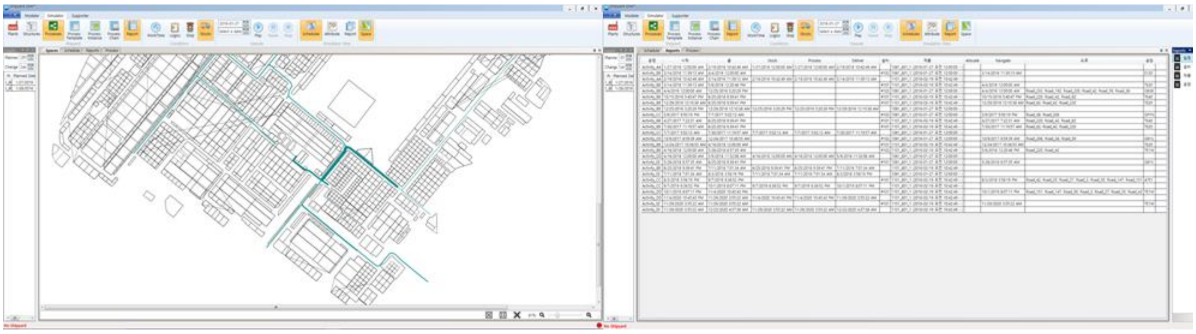


Fig.6: User interface view of simulation result

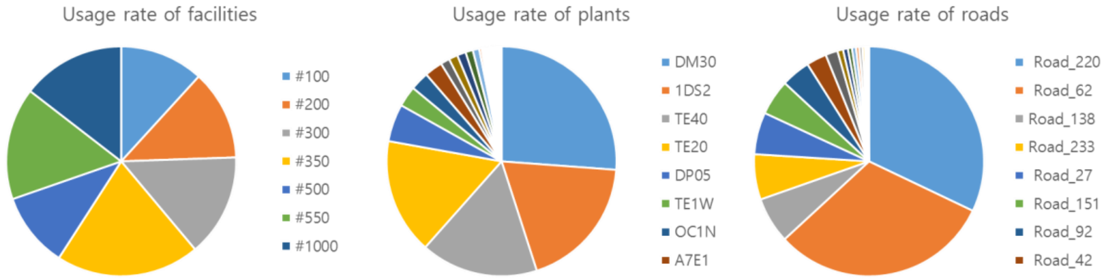


Fig.7: Usage rates of facilities, plants and roads

5. Conclusion

The loads associated with block logistics in a shipyard are high as limited facilities are used compared to the number of products to be transported. Therefore, process delay may be caused in the production stage unless the block logistics are considered in the planning stage. Hence, a method of calculating the block logistics using simulation in the production planning stage was proposed.

The process-centric simulation method which have used in another shipyard DES simulation studies is being used for block logistics simulations. However, because the conventional method has limitations in expressing the block logistics of the shipyard, an extended process-centric simulation method with the concept of a logistics token was proposed for improvement of the simulation. The proposed method can include the transporter constraints, stock area allocation logic, and path navigation logic used in the block logistics process in the model.

In addition, to validate the proposed method and the process logic of logistics simulation, a unit model was constructed. It was validated that this model produced the desired results for the usage of transporters, stock areas, and roads and that the process logic of this model successfully reflected the block logistics process. Next, the logistics simulation model of an actual shipyard was implemented using schedule data and GIS data, and the validated process logic from the unit model. Such simulation results as road usage, transporter usage, and stock area usage for an actual schedule could be calculated using this model. These calculated logistics loads can be used in the production planning stage to establish plans by considering logistics as constraints and can be also applied to the establishment of transporter operation plans.

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Toward Functional Augmented Reality in Marine Navigation: A Cognitive Work Analysis

Stephan Procee, Maritiem Instituut Willem Barentsz, Terschelling/the Netherlands, s.procee@nhl.nl
Clark Borst, Delft University of Technology, Delft/the Netherlands**,** C.Borst@tudelft.nl
René van Paassen, Delft Univ. of Technology, Delft/the Netherlands, M.M.vanPaassen@tudelft.nl
Max Mulder, Delft University of Technology, Delft/the Netherlands, M.Mulder@tudelft.nl

Abstract

Augmented Reality, (AR) also known as vision-overlay, can help the navigator to visually detect a dangerous target by the overlay of a synthetic image, thus providing a visual cue over the real world. This is the first paper of a series about the practicalities and consequences of implementing AR in marine navigation. A Cognitive Work Analysis is carried out to derive a scientific base for a functional interface that best supports navigators in their work.

1. Introduction

The task of the watch officer (WO) can be described as systems process engineering. Long periods of relative inactivity can suddenly change into a situation requiring heavy multitasking with a high level of workload. It is no surprise then that, based on the number of navigational claims, the Swedish Club has reported that in most accidents (69%), human error is an immediate cause. In this research, we focus on the prevention from accidents related to navigation, collision and grounding. From the same Swedish Club analysis it appears that lack of situation awareness is an immediate cause for collision (38%) and groundings (55%).

Although several measures like Vessel Traffic Service (VTS), separating traffic, and the introduction of electronic navigation have helped decrease the absolute number of accidents, the large annual number of accidents and dramatic loss of life motivates research into ways to further improve. Moreover, statistics in transported tonnage show that the amount of transported goods by sea has more than tripled since the 1950s and is expected to grow by approximately 2-3% per annum for the next decade *UNCTAD (2016)*. This justifies the effort spent on research and development to improve safety.

It is commonly accepted that technical malfunctioning of navigation equipment is seldom the cause of accidents, therefore focusing on human factors is opportune, however, the work routines of the navigator have barely changed over the last three or four decades. Morrel suggested already in 1960 that some form of expert aided decision support would be helpful in accident prevention, *Morrel (1960).* Despite several studies into this field, automated Collision Avoidance (CA) or decision support has still not been accepted. In the foreseeable future the human operator therefore remains the only entity to control the ‘open’ process of navigation.

The research presented in this paper aims at creating a novel interface that best supports the human in his or her role of decision maker. AR can contribute to this proposed Information Management Expert Support system. By superimposing a virtual image on the outside world, the reality is enhanced by visual cues. These cues can represent dangerous targets, however, in the E-navigation domain the functionality needs not be limited to CA alone. Using AR, we also expect to speed up effective information processing, although the practical implication of introducing this new technique is not at all clear. Although several ways to portray AR already exist, and although hardware development is ongoing, in this research we will use a Head Mounted Display (HMD) for testing.

An example of AR is shown in Fig.1 where the red projected box (c) points to a critical target, a red projected fence (a) shows the area to be avoided and a route suggestion (b) is shown by the projection of green 'runway' lighting. This projected information is corrected for the ship's attitude and motion and also takes into account the position and viewing direction of the observer.

Fig.1: Three examples of Augmented Reality

This paper is a condensed version in a series of papers on the introduction of AR in the maritime navigation domain. The first author is currently engaged in a PhD research into this subject. In his professional background, he has worked as a Maritime Officer, after which he has worked as a Nautical Cartographer at the Hydrographic Service of the Royal Netherlands Navy. Since 1998 he is lecturing Navigation at the Maritiem Instituut Willem Barentsz at Terschelling. The aim of this paper is to describe the development to obtain a scientific base for an interface that supports the navigation task. Future work entails to experimentally evaluate this interface in practice by experiments in a ship's bridge simulator. The scientific base will be developed through performing a Cognitive Work Analysis (CWA) *)* of the marine navigator, *Vicente (1999*.

2. Modelling the Marine Navigator's Work

2.1. Cognitive Work Analysis

Developments in the field of interface design and human performance modeling behold a promise of a novel approach. Rasmussen's taxonomy of Skill- Rule- and Knowledge based behavior suggests distinct levels of the skilled worker's performance and relates three different uses of available information, i.e., Signals, Signs and Symbols *Rasmussen (1983)*. One of the descriptions in his conclusion,

> *the tradition of designing interface systems based on one-sensor-one-indicator technology, where the operator is expected to 'figure out for himself' what the state of the system is based on indicator readings and training of system fundamentals*

can be regarded as typical for the 'modern' ship's bridge layout. Rasmussen suggests that the use of computer technology to optimize man-machine communication requires structured presentation of information according to the nature of the control task the operator is supposed to perform. Vicente highlights that 'open systems' by definition cannot be operated based solely on predefined rules and procedures because the designer cannot anticipate on the inherent richness of possibilities of these 'open systems'. Hence, the operator needs also information from the system that supports his task in solving unanticipated problems and situations. Bennet & Flach focus in their book on,

> *the primary purpose of an interface, to provide decision making and problem solving support for a user who is completing work in a domain*

In their book they adapt what they call a triadic approach, i.e., the design emphasis is put on the functional demands of the work domain *Bennet and Flach (2011)*. The underpinning Cognitive Systems Engineering (CSE) concept finds a broad ground, and from that the concept of Ecological Interface Design (EID) has been derived in the early 1990’s *Flach et al. (1998)*. From Bainbridge *Bainbridge (1983)* we may infer that maximizing the use of 'perceptual motor skills' and minimizing the disruption of working memory may lead to a different balance in the distribution of mental resources thus supporting problem solving tasks.

The multitude of tasks that the watch officer (WO) has to deal with, are visualized in Fig.2. The navigation process of a ship can be characterized as dealing with a highly 'open' system, meaning that it is subject to unpredictable external and internal influences. Although ships are overwhelmed by Authorities’, Class Societies’, P&I clubs’ and Fleet Operators’ rules, requirements, procedures and checklists, the work cannot really be characterized as 'normative'. Which means that, although some of the tasks have been literally described in terms of instructions or checklists, the majority of work is done at the WO's discretion within the boundaries of safe and effective operation.

Fig.2 is a representation of many of these boundaries and can therefore be regarded as a constraint-based description of the WO's tasks, also known as 'task representation'. The quality assurance systems in use primarily describe the responsibilities of the WO but not ‘how’ to fulfill these. So when we analyze the work with the aim to develop an effective interface we should go further than this constraint-based task representation. The reason for this wider scope is that the work domain, i.e., the ship, its controls and its natural environment, have a huge impact on the operation. Thus, the work of the WO cannot solely be described by 'goals to be achieved', instead the possibilities and limitations of the work domain should be taken into account as well. And, as said before, the introduction of new technology, i.e., AR, requires us to design a new interface. The effectiveness of this interface heavily depends on the 'meaning' of the portrayed information, in other words, it depends on the provided or shown consequences, limitations and affordances of the system given its state and its environment. Therefore, we have to analyze the work domain, and use this analysis together with the task representation to come to an overarching framework in order to enable effective interface design.

2.2. The Work Domain

The work domain consists of ships and sea. A ship can be defined as a floating self-propelling controllable object, guided autonomously by a licensed watch keeper, with the purpose of undertaking a voyage expeditiously. In this context the sea can be defined as any stretch of water, deep enough to allow a ship to sail in and open for navigation.

Different from air navigation, traffic at sea is in principle unguided. However, there are situations where the risk of grounding or collision is deemed so high that precautionary measures are taken. In such cases the competent authority provides guidance by means of an established VTS or by arranging compulsory pilotage. The competent authority can only rule within its own territory. Outside territorial waters the principle of free sea rules since Hugo Grotius propounded this principle in his 'Mare Liberum' in 1609 *Grotius (1609)*.

Notwithstanding the principle of free sea, several arrangements have been accepted by international agreement in order to regulate shipping in international waters to enhance safety and reduce pollution. Amongst these are for instance the International Collision Regulations *IMO (1972)*. These 'Rules of the Road' focus primarily on the mutual conduct of ships. Ships have an obligation to act conformal to the Rules, the ship's flag state is the only authority empowered to keep the law on board a vessel sailing in international waters. The consequence of unguided shipping is that every vessel is free to choose and sail its route. Although this routeing is strongly biased by cost-efficiency, the wide diversity in ship types, ports of departure and destination results in an unpredictable, sometimes chaotic, traffic pattern.

On watch the WO has the responsibility to operate the ship within the boundaries of safety and efficiency and conform to the captain's watch orders. With the introduction of technical advances e.g., Global Positioning System (GPS), Automated Identification System (AIS) and Electronic Chart Display and Information System (ECDIS), the work of the WO has gradually changed. The classical bias on navigation, i.e., position fixing by taking bearings, deduced reckoning or sight reduction, has shifted towards observing the ship's progress on electronic equipment, i.e., ECDIS or its derivatives.

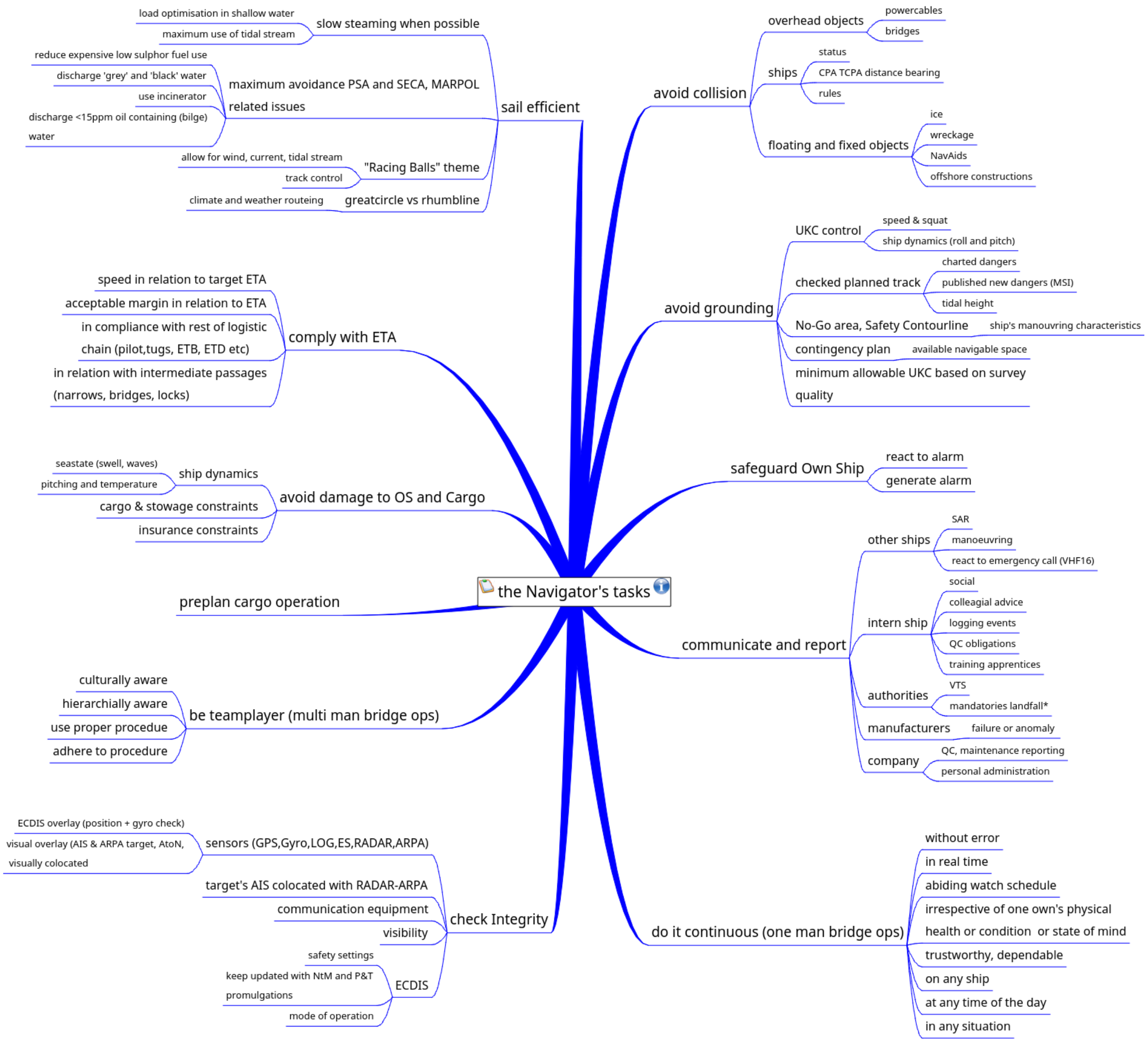


Fig.2 Constraint based description of the WO's tasks

In cases where the ship's autopilot is connected to the ECDIS the consecutive legs of the planned route are sailed without the WO's interference. This can be regarded as a basic instance of integration. Despite the claim of manufacturers that they offer integrated bridge design (IBS) and integrated equipment, real integration is not seen yet on most ships. It is the WO that does all the monitoring, integrity checking, decision making and execution. This 'human integrating' might be considered beneficial for building and maintaining Situation Awareness (SA). It can also result, however, in a wrong or impoverished determination of the situation due to fatigue and subsequent human limitations like, e.g., cognitive tunneling or negligence.

2.3. E-navigation developments in the work domain

The increase in the amount of worldwide transported goods by sea, the broadly felt public urge to reduce the environmental impact of transport in general, and the reduced cost of continuous world-wide satellite communication have led to the adoption of the E-Navigation concept by the IMO and IALA. The agreed definition of E-navigation is: *IMO (2017)*

> *the harmonized collection, integration, exchange, presentation and analysis of marine information on board and ashore by electronic means to enhance berth to berth navigation and related services for safety and security at sea and protection of the marine environment.*

An anticipated consequence of E-Navigation's safe communication possibilities is the exchange of the planned route ahead. An already materialized prototype is called “Intended Route Exchange”. This enables interacting ships to visually inform each other and even visually negotiate their planned maneuvering within a limited time frame of approximately 20 to 30 minutes *ACCSEAS (2015)*. This will lead to unprecedented interaction between ships. An interaction based on the exchange of the geographically referenced visualized planned route, and the visualized intention to deviate to avoid collision.

Without going into all detailed examples of the more or less matured E-Navigation prototypes, it is clear that the impact of these developments on the work domain will be tremendous. Whilst a materialized E-Navigation proposition has not yet emerged, nor has it been internationally agreed or adopted by IMO, we must focus on the existing work domain and keep in mind that within the next decade a drastic shift will be necessary due to the adoption of E-Navigation.

2.4. Decomposition of the Task Representation

It is obvious from the complexity of Fig.2 that, in order to analyze the total span of the WO's information needs, we have to decompose this task representation into subsets. The aim is to derive such subsets that every subset covers a logical cluster of tasks which each relate to specific information needs. From these information needs we can aggregate an overarching integrated interface which effectively informs the WO and supports him in the execution of this subset of tasks. Ultimately, the aggregation of each optimal interface should lead to an overarching interface design supporting the WO in his or her work spanning the task representation, Fig.2.

The following subsections deal with the subset of *CA*. This subset can be decomposed into three areas dealing with characteristic entities. All these entities are located on or above the sea surface, thus are, in principle, visible and do impose a real danger to the vessel. The three characteristic entities relate to the area of height restriction, e.g., bridges or overhead power cables, the area of other ships, and the area of passive objects. The other subsets, e.g., grounding avoidance, efficient sailing and damage avoidance will be covered in following papers.

2.5. Collision Avoidance, State Variables and State Dimension

In previous sections, we discussed the task representation of the WO, describing the boundaries within which she has to perform his work, or within which he has to keep the system that he's controlling. This system has its own characteristic and behavior which in its turn defines the possible outcome of control, or the possible states that can be controlled. The *State* can be defined as a vector in State Space describing the behavior of a system at a particular time. In the case of a ship this can be seen as the set of relative position, course and speed and status of the ship, wherein State Variables, such as course, speed, visual and oral declaration of the status and relative position can be used to describe this State.

The state dimension specifies the space of possibilities, a multidimensional space which can be regarded as the set of all Trajectories, hence, the description of all Behavior of a system over time.

The importance of describing the state dimension lies in understanding the intricate relation between the boundaries within which to control the system and the state of the system which initiates the need for control. The ship's State variables course and speed need not much explanation, both can be defined relative to the water as well as to the ground. The combination of the two can be used to predict the geographical position of the vessel.

The State Variable 'relative position' is used in relation to other traffic. This relative position has a consequence for the obligatory conduct of ships when they interact, thus, when risk of collision exists and ships are relatively close to each other. When the relative distance is large, however, ships are considered not to be engaged and both can voluntarily choose an evasive measure in order to prevent interaction at all.

The State Variable 'visual or oral declaration of status' applies to the special status that certain ships have in relation to their work, e.g., fishing, or limited possibilities, e.g., deep-draught vessels. The status of a vessel is made known to surrounding traffic by a visible daymark or light and can also be transmitted through marine radio by speech or by AIS-code.

2.6. Work Domain Analysis, Abstraction Hierarchy (AH)

The work domain of the subset CA can be described by two distinct hierarchies. The part-whole or decomposition hierarchy and the means-ends or Abstraction Hierarchy (AH). The former deals with zooming in or out on the work domain, thus either showing parts or the larger whole. The latter deals with relating structural means to achieve the higher-level ends, thus showing reasons for doing and ways to accomplish. A first version of AH for the task of CA is shown in Fig.3.

The scope, CA, is chosen because it is of paramount importance for safe shipping and has a strong relation with the introduction of AR as new technology in navigation. There is a relatively weak link with the safety related goal of grounding avoidance because the quality of the terrain, i.e., shallow or unsafe water, imposes a limitation in navigable space and therefore can have an impact on the CA work domain. For the sake of simplicity grounding avoidance is left out of this analysis. At a later stage this link will be revisited leading to an overarching integral work domain analysis for the worker. The generic term worker is used on purpose, and can be considered as the bridge manning varying from a team consisting of five professionals down to a single licensed watch keeper. Unmanned bridge operation is currently illegal.

The Functional Purpose is the highest level in the AH, it can be interpreted as the purpose for which the system is designed. Focusing on the nautical application we can state that a ship was designed in order to accommodate crew and cargo, stay afloat, fight fire and support its energy needs to name just a few. Of course the ship is also designed to propel itself to make progress and to manoeuvre to separate from traffic and objects, as well as designed for a specific height and or draught restriction. In this AH we discriminate three purposes that interrelate. The functional purpose of progress is carried out by means of the abstract functions direction and speed, which are carried out by means of the generalized function of Rate of Turn (ROT) and acceleration, respectively. These two functions are carried out by means of lift and thrust. Lift is generated by means of a rudder, and thrust by means of a propeller.

In this approach of maritime transport we analyze egocentric self-navigation applied to a conventional ship with one rudder and a single fixed pitch propeller. Existing variants like e.g., azimuthal-controlled propulsion, multiple propellers, bow-stern thrusters and active rudders are left out.

The other two functional purposes in this AH example are horizontal- and vertical separation. Both are dealing with CA, and relate to progress, i.e., direction and speed as well. Horizontal separation is carried out by means of a safe distance to a target, another ship, on the one hand, and on the other hand by means of a safe distance to an object, e.g., a wreck, buoy, rock or iceberg.

Vertical separation is carried out by means of a safe Under Keel Clearance (UKC) with respect to the ground and a safe Overhead Clearance (OHC) with respect to a fixed cultural object like an overhead power cable or a bridge. The reason for this diversion is the characteristics of the mentioned three object types and the different sources of information that are needed to plan for and take evasive measures. Justification for this motivation is given in the next three paragraphs.

The first abstract function deals with the safe distance to targets. We use the term ‘target’ as a generic name for active entities as opposed to objects which are passive. This function is carried out by means of the COLREGs and subsequently by means of the Own Ship’s (OS) safety zone which on its turn is defined by means of the OS’s particulars like length, breadth, speed, cargo, draught, etc. So, in order to keep a target out of OS’s safety zone we apply the generalized function of the COLREGs to the end of complying with the rules, which can be applied by means of the abstract functions direction and speed. This illustrates the relation between the functional purpose of progress and horizontal separation.

The second abstract function, horizontal distance to objects, deals with objects in the water. This varies from charted aids to navigation, charted production gear like fish farms, dredge pipelines, wind turbines and Single Point Moorings to uncharted floating dangers like debris, ice or wreckage. The commonality is that these are passive objects usually in the vicinity of shipping routes, fairways and harbours, and that their existence is not always known, so their position may not be charted, and their actual presence is not always easily noticed.

Vertical separation can be realized by means of a safe UKC, which is realized by means of a sufficient difference between the depth of the fairway and the ship’s draught which is realized by the vessel’s displacement, the route, and date and time influencing tide and seastate. This in its turn is realized by means of the vessel’s particulars, of which draught contributes most. Analyzing grounding avoidance is left for later papers.

The other means of realizing vertical clearance is a safe OHC, which is realized by means of a sufficient difference between the published safe height and the ship’s air-draught. As well as UKC, this is realized by means of draught, tide and seastate.

The safe height of bridges and overhead power cables is found in nautical publications, i.e., Charts and Pilots, and depends on the height of the water level. The height of the water level is, to a certain extent, predictable, but can show unforeseen deviations due to the meteorological and natural conditions, i.e., wind, air pressure, river down flow. The other variable, the vessel's air-draught, is based on the vessel's dimension and present draught but is influenced by the ship's dynamics like squat, trim, list and rolling. Despite these invariants and uncertainties, the number of ships colliding with a bridge or hitting the bridgedeck with their superstructure grew to an average of three per year *Gluver and Olsen (1998).*

2.7. Control Task Analysis, the Decision Ladder

The Control Task Analysis (CTA) is complementary to the Work Domain Analysis (WDA). CDA aims at describing *what* needs to be done irrespective of worker or method. For this description the decision ladder, developed by Rasmussen, is used *Rasmussen (1987)*. This tool can be used to develop control task models and provides the necessary flexibility to allow for the shortcuts and shunts that experienced workers have developed over time in their strive to work effective and cognitively efficient. Fig.4 shows an example for the task of CA. A box means action, a circle means knowledge. Although action can start anywhere in the ladder, usually the detection of an object i.e., a bridge, ship or buoy will lead to a state of alertness or alarm and starts subsequent actions. Observations are made with independent, redundant, sensors to establish integrity of detection. From this, one knows that the detected object really exists and is in the detected position, so it's not an anomaly.

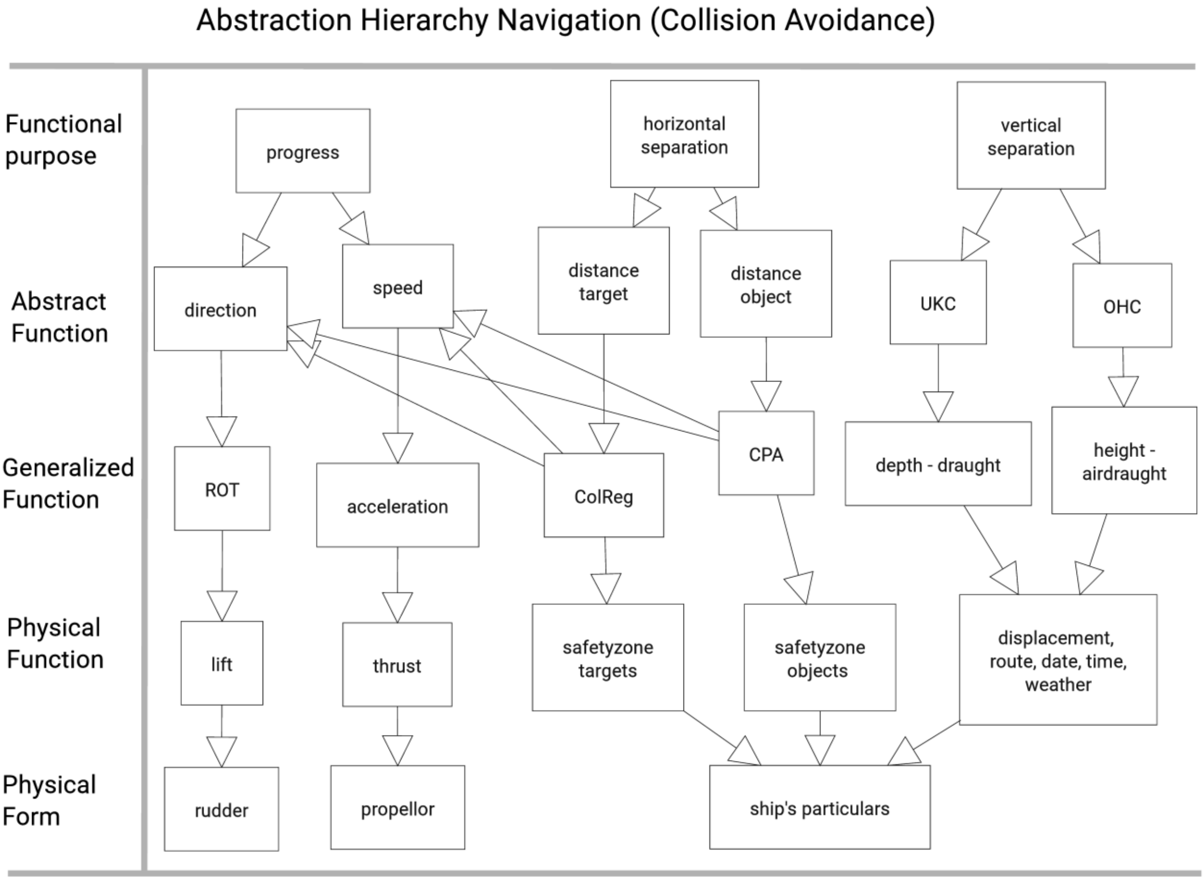


Fig.3: Abstraction Hierarchy Navigation and Collision Avoidance

Experienced workers can sometimes immediately recognize the situation from the activity of observation and take a rule based shortcut to the awareness of either the target state, the task, or even the procedure.

In case it’s insufficiently clear to take a shortcut, the next step from the set of observations is to determine what the relation the OS has with the observed object; “Will the object come nearby and how can it affect OS's safety?”. From interpreting the consequences of the system state it may be clear what the OS’s target state is, however, when the situation is not recognized or unknown to the worker, he must follow the Knowledge Based Behavior loop and formulate alternatives (options), evaluate and interpret these until a satisfactory target state is known. With this knowledge of the OS’s target state the worker can define a task, thus choosing to take evasive measures early on, or decide that the situation clearly relates to similar experience he had before. From this awareness of his task the worker decides what to do and under what prerequisite or condition he will maintain doing that action, thus, defining a strategy based procedure.

During execution of the procedure, feedback action is initiated through alertness for the situation and subsequent observing of sensors in order to become confident of the obtained safe system state. A shunt, different from the rule based shortcut, can be observed when the worker becomes aware of, or knows, one stage and associates this with the knowledge related to another stage, thus becomes aware of another stage. Such a shunt, or Associative Leap, for example can be observed between the awareness of system state and target state. An example is that the worker, becoming aware that the observed target is not an anomaly, but recognized rather as a buoy or floating object which is located in a position close to the bow of the vessel, immediately knows what the procedure is for action.

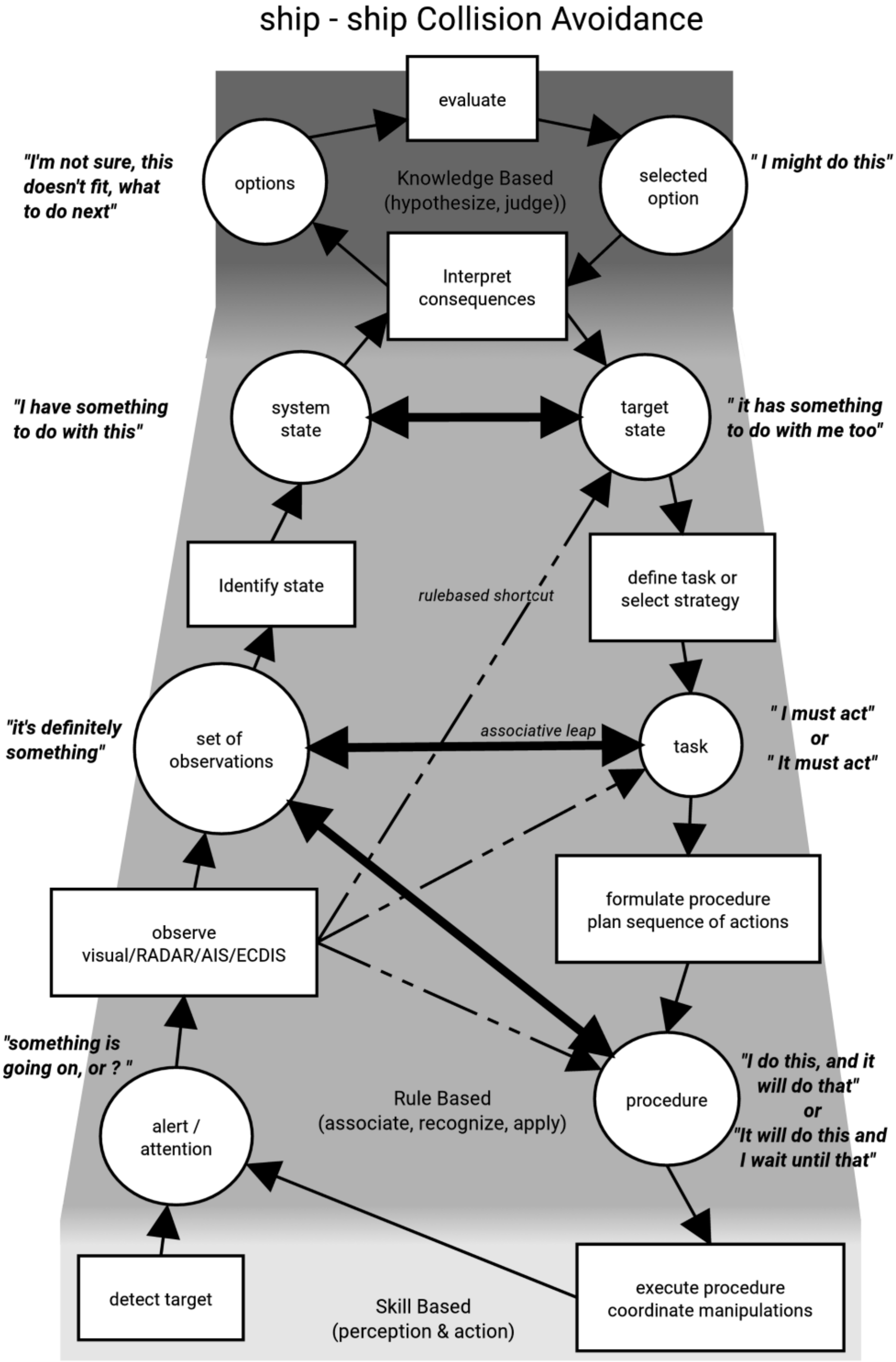


Fig.4: The Decision Ladder Ship-Ship Collision Avoidance

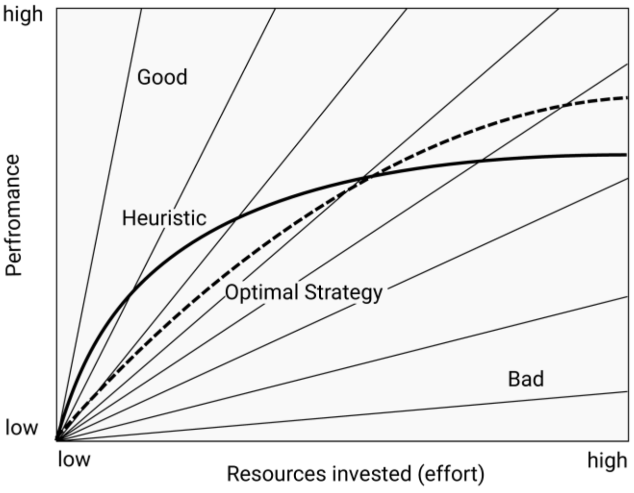
The categories of human behavior according to Rasmussen's SRK taxonomy are shown in the Decision Ladder by the Grey areas. The lightest shade of Grey, at the bottom, represents activities related to the lightest cognitive strain, the Skilled Based Behavior (SBB). Both target detection and the execution of a predetermined procedure is a rather standard task to perform, it interacts entirely with Signals and requires therefore little or no cognitive labor. In a distributed bridge organization these tasks are deployed by a lookout and helmsman, respectively.

The darker Grey area represents all activities and knowledge states that can be related with Rule Based Behavior (RBB). The related information can be regarded as Signs, which become meaningful by the worker's interpretation. This interpretation demands more of the worker's cognitive resources than SBB, but, as is illustrated by the Rule Based Shortcuts and Associative Leaps, the experienced Watchkeeper recognizes normal behavior in normal situations and shortcuts many steps in the Decision Ladder thus reducing his cognitive strain. Important in the design of a new interface is that these shunts must be recognized by the WO himself and the flaw of shunting too fast or too deep must be detected and re-iterated. The darkest shade of Grey is connected to the cognitive high demand of problem solving or, according to Rasmussen's SRK taxonomy, Knowledge Based Behavior (KBB). A typical example of this is noticing a real-life feature (e.g., a buoy) that is not charted. Several explanations are possible, of which some are relatively harmless, like observing a Waveheight Measuring Buoy at some distance abeam of the OS that is missed by a previous chart correction, while others might require immediate action like observing a wreck buoy ahead which is missed because the recently promulgated NAVTEX warning has not yet been noted in the Chart. In any case this needs serious checking, fault finding and observation in order to restore the navigation system's integrity. Even the experienced Watchkeeper needs all his knowledge, creative thinking and causal reasoning to do this in the limited available time. In the following papers, we will discuss the consequences this CWA has for the design of an effective interface.

2.8. Strategies Analysis

In the selected scope of CA we have analyzed the functional structure of this work domain where the worker acts upon. This is schematized in a model, the Abstraction-Hierarchy (see Section 2.6). We have also analyzed the actions that the worker performs to fulfill the task of CA. This is schematized in a model, the Decision Ladder (see Section 2.7). These two models are strongly interrelated, the actions 'what is done', are constrained by the domain that is acted upon.

From observing workers in this domain, it becomes clear that several ways, or strategies, exist and are being employed to reach the goal of safe sailing. The choice for a particular strategy is subjective and depends on the situation and the workload. A worker may apply different strategies to consecutive situations, he can also switch from one strategy to another while engaged in the same situation. Formal training provides usually one strategy that a worker employs at the beginning of his career. Experience, however, can expand the number of trusted strategies used by an individual worker. Apart from the taught strategy and the experience-driven strategies developed by the individual, much research has been conducted over the last five decades on alternative strategies for CA *Wilson Harris and Hong (2003), Zhao-Lin (1984).*



(slightly adapted from "Engineering psychology and human performance" 3d ed. p.443 Wickens and Hollands)

Fig.5 Performance Resource function

Wickens and Holland explain and illustrate, Fig.5, with the Performance Resource Function (PRF), why alternative strategies develop in the first place and that workers switch between them to perform their task effectively and efficiently. The Heuristic, seen as a mental shortcut that provides reasonable good performance without the investment of too much effort, varies greatly from worker to worker, but it also changes over time. For example, in the Netherlands the taught strategy for CA has moved, from keeping course and speed until engaged in a risk of collision situation, towards a more pro-active strategy where, with a timely slight alteration of course, engagement can at all be avoided. Apart from this, examples of strategies to give way in any situation (crossing ferries), or to claim right of way by VHF voice communication (AKA "Courseline Fetishism") are reported by workers. *MARS (2017)*

In the maritime domain, the typical examples for display are RADAR/ARPA and ECDIS/GPS, sometimes superimposed onto each other and/or enriched by AIS information. The experienced worker has learned to interpret these two displays and use them to simulate and hypothesize on the developing situation. Thus building Situational Awareness whereupon he or she chooses for a trusted strategy.

Because several strategies already exist, these typical examples for display seem to be of no hindrance to the professional creativity of the worker. However, that does not mean that these displays are optimally supportive for the chosen strategy or to switch between strategies, neither does it mean that these displays support developing a Heuristic strategy. Therefore it is arguable that the task of CA in an 'open' system, is optimally supported by the aforementioned systems. Recent development in e-Navigation shows a prototype of "Tactical Exchange of Intended Route" as an example of the extension of RADAR, AIS and ECDIS. This example provides a way to visually share the intended route for the next limited interval of time and even negotiate about actions by visually changing the intended route and ask for confirmation. From the early testbed experiments we learned that workers adapt to this new functionality relatively fast and develop a, heuristic, strategy to use this new aid in their task of CA. In the latter example, it is important to understand that there hasn't been a strategy designed beforehand. Another important point is that the testbed users questioned the depiction of the displayed features and showed their concern about the anticipated workload on marginally vetted ships (e.g., coastal traders). This illustrates nicely the need for work analysis to be done in parallel with the introduction of this technically driven innovation.

Vicente suggests the use of an information flow map as a modeling tool with which to design dialogue modes *Vicente (1999) pp.224-234*, thus resulting in a specific designed display to support actor independent strategy. Assuming that strategies indeed can be generically used, justifies the research into, and development of information flow maps partly based on known strategies, partly based on yet undeveloped strategies thus supporting the user in dealing with the unprecedented event in the open system. One example of each information flow map is discussed in the following paragraphs.

For simplicity, the Information flow map for CA is limited to ship-ship encounters. In a following paper more complete analysis of the information flow will be used to design the dialogue modes mentioned before resulting in a display design.

Irrespective of the experience of the individual worker, or the team, and irrespective of the work domain itself, and irrespective of the actions on the work domain as well, the information flow constitutes of invariant sources and information retrieved from these resources as well as cues derived from the retrieved information. An example is shown in Fig.6. There can be automation involved, e.g., the Automatic RADAR Plotting Aid (ARPA) which provides a concise report about the detected target comprising of CPA, TCPA, true Course and true Speed on the basis of target following and the OS's course and speed. Also the received AIS message of the target, comprising of position COG and SOG i.a., can be used to calculate CPA and TCPA automatically. Without automation, risk of collision can be determined by observing the change in visual bearing, after which visual reconnaissance is needed to determine eventual action. In all cases multi-sensor identification and confirmation is desired to enable an integrity check of the used systems. During engagement with the target, a constant interchange of information and derivation of cues is entertained in order to maintain safety and eventually decide to initiate, alter or adjust the determined action.

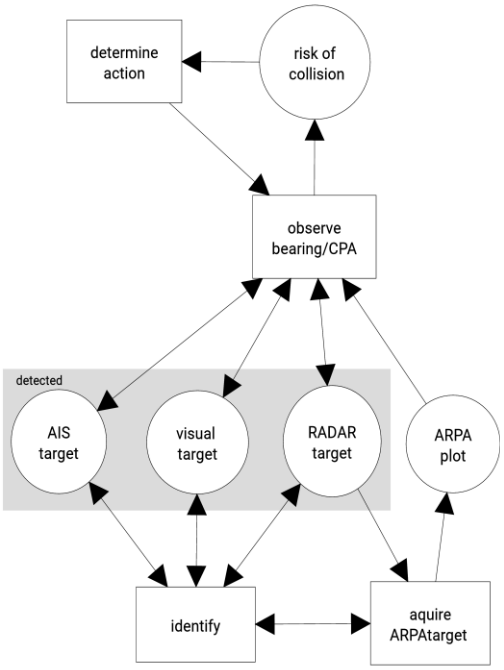


Fig.6: Information Flow map Conventional Approach

In the conventional bridge configuration, the worker integrates the retrieved information and searches for cues in order to build SA whereupon he can act. This human integration is supported to a certain extent by accepted automation like ARPA and AIS and their inferred alarming. Despite the fact that the concept of Maritime Collision Avoidance System (MCAS) was already introduced 50 years ago *Morrel (1960)*, Automated Collision Avoidance Systems (CAS) have still not been accepted by the marine industry for various reasons.

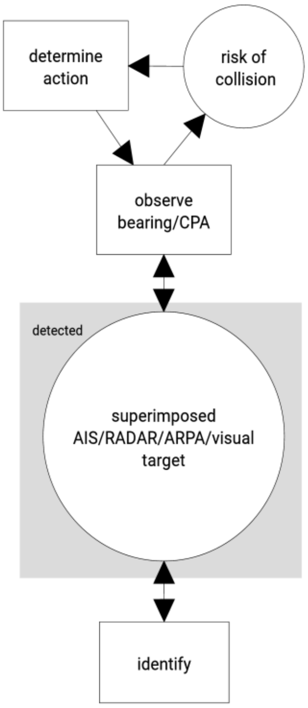


Fig.7: Information Flow map Augmented Reality

As said before, the introduction of new technology, like AR, requires careful rethinking and redesigning of the work process and its inherent information structure. This will have an impact on the information flow map, and to a much lesser extent on the work domain and control tasks. The impact on the latter two can probably be determined only after completion of the work analysis.

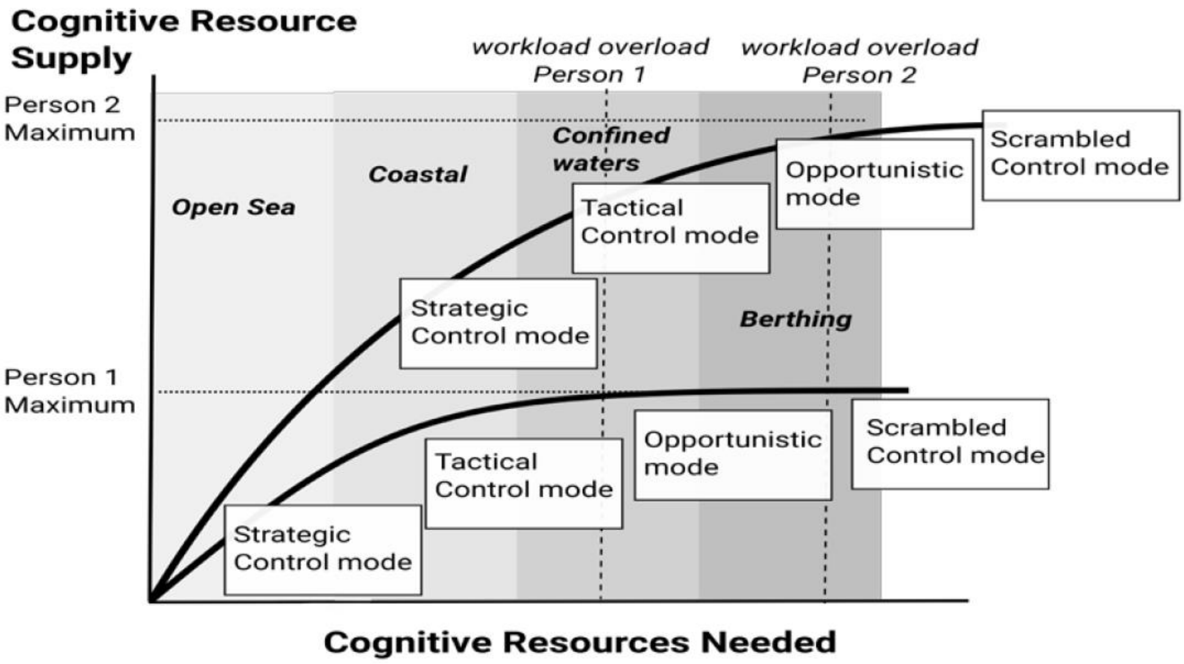
The Information Flow Map incorporating AR is sketched in Fig.7. The main difference between this suggested Information Flow map introducing AR and the conventional Information Flow map is that the identification is done implicitly by superimposing the AIS and RADAR/ARPA target on the visual target. On one hand this solves integrity question, because a co-location of AIS/RADAR/ ARPA markers and the visual target implies proper functioning positioning systems on both ships as well as a proper functioning heading system on the OS. This implicit identification and integrity solving reduces the cognitive load of combining and integrating two displays and the outside world.

On the other hand, however, it may as well increase cognitive load because any mismatch in the superimposed targets e.g., due to each of the position systems, or a shift in RADAR cross section, or an incorrect gyro will be noticeable and probably lead to problem solving behavior which might even distract the worker from a higher target i.e., noticing a possible risk of collision. Therefore, careful design and empirical testing is necessary.

2.9. Social-Organizational (leading to role allocation, organizational structure)

As already mentioned in Section 2.7, the worker is regarded as a varying entity. It varies from the individual WO, up to a bridge-team consisting of perhaps five, i.e., Captain, Pilot, Mate, Helmsman and Lookout. Rasmussen identified six criteria for dividing work demands, all of them are applicable to the maritime work domain *Vicente (1999) pp.254-255*. The normal situation, however, is that the bridge is operated by a single WO during daytime, helped by an obligatory Lookout during dark hours. The latter can be regarded as the sixth of Rasmussen's criteria i.e., regulation compliance. Examples of the other five criteria are: The engineer called by the WO to fix a problem with machinery: actor competency; The Harbour Pilot carrying specialist local knowledge advising the Captain during berthing: access to information; The Captain intermediating with Deck, Engine Room, Pilot and bridge-team during berthing: facilitating communication needed for coordination*;* A helmsman responsible for course-keeping: work load sharing; The captain playing a supervisory role instead of the single acting authority: safety and reliability.

Porathe (2017) adapts Hollnagel’s four stages of control *Hollnagel (2017)* with Wickens’ model of Cognitive Resource Supply vs. Cognitive Resources needed *Wickens and Hollands (2000) p.443,* Fig.8 to a situation where, depending on the phase of navigation, i.e., Open Sea to Berthing, the single WO (Person 1) gets overloaded with the workload somewhere during the phase of sailing in Confined waters. Adding a second person immediately relaxes the workload of the team, however, as complexity increases during berthing, the team of two Persons can again reach a state of Workload overload. Hollnagel suggest four stages of Control. Strategic Control where the worker (one, two or more) can plan far ahead in time, partly because of the low level of complexity, partly because of the surplus of available cognitive resources. When, due to higher complexity, more cognitive resources are required the time horizon of planning is reduced leading to less efficient or even ad hoc decision making. This is called Tactical Control. If the workload gets even higher or the situation gets more complicated, it is called Opportunistic Control meaning that the worker barely controls the situation thus leading to ineffective or even useless attempts being made. The Scrambled Control Mode is characterized by blind trial and error performance with little or no correspondence between the situation and actions. In this stage the worker has practically no control because the margin to allow for preemptive and pro-active work is reduced to nil. From this we can conclude that control over the work process deteriorates with increasing demand for cognitive resources. We can also conclude that adding more workers enables strategic control over the more complex process like navigating in confined waters, thus enabling to plan ahead and prepare for contingencies. Automation can reduce the workload of the worker. Assuming Porathe's adaption is based on workers without any aid of automation, the introduction of automation will have an obvious impact on the Resources Supply versus Need diagram, by shifting the boundaries between the control modes to the right.



slightly adapted after Wickens, Hollands, Parasuraman,Banbury (2012) "Engineering Psychology & Human Performance (4t Edition)" Pearsons p. 348

Fig.8: Cognitive Resources Needed versus Resource Supply

In practice, well accepted and applied forms of automation are the ECDIS and the Autopilot. When we schematize stages and levels of automation according to Wickens and Holland, ECDIS is a typical example of stage one,‘Information acquisition and analysis’. The OS's GPS position is plotted on the Electronic Chart and checked against both the maximum allowed deviation from the intended route and the distance to the determined safety contourline. This is a high level of automation, it leaves practically no manual work for the WO. The latter form, the Autopilot, can be regarded as stage two automation, decision and choice. The level of this automation depends on the technical advancement of the autopilot fitted on board. The advancement varies from basic heading control, the lowest level of this stage, to an integrated system (ECDIS and autopilot). This system enables track control and curve control at Level 4 or 5, that is automatic action with human consent or unless human vetoes, respectively. It is much dependent on the individual worker's experience and trust in the system to what level he will employ this advanced possibility. A formative working practice on this automation has not been adopted, although the opinion that this should be done is advocated by some, e.g., Sagen hypothesizes in his article that the disaster with the Costa Concordia would have been prevented using such high-level automation like track and curve control *Sagen (2015).*

More applicable to the focus of CA is a third example of automation, the Automated RADAR Plotting Aid, ARPA. This is clearly stage one automation, information acquisition and analysis. In general, ARPA is trusted as a primary information system providing several features of the tracked target up to a visual and audible warning for critical CPA. The level of automation is high, because manual intervention or a check on the plotting process is seldom done, which in few occasions has led to accidents due to misinterpretation or trust in wrong information.

Focusing exclusively on ship-ship CA, the mentioned examples of automation can be distributed over the abstraction decomposition and also over the decision ladder. The latter has the greatest impact on our analysis.

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Fast Leaps and Deep Dives towards Autonomous, Fast, and High-Resolution Deep-Sea Ocean Exploration

Gunnar Brink, IOSB Fraunhofer, Karlsruhe/Germany, gunnar.brink@iosb.fraunhofer.de
Gaurav Mulay, IOSB Fraunhofer, Karlsruhe/Germany, gaurav.mulay@iosb.fraunhofer.de

Abstract

The global map of the Earth's ocean floor is significantly less detailed when compared with maps of other planetary bodies such as Mars, Venus, and the Moon. Thus, the aim of the Shell Ocean Discovery XPRIZE involves resolving this issue, and it is a demanding ongoing global competition to advance technologies for autonomous, fast, and high-resolution deep-sea ocean exploration. This study describes the Arggonauts project that is part of the race to develop, build, and apply a fleet of AUVs (autonomous underwater vehicles) and ASVs (autonomous surface vehicles) to explore and map the deep-sea floor. Due to the ambitious timing, agile project management methods are being used and improved for planning and implementation.

1. Introduction

It is often said that only 5% of the ocean floor of the Earth is mapped while in contrast, the surfaces of the Moon, Mars, and Venus are thoroughly mapped. In this abbreviated form the statement is misleading. Current maps of the ocean floor were gravimetrically created and represent all seas on Earth, *Sandwell et al. (2014)*, *Fecher et al. (2015)*. The maps show several previously relatively unknown details of the ocean floor. However, even extant maps are relatively crude and the observations only include a resolution ranging from 1 km to 5 km such that it is not possible to detect objects like crashed planes or shipwrecks on maps of this size. Additionally, many geological structures are indistinguishable, and it is very difficult to analyse features of ecosystems at the fore-mentioned resolution range. In contrast, knowledge of other celestial bodies is significantly more advanced, and resolutions range from 100 m for Venus, *Lee (2012)*, and 7 m for the Moon, *Ren et al. (2014)*. This discrepancy exists partly because taxpayers in several countries of the world spend a significantly greater amount of funds on space travel when compared with that on deep-sea research. Another reason which we as scientists and engineers have to cope with is that a thick layer of water surrounds the ocean floor and increases the difficulty of explorations.

Satellite based gravimetry has a resolution of several kilometres. Acoustic measurements from hull mounted sonars on boats on the surface are imprecise and require high sound pressure levels that can adversely affect marine mammals apart from other drawbacks. Thus, it is necessary to bring sonar systems very close to the ocean floor (by using autonomous underwater robotic explorers or tethered instruments) to identify things that are only a few metres high from the ocean floor such as mineral spires of submarine volcanoes or wrecks of crashed planes or sunken treasure ships. Currently, approximately less than 0.05 percent of the ocean floor is mapped to the highest level of detail by sonars, http://moocs.southampton.ac.uk/. The Hubble Space Telescope is used to view stars and galaxies that are billions of light years away. In contrast, the wreck of a MH370 plane that crashed several years ago on our own planet is not located to date, *Li et al. (2016)*.

An optimal method involves performing measurements from vehicles that travel distances ranging from a few metres to 100 m over the ocean floor and to identify the relief of the ocean floor and the objects lying on it by using optical methods or acoustic methods.

2. Challenges and Current Systems

The construction and operation of the fore-mentioned types of vehicles poses several difficulties. A pressure of 400 bar exists at a water depth of 4,000 m, and this is equivalent to a force exerted by a weight of approximately 4000 tons on one square metre.

Furthermore, the maximum distance that can be travelled by light and electromagnetic waves corresponds to 100 m in seawater. The ocean is pitch-black, and thus it is necessary to transport energy to or with the underwater vehicle. It is not possible to recharge the energy via solar collectors as opposed to that in the case of many satellites. Photography is only possible when a scene is illuminated with a large amount of electrical energy by using lamps or flashlights. Furthermore, it is only possible to operate a vehicle via remote control acoustically and this is limited to a very low bandwidth connection (less than 10 kbps) or by using long and cumbersome cables that obstruct the purpose of the mission. Global navigation satellite systems (GNSS) are facilitated by electromagnetic rays that end on the surface of water. Georeferencing involves the right location of maps on a globe, and it is necessary to acoustically connect the GNSS on the water surface by using vehicles or buoys on the surface to vehicles in the deep sea.

Waves and wind exert a powerful dynamic effect and force on the water surface. It is a demanding task to connect spacecraft or to build components on the International Space Station ISS in space. Conversely, with respect to high sea waves, objects in the wave zone can be poorly visible and can also be tossed back and forth for a distance corresponding to several metres at a time. Thus, tasks including catching a underwater robot or docking for recharging purposes poses a major challenge.

Thus, major technical challenges that require state-of-the-art electronics, mechanics, material science and software technology exist with respect to ocean environments. It is expensive to develop the technologies, and it is only possible to achieve reasonably priced technologies through economies of scale. Various components are required and most of these components, such as cables, inertial navigation systems, and sonars, remain extremely expensive to date, as there are no economic incentives to produce individual components in large numbers. Therefore, it is necessary to first create a market for large-scale marine exploration in order to obtain an affordable method of surveying and inspecting the deep sea.

Hence, the development of methods to facilitate better exploration of the world's oceans are seen as an important technological challenge for players including Shell, the XPRIZE Foundation, and the US marine research agency NOAA, and this has led to the competition for the US$7 million Shell Ocean Discovery XPRIZE.

3. The $7 million Shell Ocean Discovery XPRIZE

The mission of the XPRIZE Foundation is to encourage "radical breakthroughs for the benefit of humanity" by holding competitions. It promotes high-calibre competitions to motivate individuals, companies and organisations to develop innovative ideas and technologies for the great challenges that limit the progress of humanity.

The concept of such innovation challenges can be traced back in history, *Morgan (2008), Brennan et al. (2012).* The "Longitude Act" passed by the British Parliament in 1714 offered £20,000 (equivalent to £2,610,000 in 2015) for a method that could determine the line of longitude along which a ship travelled across the seas. Previous techniques to determine the line of longitude were imprecise, and this led to dangerous and expensive navigation. This challenge was successfully solved by John Harrison (1693-1776) who proposed the famous no. 4 sea watch that consisted of a chronometer with a diameter of 12 cm. The chronometer was successfully tested and made sea travel less dangerous and more profitable.

Another example involves the prize of 12,000 French francs that was given by Emperor Napoleon in the 18th century to find ways to preserve the food supplies of soldiers. A Frenchman, Nicolas Appert presented the solution in 1795, and it involved glass jars that were sealed airtight with wax.

Similarly, shortly after the invention of an aircraft by the American Wright brothers, several competitions were launched to promote further development of flying. This included the prize of £1,000 that was offered by the Daily Mail newspaper for the first flight across the English Channel and was won by a Frenchman, Louis Blériot, in 1909. Although the prize sum was not huge, it was a financial success for him: Blériot subsequently sold more than 800 aircraft in 1913.

The $25,000 Orteig Prize (that is equivalent to approximately $342,000) was offered by the New York hotel owner Raymond Orteig in 1919 for being the first aviator to fly non-stop from New York to Paris. Charles Lindbergh won the prize by flying non-stop in his aircraft "Spirit of St. Louis" in 1927. The successful flight was followed by a public interest in aviation, and the possibility of travelling in an aircraft as a passenger suddenly increased. Within three years of the prize and the transatlantic flight, the number of aircraft passengers rose from 8,679 in 1927 to 384,506 in 1930.

The first and most famous XPRIZE, the $10 million Ansari XPRIZE was awarded in 2004 for the first space flight by a private company. Sir Richard Branson's company Virgin Galactic took over the technology in 2005 and 2012 in two steps. Branson intends investing around $110 million in the construction of a passenger spacecraft over the next few years.

The Ocean Exploration XPRIZE requires applicants to map and photograph an area corresponding to the size of Lake Constance in a period of only 16 h without human involvement and with diving vehicles and measurement devices that fit in a single medium-sized truck. The depth of the deepest point of Lake Constance corresponds to 250 m. Explorations need to be carried out at a water depth of 2,000 m (phase 1) or 4 km (phase 2) for XPRIZE, however. Only 48 hours is afterwards available for evaluation and creation of the maps. The highest prize of $4 million will be awarded to the best and fastest team at a water depth of 4,000 m. If none of the teams manage to map an area of at least 100 km², the prize will not be awarded. The size of the ISO 40-foot container in which the entire equipment needs to fit according to competition regulations, measures 12.03 m in length, 2.35 m in width and 2.38 m in height. The competition involves two different sets of requirements. First, values listed in the following table precisely describe the values required by each team to satisfy any chance of winning the prize. The prize is not be awarded if none of the teams manage to satisfy the fore-mentioned requirements. Here we can precisely calculate targets to be achieved and avoid unnecessary tasks.

Additionally, a maximum of 10 teams proceed from the first round of the competition to the second round. In the second round, only the teams ranked in first and second places receive awards. If more than 10 teams satisfy the requirements specified in the first round, then the teams are ranked and only the 10 best teams continue in the competition. Apart from the fixed requirements, it is thus necessary for the teams to put forth their best performance as they are unaware of both the intensity of the competition as well as the amount of effort necessary to be ranked among the top 10. Specifically, 50% of this ranking is based on the area achievement, 20% of the ranking corresponds to the resolution of the bathymetric map, and 30% is awarded for the quality of the five images.

Table I: Summary of judging criteria

Judging Criteria	**Round 1 (2000m depth) Minimum Requirements**	**Round 2 (4000m depth) Minimum Requirements**
Area Mapped	20% of competition area (100km^2)	50% of competition area (250km^2)
Resolution	5.0 meters horizontal 0.5 meter vertical	5.0 meters horizontal 0.5 meter vertical
Bathymetric Map accuracy	Pass/Fail vs Statistical Accuracy relative to Baseline Map	Pass/Fail vs Statistical Accuracy relative to Baseline Map
Depth	Find and image 1 specifically named item at 2,000 meters	Find and image 1 specifically named item at 4,000 meters
Additional Features	Identify and image 5 archeological/biological/ geological features at any depth	Identify and image 10 archeological/biological/ geological features at any depth
Chemical/Biological Signal	Pass/Fail vs. Detection of Signal and Location of Known Feature	Pass/Fail vs. Location of Known Feature

4. Our technological approach

At the beginning of the project, our institute had built a self-developed deep-sea vehicle called DEDAVE. Two of these vehicles were constructed. One of these vehicles was developed for use at a depth of 6,000 m, and the other vehicle was developed such that it could be used at a depth of 2,000 m. Both vehicles were suitable for use with different sensors in the long term due to their flexibility and modular construction. Thus, they presented attractive options for both users and customers and especially with respect to scientific research. The first of them was sold to a customer recently.

Theoretically, it would have been possible to transport eight of these vehicles in a 40-foot container as prescribed by the XPRIZE guidelines. However, this would not leave any room to transport the escort boats or buoys that are required to transmit geo-referencing signals through global satellite navigation into the deep sea. Furthermore, the project budget was too small to be able to acquire all the high-quality equipment that was installed in the DEDAVE vehicles.

Therefore, the project required a new development that is targeted at specifically addressing this task and building on the knowledge gained from the DEDAVE project. It corresponds to a scalable fleet ranging from a minimum of five and up to a maximum of 12 AUVs in which the length and weight of each vehicle is less than 2.5 m and 300 kg, respectively.

To achieve the specific requirements of the competition, a development from the former Soviet Union was used where individuals attempted to travel in their own sailing boats although personal ownership of sailing boats and yachts was frowned upon. At this time, public transport was well established, very few people had their own cars, and many roads were in a poor condition. There was a lack of private space to keep sailing boats, and apartments were small. This led to a community of inventors who developed relatively safe boats in the form of inflatable and yet stable catamarans that could be stored under their beds and transported by the crew everywhere in bags. A team member from our project team had belonged to this mentioned community and had sailed thousands of miles in his boats on the high seas in difficult waters such as waters around Cape Horn or off the coast of Greenland, boats that are meanwhile classified and approved by Lloyd’s Registers in Class C.

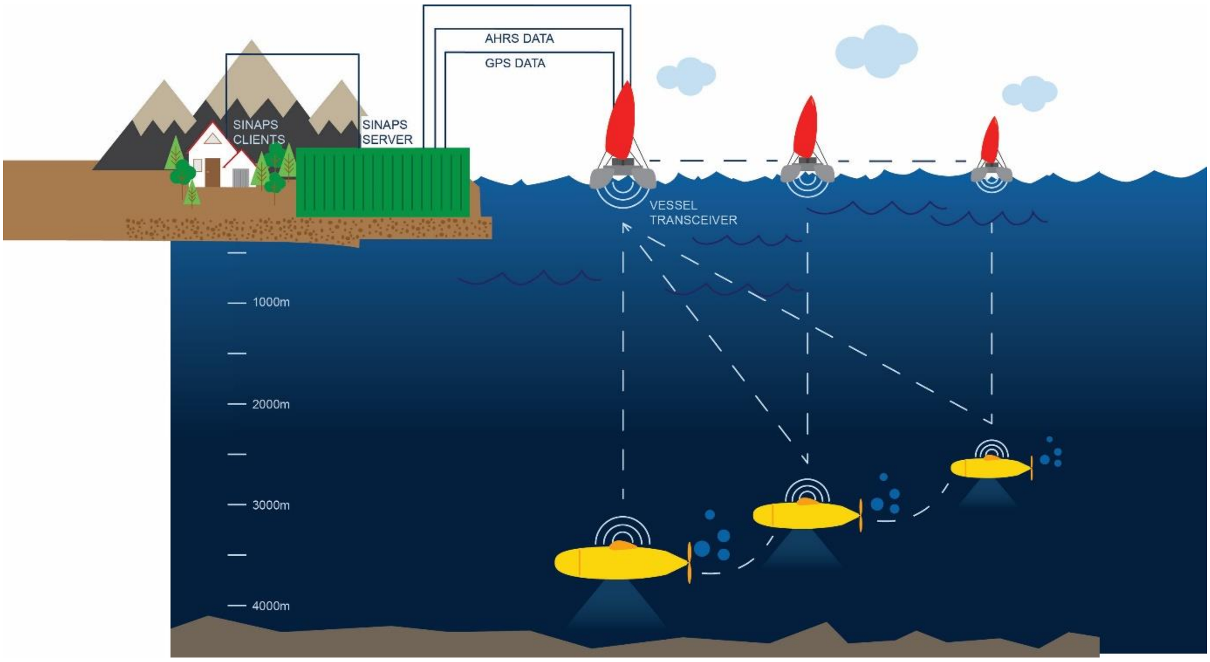

Fig.1: An overview of the complete project

These boats will now be modified by us to be used as autonomous surface vehicles. Their task will be to bring the underwater vehicles from the coast to the test area before the mission, to receive satellite navigation during the mission and translate it into acoustic signals so that the underwater vehicles can receive the necessary georeferencing and navigate. After the mission, each autonomous catamaran will pick up one AUV and bring it back to the coast so that the 48 or so terabytes of data per AUV from the diving vehicle can be transmitted and evaluated.

As previously mentioned, the AUVs used in the study are more compact when compared with previously available deep-sea AUVs such as the Hugin or DEDAVE. They are equipped with a propeller power unit and are optimised to map a large area in a short time.

All components on the vehicles will be integrated using ROS (Robot Operating System) middleware to significantly facilitate the transfer of commands and data.

A station for mission/vehicle control exist on the shore, and a control room will be installed for mission supervision. The hardware used in this control room will also be used for post-processing the collected data following the safe return of the vehicles.

5. SCRUM, eXtreme Manufacturing, and eXtreme Innovation

The Shell Ocean Discovery XPRIZE competition involves a total of over two and a half years from registration to the announcement of the winner. However, the period from obtaining the financing to the first competition round at a depth of 2,000 m only corresponds to 8 months. Additionally, work on the AUV project as well as several other AUV and deep-sea projects indicated that a period ranging from 3 months to 9 months is required to solve any compatibility and interoperability problems or resolve questions in situations when suppliers do not comply with specifications or when the tasks only become visible when the whole system is underway. The time for adjustment and completion is not available in the fore-mentioned circumstances.

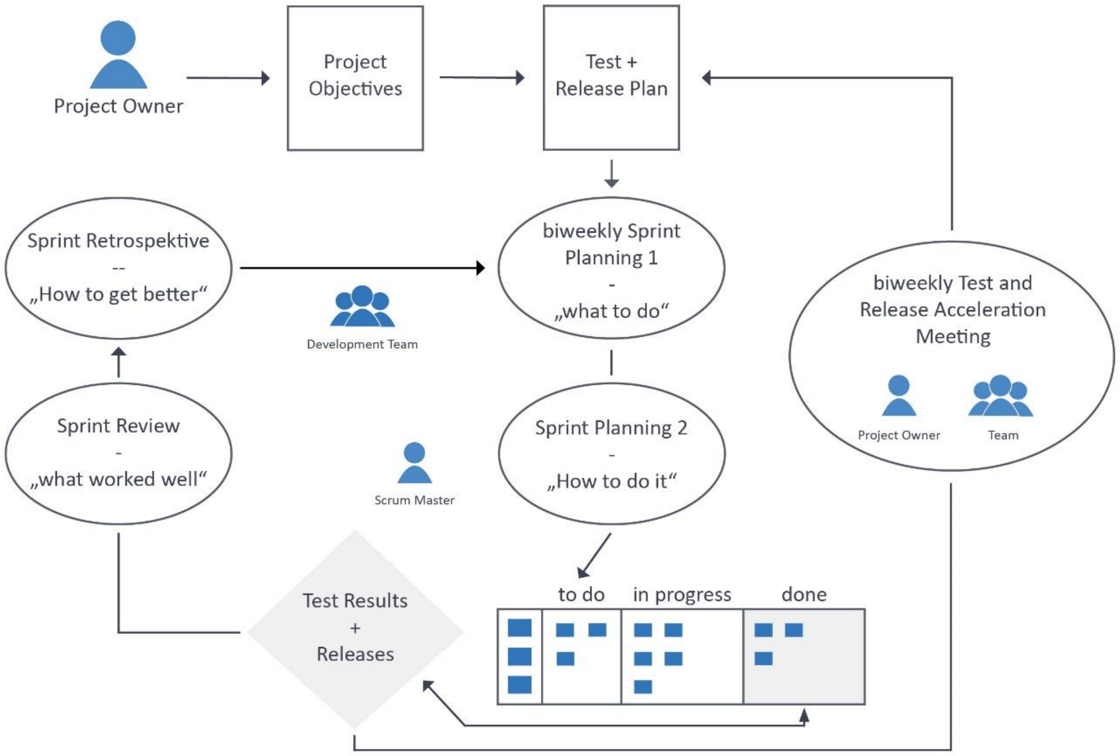

Fig 2: eXtreme Innovation Work Flow

In order to achieve the goals specified by XPRIZE, the ARGGONAUTS team used the support of a consultancy with decades of experience in SCRUM and adopted principles and practices of agile software development. The practices and principles were developed further to consider a context involving maritime robotics, deep-sea technology with its supplier structures.

Agile software development evolves independently of agile non-software product development methods although both are based on the same basic principles. The founder J. Justice of the Team WIKISPEED managed with a distributed, collaborative, volunteer team to reach the 10th place in the Progressive Insurance Automotive X Prize. In the process he formalized eXtreme Manufacturing, a process adapting the agile methods of software development to non-software development, testing, and manufacture, *Denning (2012), Socha et al. (2013).* Joe Justice also pointed out that the word “agile” was applied to manufacturing literature as early as in *Youssef (1992)*. The term did not apply to software development processes until 1998, *Dyba (2008).*

Agile software development has a long history and has its roots in an iterative and incremental approach that is used in specific software development projects for a long period, *Alzoabi (2013)*.

Agile methods are considered as a counter concept to traditional” or “waterfall” processes that are distinguished by a series of steps, which are sequentially followed as detailed below:

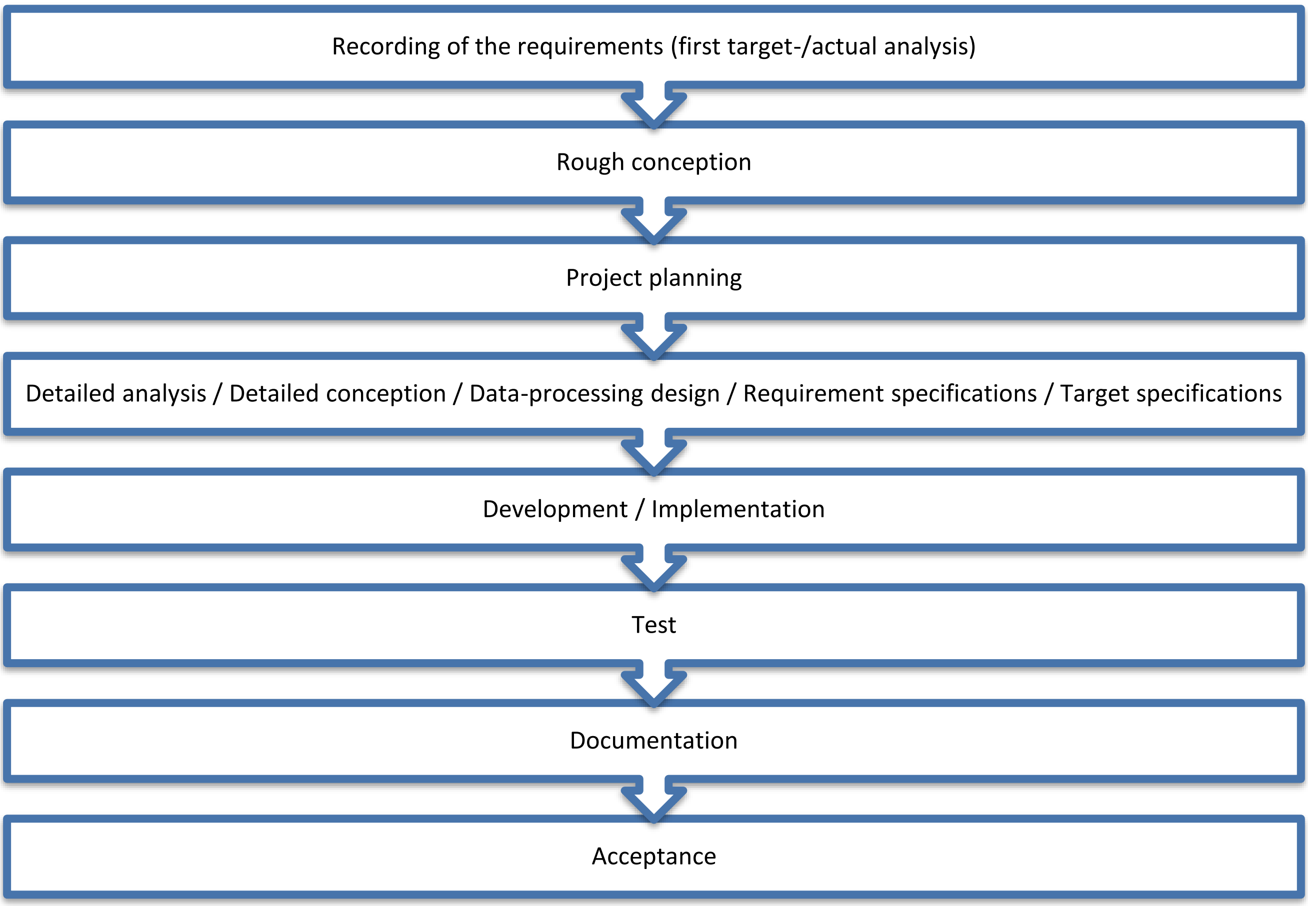

Fig. 3: Flow of steps in Waterfall approach

A traditional approach was not an option in this project due to the previously mentioned reasons. Furthermore, some special constraints need attention in the ARGGONAUTS project. For example, there are only 8 months between financing and the first operation, and thus significant budget constraints exist, and the competition also imposes additional limitations such as the restrictions on the entire volume of all parts and equipment as prescribed by competition rules (the limitations of a 40-foot container). There was a lack of information (on where the other teams stand, where the test location would be and on other parts of the project) at the beginning.. It is also necessary to account for delivery times of some components that can correspond to a maximum of 5 months. Experience tells us that the deliveries of parts will not always comply with the specifications, they frequently tended to describe ideal values that are only valid in ideal circumstances, and unforeseen complications emerged when parts were combined with other bought-in components. Therefore, the approach was modelled on "effectuation", which is a concept introduced by Saras Sarasvathy and is used by experienced entrepreneurs in situations characterized by uncertainty, *Sarasvathy (2001).*

Effectuation runs contrary to decisions based on causal logic, which are based on justified predictions of the future. Effectuation and causal logic differ in their basic assumption of the nature of the future. Causal logic forms the basis of the above-mentioned waterfall model and assumes that it is only possible to control an event that can be predicted. In contrast, effectuation is based on the attitude that it is not necessary to predict everything that can be influenced by control. This attitude is compatible with the current project. Sarasvathy related effectuation to the agile technology SCRUM, *Schwaber and Beedle (2002),* as a method with effectuation principles.

The purchase of essential components requires a medium-term plan due to the delivery time and compliance rules for procurement by public-sector organisations, and the fore-mentioned plan will extend the SCRUM Sprints significantly into the future.

In SCRUM, the team acts as a unit. The name "scrum" is derived from rugby in the article "The New New Product Development Game" by Hirotaka Takeuchi and Ikujiro Nonaka was published in the Harvard Business Review in 1986 and inspired scrum for software. The authors compared the way in which a rugby team moved forwards together by throwing the ball from an individual person to another with sequential operations (such as a relay race) in traditional product development. They coined the word "scrum" from the sport of rugby for the first time to describe that a team is formed to play together and convey the ball forwards in which the general idea involved moving in a scrum as a unit on the rugby field.

However, in our case team members only possessed partial knowledge on the entire project. Only some of the team members had ever participated in the construction of an AUV, and these individuals were largely committed to other projects. Only an individual possessed intensive maritime experience related to months and years spent on small boats on the high seas. On the other side, this team member did not possess any personal experience corresponding to deep sea projects.

According to SCRUM rules, a project team should preferably remain constant throughout the entire project. Each worker should only work on a single project. Ideally, all team members would communicate closely, and they can even maybe work together in the same room.

However, our team included students working on the project who were available all day during the semester break but much less during the semester. Availability issues also existed for several permanent employees who were involved on other projects at the beginning or intermittently or who were not consistently available due to family commitments. Therefore, it was not possible to apply all SCRUM steps in a one-to-one manner in the project.

In agile software development, every development step is regulated with the principle of timeboxing. The process is concluded after the specified time period even if it is not possible to complete all the planned contents involved in the process. Any outstanding parts are moved to a subsequent time box or are cancelled. The fundamental time box of the development process is termed as a "Sprint". In our project, each Sprint lasts for exactly 14 days.

The following elements are adopted from the SCRUM in the present study:

- Daily Scrums and biweekly Sprints

- Sprint Review
- Product Backlog Refinement
- Project Burndown chart

In contrast to SCRUM, a few elements were introduced in the process developed in the present study (which we termed as “eXtreme Innovation”).

In eXtreme Innovation the most important innovation is termed as “The Ship of Theseus”. This metaphor is actually derived from philosophy and describes a problem of identity. According to the metaphor, Theseus was a hero in ancient Greek mythology who possessed a fairly old yet seaworthy ship. He decided to take the ship to a shipyard to restore it and asked the shipyard owner to replace all the planks with new ones. The shipyard owner had several docks and thought it would be a pity to throw away the old planks from the ship of Theseus. Thus, he decided to gradually replace the parts of the ship of Theseus in Dock A and to take the old planks to Dock B where they were assembled in the original order and in their original position to create a new ship.

In our approach, this metaphor describes a concept for a test-operated development of a project that comprises of electronics hardware, software, and mechanical components to avoid waiting until the end of the project to integrate individual parts. A testing object, a so called dummy, is built at the beginning of the project, and it possesses only a few features of the finished product. This permits a trial of various tasks, such as towing, releasing, and retrieving the AUV, by using the dummy. The dummy corresponds to the Ship of Theseus in the present study. During the development project, a growing number of components is replaced by new components that can be used in the finished product until eventually a finished deep-sea vehicle is created. During this process it is subjected to various integration tests.

Another difference lies in the management of the Product Backlog, which corresponds to the usual list of all the overriding work packages in SCRUM. In SCRUM, the Product Backlog is actually compiled by the whole team but prioritised each time by the Product Owner during the Sprint. In SCRUM the Backlog Owner makes a selection (ad hoc) with respect to the tasks that will be prioritised for the next Sprint. The team processes as many of these tasks as it considers manageable.

In our “eXtreme Innovation” approach the team and the Product Owner together prioritise and structure tasks towards the beginning of the project and then use this priority list as a test-and-release plan and implementation checklist. The checklist is then revised and updated biweekly by the entire team in the Product Backlog Refinement. The Product Owner is responsible for ensuring that sufficient capacity is available or other solutions are found to work through the checklist.

Table II: Division of Scrum Features

Features of the SCRUM method taken over by the ARGGONAUTS	**Features of the ARGONNAUTS approach that differed from SCRUM**
Empowerment of the team, own decision as to workload	The goals are specified by the XPRIZE competition. The Product Owner is not responsible for the market but for long-term planning and to ensure the various aspects fit together.
Daily stand-ups with a SCRUM Master	Test-driven: • Test-and-release plan • Ship of Theseus
Biweekly Sprints with a SCRUM Master	Pow-wows for a content-related exchange of ideas alternating with strict Sprint Planning in accordance with SCRUM

Individual subtasks are addressed in advance for later Backlog items even if they are not currently planned in the checklist or if significant lead-time is required for the tasks, or if partial results are needed for other Backlog Items.

Another difference involves the pow-wow as another possibility, *Cobb (2015)*, entailing a one-hour weekly meeting with Product Owners, Scrum Masters, software architects, and other IT managers, to consolidate interdependencies for the current Sprint, the next Sprint, and the cross-team roadmap. In "eXtreme Innovation", the pow-wows constitute a key element of coordination and knowledge transfer that supplement the meetings for Sprint Planning and Sprint Retrospectives as a necessary meeting, occur alternately with respect to these meetings, and last for the same time period as the Sprint Meetings.

6. Conclusions and Approach

This study is the first publication to examine the project in an academic context. Nevertheless, only the first field test is half way through as of the date of this publication. It remains to be seen as to whether the team will actually manage to satisfy the competition requirements with respect to the above-mentioned concepts and achieve a top ranking. A significant amount of work is entailed, and several problems can potentially occur in the interim. Additionally, the conditions of the competition are artificial to a certain extent. Specifically, 21 teams are supposed to map the same test area at a certain distance from the coast. In reality, with respect to an extensive exploration of the world's oceans, certain criteria are irrelevant such as the necessity for equipment to fit in a 40-foot container. It is more important to obtain an affordable solution. Other challenges include the long-term energy supply of an autonomous fleet of underwater and deep-water vehicles despite the autonomous operation of the fleet for days and weeks at a time, maintenance of the vehicles, and coping with challenges (such as seaweed, high waves, and storms) that occur in seas.

In addition to the current competition, an important function of the project involves establishing a development methodology that can be used to develop complex technologies, fast-track projects, and major advancements that are necessary with the involvement of large companies. The recent emergence of a strong global competitive environment has led to the emergence of a number of new challenges that require radically new technological solutions including energy transition, emergence of electro-mobility, as well as the concept of an autonomous ship, which is specifically important in the context of this conference and is characterized by increasing debate and promotion.

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Prediction of Work Content in Shipbuilding Projects Using Extrapolation Methods

Lode Huijgens, TU Delft, Delft/The Netherlands l.j.g.huijgens@tudelft.nl
Frank Verhelst, Damen Schelde Naval Shipbuilding, Schelde/The Netherlands,
f.verhelst@damennaval.com
Jenny Coenen, TU Delft, Delft/The Netherlands, j.m.g.coenen@tudelft.nl

Abstract

A method to quantify manufacturing activities for shipbuilding projects is devised, based on extrapolation of historical projects. Extrapolation rules are based on first principles and fine-tuned using empirical data. A 4-tier hierarchical system structure is proposed, incorporating different types of interrelations. Subsequently, it is investigated how design principles can be used to mathematically define these relations, resulting in a substantiated work content estimation model. Several shipbuilding projects, some of which recently executed, were used as data source to support the proposed theory. It is demonstrated that detailed production man hour estimations can be made using limited sets of input data.

1. Introduction

In an open competitive environment, contracts are usually assigned to parties that are able to offer what is perceived as the optimal combination of quality, price and delivery date. This implies that information on these subjects is required already in the earliest phase of a project, and that this information is usually considered as binding as it forms the motive for assignment of a contract.

Determination of a correct price, taking into account the production cost, can be especially challenging for one-off projects: even if the product incorporates nothing but proven technology, the components have never before been assembled in the same combination, leading to uncertainty regarding production work content.

In order to be able to obtain an early insight in work content related to production of shipbuilding projects, and hence work force cost and throughput times, it was investigated how a method for extrapolation of historical shipbuilding projects could be devised. Project data and practical knowledge used in the described research were made available by Damen Schelde Naval Shipbuilding (DSNS), a subsidiary of the Damen Shipyards concentrating on the naval market.

2. Research Objective and Scope

2.1. Research Objective

The objective of the research described in this paper is to devise a method which allows for generation of an accurate estimation of work content in the earliest phase of a shipbuilding project. Such a method has to be able to generate a per-system indication of work content based on only a few input parameters. Historical data of previous projects can be used on the condition that sufficient similarities exist between the systems considered. Therefore, output is given as non-dimensional factors expressing the ratio between work content of an evaluated project and a reference project.

To arrive at such a method, it was investigated how systems and components can be categorised as well as the relations between these systems and components, and which set of formulas can be used to describe these relations in an effective and standardised manner.

2.2. Definition and Estimation of Work Content

Traditionally, work content is expressed in man hours and is considered to be a function of a scale metric (often tons, GT or CGT) on one hand and a complexity metric on the other (man hours per ton, per GT or per CGT):

$$Work\ content = Scale \cdot Complexity$$

Eq.(1): Breakdown of work content into scale and complexity

This definition of work content is adopted for this research. Both in literature and in the more practical environment however, there is discussion on which metric is most suited to express “Scale” and how existing metrics such as CGT can be improved. The extrapolation method proposed in this paper does not aim to contribute to this discussion by differentiating between scale and complexity; rather than that, it aims to arrive at work content estimations based on the relations between system specifications, component dimensions and evolutions in work content related to these components.

2.3. Definition of Complexity

Although establishing metrics that allow differentiating between scale and complexity were not the goal of the research, it is important to distinguish between two different kinds of complexity, *Baccarini (1996)*.

Organisational complexity refers to effects on work content by the hierarchy of the organisation and the relations between departments.

Technological complexity is related to physical properties of the project: numbers and attributes of individual components, and relations between systems and components (for example, inputs and outputs for communication systems, or capacity requirements for connected auxiliary components).

The research project described in this paper focuses solely on technological complexity; as such, the proposed extrapolation method should only be applied when organisational complexity can be considered to be constant.

3. Method Principles

3.1. Categorisation of Systems and Components

A division into four categories was proposed in *Hubka and Eder (1988)* and adapted, Table I. Table I shows the hierarchical categorisation of systems and components as used by the extrapolation method. As an example, elements of the CODELOD propulsion system (Combined Diesel-Electric Or Diesel, a propulsion layout usually designed to offer the choice between diesel-electric cruise or diesel-mechanical top speed) of a surface combatant vessel are given in Table II.

Table 1: Hierarchical categorisation of systems and components

Level	Designation
4	Main system
3	Subsystem
2	Primary component
1	Secondary component

The reasoning behind the categorisation is described in the following.

- Main systems represent high-level groups of components that allow the ship to fulfil its main functional requirements: hull integrity and self-buoyancy, possibilities of propulsion, cargo capacity and armament are instances of such requirements.
- Subsystems group the components that allow for different strategies to fulfil these requirements. In the example with the CODELOD drive, diesel-electrical propulsion is another subsystem.
- Main components refer to components that physically and directly enable fulfilment of the subsystem's requirements: the main diesel engine for instance develops sufficient power to achieve the diesel-mechanic design speed.
- Secondary components are auxiliary components to the primary components, ensuring that these can operate without failure, such as cooling water pumps.

Table II: Hierarchical categorisation applied on CODELOD propulsion system

Level	**Item**
Main system	CODELOD system
Subsystem	Diesel-mechanical drive
Primary comp.	Main diesel engine
Secondary comp.	Cooling water pump

Fig.1 illustrates how systems can be divided according to the categorisation given in Table I. Included in the outer frame is the main system (CODELOD propulsion system), while the frame around the main diesel engine and the cooling water pump contains subsystem diesel-mechanical propulsion. Primary components are written and framed in bold, secondary components have standard font.

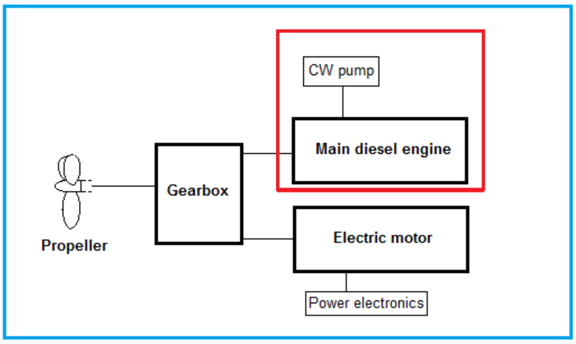

Fig.1: Categorisation of a CODELOD propulsion plant

Of course, there are components that allow for discussion regarding the category they belong to. Providing guidance to setting up a functional system breakdown structure suited for use with extrapolation models is the aim of this categorisation, rather than to give definitive rules regarding this categorisation. Correct definition and quantification of relations is of more importance than adhering to precise definitions regarding component and system classes.

Moreover, main and secondary components can also be used to describe non-physical quantities such as propulsion power, or relative size of components if exact dimensions are not known.

3.2. Definition of Relations

After evaluation of literature, *Baccarini (1996),* and practical experience within DSNS, two types of relations in the context of technological complexity were defined:

- Differentiation: refers to the number of systems and components and its influence on work content of individual components.

- Interdependency: refers to relations between systems and components and how these influence work content

Based on elaborations given in *Williams (1999)*, interdependency is divided into two subcategories:

- Vertical differentiation: top-down influence of high-level systems on lower-level components (mainly from level 3 items on level 2 items, as described in section 0)
- Horizontal differentiation: influence of components on other, same or lower level components (mainly from level 2 and level 1 items on level 1 items)

Based on these definitions, an interdependency factor f_i and differentiation factor f_d is determined per component. To finally estimate the ratio between work contents for evaluated and reference projects, these two factors are multiplied to obtain a complexity factor:

$$f_c = f_i \cdot (f_d)^{e_3}$$

Eq.(2): Complexity factor

Refer to the Nomenclature for a list of variables.

An exponential variable was added to the differentiation factors in order to allow non-linear effects resulting from system density to be taken into account.

The complexity factor expresses the ratio between man hours for the evaluated and the reference project. Or:

$$f_c = \frac{MH_b}{MH_a}$$

Eq.(3): Relation between complexity factor and work content

As the horizontal and vertical relations define the influence of design parameters down to component level, *complexity factors* are calculated per component. For an overview on work content ratios on higher levels, these factors are combined as follows:

$$f_{cc} = \frac{\sum_{i=1}^{n} MH_{b,k}}{\sum_{i=1}^{n} MH_{a,k}}$$

Eq.(4): Combined complexity factor

3.2.1. Differentiation

Gidado (1979) states that organisational complexity is driven by the number of departments and organisational units. This effect is referred to as horizontal differentiation. It is deemed that the concept of horizontal differentiation is as applicable on technological complexity as it is on organisational complexity: experience within DSNS has shown that an increasing number of components present in a specific room has a negative impact on efficiency and productivity of the work force, and as such increases the work content connected to installation of the individual components (referred to as system density). These observations have led to the proposal of the concept of differentiation in the context of technological complexity: the influence on work content per component by the number or dimensions of components per unit of space.

In the proposed mathematical framework for estimation of work content, differentiation is taken into account as follows:

$$f_d = \frac{V_a}{V_b} \cdot \left(\frac{\sum_{i=1}^{p} d_{b,i}}{\sum_{i=1}^{p} d_{a,i}} \right)$$

Eq.(5): Differentiation factor for specific component

The term “Volume” is avoided in this approach because not in all situations, components are grouped in a single space or object with physical dimensions (for instance, number of inputs and outputs on a network). To allow for a broad interpretation of the concept, the “volumes” defined in the context of differentiation are generally referred to as differentiation groups.

3.2.2. Interdependencies

As was stated before, interdependency refers to physical relations between systems and components. An example of vertical interdependency is the relation between diesel-mechanical design speed and the power of the main diesel engines. Horizontal interdependency can be illustrated by describing the relation between the main diesel engine and the cooling water pumps: increasing engine power linearly raises the amount of waste heat to be dissipated through the heat exchangers, and hence the pump capacities (assuming constant fluid strengths and temperatures).

The interdependency factors can not only be used to estimate physical relations between components, but also how work content per component evolves with component dimensions. Estimation of propulsion engine power for example can be done by only taking into account physical relations such as the Admiralty law. The number of engines, a component which can be additionally defined to estimate required installation hours, may not be linearly related to propulsion power, as doubled engine size does not necessarily imply twice the number of installation hours. The number of man hours connected to installation of the main engines in the benchmark can hence be assigned to a virtual number of engines, which in turn has a non-linear, horizontal relation with component engine power.

Vertical and horizontal interdependencies are calculated as follows:

$$\frac{d_b}{d_{a_{vertical}}} = l_{1,g} \cdot \left(\frac{r_{b,g}}{r_{a,g}} \right)^{e_{1,g}}$$

Eq.(6): Vertical interdependency factor

$$\frac{d_b}{d_{a_{horizontal}}} = \frac{\sum_{t=1}^{q} s_t \cdot l_{2,t} \cdot {d_{d,p}}^{e_{2,t}}}{\sum_{t=1}^{q} s_t \cdot {d_{c,t}}^{e_{2,t}}}$$

Eq.(7): Vertical interdependency factor

It can be expected that horizontal dependency factor will be used to describe groups of components as well (for example, the evolution of power required by a set of auxiliary engine room equipment). For this reason, the horizontal interdependency equation has been defined in such a way that components can be summated, and if necessary, weight factors can be assigned. As such, dimensions such as power in kilowatt can be summated without the need for weight factors, or, components can be summated merely by their amounts using the weight factors to account for different power requirements per component.

Horizontal and vertical interdependency factors are combined into a single interdependency factor f_i:

$$f_i = \frac{d_b}{d_a} = \frac{d_b}{d_{a_{vertical}}} \cdot \frac{d_b}{d_{a_{horizontal}}}$$

Eq.(8): Interdependency factor

Horizontal and vertical interdependency factors are multiplied as it can be expected that they reinforce each other rather than to act independently. For example, if bunker tank capacity is estimated and considered as a primary component, engine power has a horizontal influence on this component. Required autonomy in days however can be considered as a requirement, imposed on subsystem diesel-mechanical propulsion for instance, having a vertical influence on the bunker tank capacity. Now if the range is tripled and so is the engine power required to achieve cruise speed, the required bunker tank capacity will have to increase nine-fold.

3.3. Extrapolation of Work Content

A hallmark of the proposed extrapolation method is its first-principle approach: knowledge on marine engineering and naval architecture as well as experience with projects in the past are used to define and fine-tune the relations used to extrapolate work content. Such a method allows for better substantiated and more detailed estimations than methods based on only a few indicators (such as expected man hours per ton for the considered ship type), and allow planners to combine their experiences with bottlenecks and problematic technical characteristics into one, standardised mathematical framework.

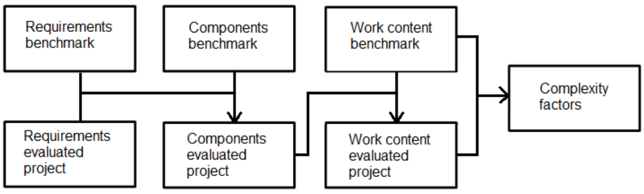

Fig.2: Schematic representation of extrapolation method

As can be seen in Fig.2, the estimation of work content for a new project starts from a benchmark project. This benchmark project is a collection of data from a historical project, containing all systems and components relevant to the newly evaluated project along with system requirements and component dimensions as well as man hours related to production and/or installation of these components. A benchmark project needs to be defined once, following which it can be used to evaluate a multitude of new projects.

For the evaluated project, system requirements need to be given. If known, the dimensions of these components can be specified, leading to more accurate results. In general, reliability of the work content estimation increases as more input data are supplied (this will be recapitulated in a later section).

Through the mathematically defined relations, component dimensions and numbers are estimated, as well as the production man hours related to these components.

Finally, work content for the reference project and the newly evaluated project are compared, resulting in non-dimensional *complexity factors* expressing the ratio between work content of the evaluated and reference project. Such complexity factors are determined on component levels and system (or, for example, Damen SWBS) levels as well as on project level.

An important side note is that, as the extrapolation network delivers only approximations, estimations of new projects become more accurate as more input data is supplied to the model.

4. Defining Benchmarks

Accurate definition of benchmarks is paramount to successful evaluation of new projects, as these benchmarks make up the basis of any estimation.

Benchmarks are based on historical projects and contain data such as systems requirements, key components that are part of these systems and the man hours connected to these key components. This implies that, before an estimation model based on extrapolation can be applied, a historical project for which detailed man hour data were registered must be available. For the demonstrative model developed during the research, data for the Damen Sigma 10514 surface combatant were used. Being equipped for anti-submarine warfare as well as surface actions in a broad spectrum of conflict, this frigate possesses many military and civil systems, resulting in a widely applicable benchmark. Combining historical man hour data and validated estimates, 120 key components (for example, hull welds) were identified, categorised and assigned a fraction of total work content. Using over 300 interdependency relations and 7 differentiation groups, specifications and man hour data can be extrapolated to evaluate new projects. The interdependency factors were derived from first-principle models, relating for instance hull welds to the number and size of plates, while the differentiation groups refer to groups of components which, usually due to spatial constraints, mutually influence production work.

For definition of future benchmarks, it is advisable to investigate first which components are actually decisive for the evolution of work content of a shipbuilding project.

For instance, it can be expected that generator sets determine the majority of work in the engine room, however auxiliary equipment contributes an important share as well. Therefore, installation hours for multiple projects should be registered precisely (for one specific engine along with those for selected auxiliary components considered as representative for most of the auxiliary equipment related to power generation). Apart from that, a more general account of division of man hours for engine room equipment can be kept. This way, insight is generated in how man hours are distributed over primary and secondary components, as well as the way in which the work content for secondary components evolves with increasing or decreasing primary component dimensions.

5. Determining Relation Factors

The extrapolation method is devised to deliver estimates for a new project, comparing functional requirements of the benchmark and the new project and using the differences in requirements to extrapolate the benchmark components to dimensions for the new project, allowing work content to be estimated in this manner. These extrapolations are based on the set of formulas proposed in section 0. These equations require constants and exponents (referred to as relation factors) to be supplied. This is quite a laborious activity but it does not need to be performed for each evaluation: as it can be expected that physical relations, on which these relation factors are usually based, remain virtually the same for most vessel types.

Two principal strategies can be followed to assign meaningful values to relation factors, as will be described in the following sections.

5.1. First-Principle Estimation Models

5.1.1. Hull Construction

Models estimating physical properties of systems are, for instance, a logical way to determine relation factors for hull construction. In the context of this research, a model based on the Sigma 10514 estimating weld lengths, number of frames and steel plates, steel weight and other relevant values was set up. As a validation, it was shown that weights estimated by the model differed by less than 7% from the actual weight of the hull.

This allowed to investigate how output values frame area, weld lengths for structural members, weld lengths for skin plates and number of skin plates, which were assumed as determining for hull construction work content, evolved with varying input parameters such as ship length, frame spacing, deck height et cetera. Additionally, it was estimated how producibility of the skin plates affected steel processing as but experience in the DSNS production department and literature learned that this too is a factor of importance when hull construction work content is considered, *Brown and Barentine (1996)*. Regression analysis was performed on the results, leading to a set of relation factors allowing accurate estimation of hull properties and work content.

For example, the regression analysis shown in Fig.3 investigated the vertical interdependency acting from subsystem requirement frame spacing on component steel work structural members; the assumption was made that total area of the structural members is determining for steel work connected to structural members. Regression analysis led to a constant l_1 of 1 (as it can be assumed that, if frame spacing remains constant, so does frame area), and a dimension exponent e_1 of -0.951 (the original value of -0.931 was corrected to achieve the best curve fit after l_1 was adjusted to 1).

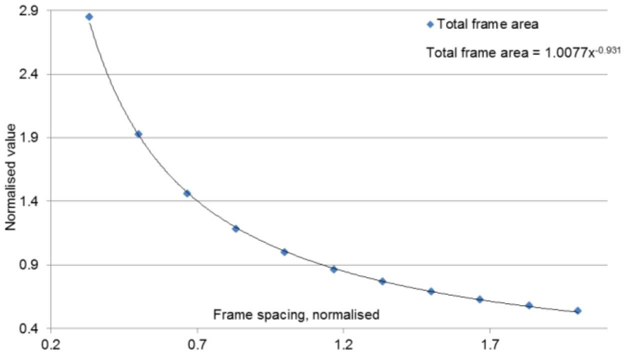

Fig.3: Regression analysis identifying effect on frame area of frame spacing

$$\frac{SW_e}{SW_r} = 1 \cdot \left(\frac{dt_e}{dt_r}\right)^{-0.951}$$

Eq.(9): Vertical dependency: frame spacing and steel work large structural members

Applied in Eq.(5), this leads to the formula given in Eq.(9).

5.1.2. Electric Power Systems

Another example of application of a first-principle model is a load balance, giving insight in distribution of power in different operational modes. If it is known to which operational mode the vessel's power plant is optimised, weight factors describing power requirements can be assigned to different components as was described in section 0.

5.1.3. Propulsion Power

The Admiralty law provides a suitable method to obtain a basic estimate of propulsion power, *Klein Woud and Stapersma (2002).*

$$C_{adm} = \frac{\Delta^{2/3} \cdot v_s^3}{P_D}$$

Eq.(10): Admiralty law

The relation implied by the Admiralty constant can be easily transformed in a set of relation factors:

$$\frac{PP_e}{PP_r} = 1 \cdot \left(\frac{v_e}{v_r}\right)^3 \cdot \frac{1 \cdot 1 \cdot \Delta_e^{2/3}}{1 \cdot \Delta_r^{2/3}}$$

Eq.(11): Interdependencies: propulsion power, design speed and design displacement

Vertical dependency between design speed (subsystem requirement) and propulsion power (primary component dimension) is assigned an exponential factor e_1 of 3, while the horizontal relation between propulsion power and design displacement (primary component dimension) is assigned an exponential factor e_2 of 2/3.

5.2. Regression Analysis of Historical Data

Regression analysis of historical man hour data sets may provide an efficient way to assign values to relation factors describing evolutions of key components and man hours. In this area, possibilities exist for application of neural networks; it may however pose a challenge to gather sufficient production man hour data to properly train these networks.

6. Input of Applied Model

6.1. Benchmark Data

For the benchmark set up in the context of the research, data for the Damen Sigma 10514 were used. Since actually registered man hours were available only for certain parts of the vessel, the benchmark had to be based partly on (detailed) DSNS estimates as well. As a validation, it was shown that estimation for the parts for which actual man hours were registered deviated by less than 4% from the actually registered production man hours.

The definition of the Sigma 10514 benchmark was done after project completion: detailed data were available concerning functional requirements, technical specifications and production man hours, leading to certain conclusions regarding distributions of work content and expected dominant components.

6.2. Relation Factors

Relation factors were mainly derived from first-principle estimation models such as described in section 4.1.

The method of gathering historical data as proposed in section 0 also allows for determination of relation factors: on the data sets obtained from a variety of projects, regression analysis can be performed in order to quantify trends.

7. Output of Applied Model

The result of the extrapolation method is a set of non-dimensional factors, expressing the ratio between production work content for the evaluated project and the benchmark project. To illustrate how these results could be presented, a demonstrative model based on the Sigma 10514 surface combatant benchmark was set up, and evaluations of the Sigma 6110 surface combatant, and PSV 3300 and PSV 5000 platforms supply vessels were made. In this paper, the results for the Sigma 6110 will be analysed.

The Sigma 6110 surface combatant is comparable to the Sigma 10514 in terms of functional requirements. Notable differences are size (Length x beam: 105 m x 14 m for Sigma 10514, 59 m x 10 m for

Sigma 6110), a simpler CODAD propulsion system (propulsion plant consisting of two sets of diesel engines, allowing cruise speed on one pair of engines or top speed on both pairs), absence of helicopter facilities and a considerably smaller complement number for the Sigma 6110. Armament and sensor systems are comparable, despite the difference in vessel dimensions.

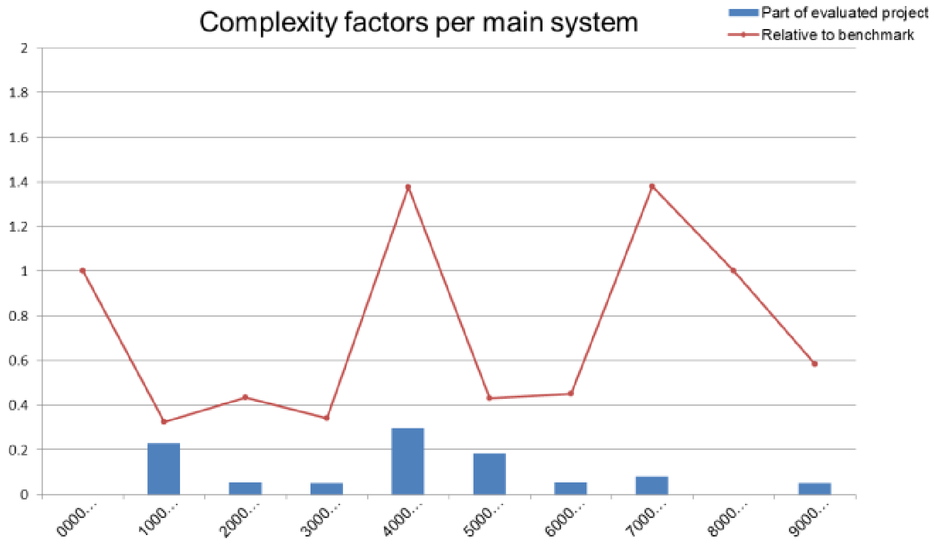

Fig.4: Results of work content estimation for Sigma 6110 surface combatant

In Fig.4, the red line connects the complexity factors per main system, the blue bars indicate the share of work content the main system has in the total for the evaluated project. Main systems are as given by the Damen SWBS structure:

0000 Guidance and administration
1000 Hull structure
2000 Propulsion Plant
3000 Electric plant
4000 Command and surveillance
5000 Auxiliary systems
6000 Outfit and furnishing
7000 Armament
8000 Integration engineering general
9000 Ship assembly and support systems

It can be concluded that for the Sigma 6110, categories 4000 and 7000 represent a much larger fraction of work than for the Sigma 10514, both in relative as in absolute terms, while complexity factors for other categories are all about 0.4. Note that no work content was connected to categories 0000 and 8000 as engineering was not part of the scope of this research. Hence, complexity factors for these main systems remain constant at 1.

The peak for category 4000 (command and surveillance, comprising mainly networks and sensor systems) can be partly explained by the fact that the Sigma 6110 has a much higher degree of automation: about the same number of sensors and combat systems, with a complement of only a little more than one third of that of the Sigma 10514. Furthermore, installation of the same number of sensor systems and control units on a considerably smaller vessel complicates installation of individual components.

Category 7000 (armament) entails more installation work principally because of the higher system density: deck area and space for combat systems is much more limited. Although this increase in work content, mainly caused by differentiation, could not be validated by first-principle models due to the non-physical nature of the concept of differentiation, this result was quite in line with experience by the DSNS project department.

8. Application of Proposed Method

Knowledge on expected production work content connected to new projects is of use when planning production activities as well as during negotiations with customers. The complexity factors present an easy-to-use result in this respect; it is assumed that this mode of application does not require more elaboration.

Extrapolation methods however are also suited to for use in the earliest design phases of a project. For example, reducing skin plate thickness brings down light ship weight (LSW), leading to a somewhat lower raw material cost but more notably, to lower operational costs (through reduced fuel cost). To maintain sufficient hull rigidity however, frame spacing must be reduced as well, and experience has shown that this considerably increases the number of man hours associated with hull construction.

The method proposed in this research can be used to evaluate this option without raising the need for extensive calculations, allowing optimisation of the design also in terms of production cost as early as in the basic engineering phase.

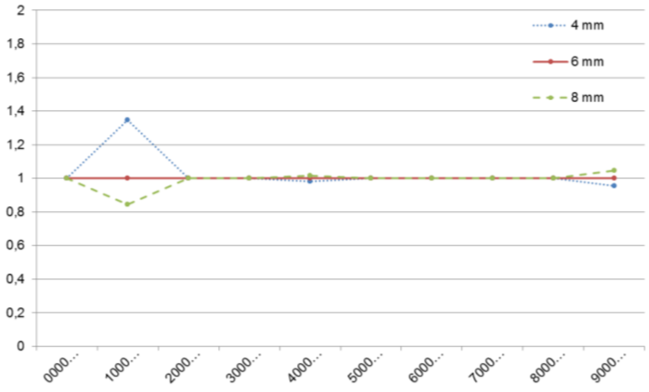

Fig.5: Analysis of effect of plate thickness on production work content per SWBS category, Sigma 10514

In Fig.5, the red line represents the benchmark, the Sigma 10514 with a plate thickness of 6 mm. The blue line shows how work content increases if plate thickness is reduced to 4 mm: LSW is reduced by an impressive 17%, however man hours for hull construction rise by over 35%, increasing the production man hours for the complete project by almost 13%. On a project as complex as a surface combatant, this makes up a considerable amount.

9. Conclusions

The extrapolation method described in this paper can be applied at various stages of a newbuilding project, such as determination of a correct quotation, optimisation of the design in terms of production cost, and allocation of resources during project planning. As the extrapolations it makes use of are primarily based on first-principles, the results can be expected to be of considerably higher accuracy than the straightforward man hour-per-ton figures traditionally used in the shipbuilding industry, especially if effort is dedicated to fine-tuning of relation factors.

10. Recommendations

At the time of the research, no detailed production man hour data for other projects than the Sigma 10514 were available so relation factors could not be fine-tuned. Regression analysis of extensive man hour data sets may provide an efficient and more exact way to assign values to relation factors describing evolutions of key components and man hours. In this area, possibilities exist for application of neural networks; it may however pose a challenge to gather sufficient production man hour data to properly train these networks.

When defining new benchmarks, it may be interesting to try an alternative approach: instead of basing a new benchmark exclusively on available, historical data, it can be chosen to use these historical data to identify, for example, a top-200 list of key components (including steel work related activities) which represent the majority of work content. It can then be investigated how other equipment is functionally related to these components. Subsequently, man hours can be tracked for these key components, along with man hours for a selected group of functionally related equipment in order to gain insight how this ancillary equipment evolves in terms of man hours.

These focused registrations of work content can be performed for multiple projects with differing specifications, on the longer term leading to profound insight in which components drive production work content and how these key components influence auxiliary components.

Abbreviations

CGT	Compensated Gross Tonnage
CODAD	Combined Diesel And Diesel
CODELOD	Combined Diesel-Electric Or Diesel
DSNS	Damen Schelde Naval Shipbuilding
GT	Gross Tonnage
LSW	Light Ship Weight
PSV	Platform Supply Vessel
SWBS	Ship Work Breakdown Structure

Nomenclature

f_c = [-] complexity ratio for component
f_i = [-] interdependency factor for component
f_d = [-] differentiation factor for component
e_3 = [-] differentiation – man hours exponent
d_a = [kW, kg, t, …] dimensions of influenced component in reference project
d_b = [kW, kg, t, …] dimensions of influenced component in evaluated project
V_a = [m3, m, …] available space for component in reference project
V_b = [m3, m, …] available space for component in evaluated project
i = [-] index for components present in room
p = [-] number of components present in room
f_{cc} = [-] combined complexity ratio for higher level
k = [-] index for lower level components, subsystems or main systems
n = [-] numbers of lower level components, subsystems or main systems
MH_b = [hrs] estimated man hours for installation of evaluated component
MH_a = [hrs] man hours for installation of reference component
l_1 = [-] vertical dependency constant
r_a = [kn, complement, …] system requirements for reference project
r_b = [kn, complement, …] system requirements for evaluated project
e_1 = [-] vertical dependency dimension exponent
s = [-] coefficient of effect (“weight factor”)
l_2 = [-] horizontal dependency constant
d_c = [kW, kg, t, …] dimensions of influencing components in reference project
d_d = [kW, kg, t, …] dimensions of influencing components in evaluated project
t = [-] index for components of influence on horizontal dependency
q = [-] number of components of influence on horizontal dependency
e_2 = [-] horizontal dependency exponent

SW_e = [hrs] work content steel work large structural members, evaluated project
SW_r = [hrs] work content steel work large structural members, reference project
dt_e = [m] transverse frame spacing, evaluated project
dt_r = [m] transverse frame spacing, reference project
C_{adm} = $[t^{2/3} \cdot kn^3/kW]$ Admiralty constant
Δ = [t] displacement
v_s = [kn] ship speed
P_D = [kW] power delivered to propulsors
PP_e = [kW] propulsive power, evaluated project
PP_r = [kW] propulsive power, reference project
v_e = [kn] design speed, evaluated project
v_r = [kn] design speed, reference project
Δ_e = [t] design displacement, evaluated project
Δ_r = [t] design displacement, reference project

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Multidisciplinary Process Integration and Design Optimization of a Hybrid Marine Power System Applied to a VLCC

Sabah Alwan, NTNU, Trondheim/Norway, sabah.alwan@ntnu.no
Kevin Koosup Yum, SINTEF Ocean, Trondheim/Norway, KevinKoosup.Yum@sintef.no
Sverre Steen, NTNU, Trondheim/Norway, sverre.steen@ntnu.no
Eilif Pedersen, NTNU, Trondheim/Norway, eilif.pedersen@ntnu.no

Abstract

In this paper, we explore the use of multidisciplinary and high-fidelity simulations for multi-objective design optimization of a marine hybrid propulsion system with application to a very large crude oil carrier (VLCC) tanker. The optimization is achieved by utilizing a process integration and design optimization (PIDO) to support multidisciplinary design optimization (MDO). We performed a minimum number of simulations to explore the design space through algorithm-guided design-of-experiments (DoE). Based on those experiments, response surface models (RSMs) were constructed. Further, sensitivity and correlation within design parameters and with the design objectives from the simulations are simultaneously examined and elucidated. Subsequently, the quality of the RSMs is validated using the simulation models. A multi-objective optimization is then carried out by utilizing the RSMs rather than the high-fidelity simulation. Standard particle swarm optimization (sPSO) was used with the RSMs while a very large number of design variation and alternatives are swiftly examined. Remaining work is to test optimal design solutions for their reliability and robustness through sensitivity to changes in operational requirements, changes in environmental conditions and imprecision in design parameters.

1. Introduction

A ship is a complex system in which many designers develop and consider different aspects of the system to meet various functional requirements. Traditionally design decisions are made in two different levels, that is a system level and a component level. In the system level, often the optimization objective is to make the ship as economic as possible, whereas in the component level, the objective is to meet the component's solitary functional requirements within the given constraints. In this paper, we hope to shed light on the use of an integrated multidisciplinary simulation-based framework for multi-objective design optimization of a vessel system performance rather than component based design and optimization. These approaches are recently and widely in use within the aerospace and automotive industries alike *Frenzel, Heiserer et al. (2015)* and *Van der Auweraer, Donders et al. (2008)*, with lesser usage in the maritime industry where its often discipline specific *Liu and Collette (2014)* and *Parsopoulos and Vrahatis (2002)*. Using a well-established approach from other industries can potentially improve design outcomes *de Weck, Agte et al. (2007)* by simultaneously considering different aspects of the system. Therefore, process integration and design optimization (PIDO) tools are used to support multidisciplinary design optimization (MDO). In MDO, a metamodel is often derived from performing a minimum number of multidisciplinary system simulations guided by smart algorithm such as Latin Hypercube *Eglajs and Audze (1977)* or Factorial Design *Box and Hunter (1961)* through design-of-experiment (DoE). In the system simulation, several domain specific virtual models and processes are interlinked in accordance with the design task. In this paper, models include ship operational model, metocean models, ship hydrodynamics, propulsion, electrical load and powering models to simulate the total system performances. The metamodel can be in the form of a response surface model (RSM) *Box and Wilson (1992)* that is constructed by a polynomial, support vector machine (SVM) for supervised machine learning, a neural network, Kriging, etc. Subsequently, multi-objective optimization is achieved by the utilization of the metamodel and varying design parameters with optimization algorithms within some design constraints to achieve certain performance objectives. Several optimization algorithms were tested and found to vary in their performance and convergence.
In this paper, we present an application of MDO using a PIDO platform for the design of a hybrid

marine power plant for a VLCC. In the power plant, the main engine drives the propeller shaft as in the conventional system, and the power take-in (PTI) / power take-off (PTO) device is used to harvest or boost power to the propeller shaft. To maximize the capacity of the PTI/PTO device with minimal influence on the electrical power plant, an energy storage system such as battery pack or a super-capacitor bank is used. The aims of this particular configuration are: (1) to reduce the fuel consumption in low load operation by reducing the main engine power without losing extra propulsion power for rough weather, and (2) to enhance the dynamic response of the propulsion system, reducing the fluctuation of the propeller speed and, thus, the chance of over-speeding. The numerical simulation provides the average fuel consumption for the given probabilistic operational conditions from weather and speed, and the dynamic response of the system in time-series. The goal of the optimization is to find the best configuration of the main components in terms of capacity to achieve the minimum fuel consumption. The capacities of the components in question are those for the main engine, the PTI/PTO device, the auxiliary engine, and the battery. This paper includes a description of MDO method and discusses the applicability and challenges in ship design. Uncertainties related to operational condition and system design variables and parameters were examined to achieve the required level of system reliability and efficiency. A MDO case study of a tanker operating in adverse condition is presented.

2. Process Integration and Design Optimization

Four main objectives behind Process Integration and Design Optimization (PIDO) tools are to create an automated design process, design space exploration, design optimization and ultimately design for value robustness. In process automation, separate engineering disciplines can be integrated for better design performance evaluation and reducing repetitive design tasks, development time, and trail & error. Designers can perform and evaluate multiple designs simultaneously by exploiting the rapid increase in computational power and parallel processing. Also, explore the design space methodically by investigating large numbers of possible design alternatives and employing specialized search algorithm on different design combination. Visualize and analyze statistically various design parameters relations through sensitivity analysis, screening and intelligent sampling.

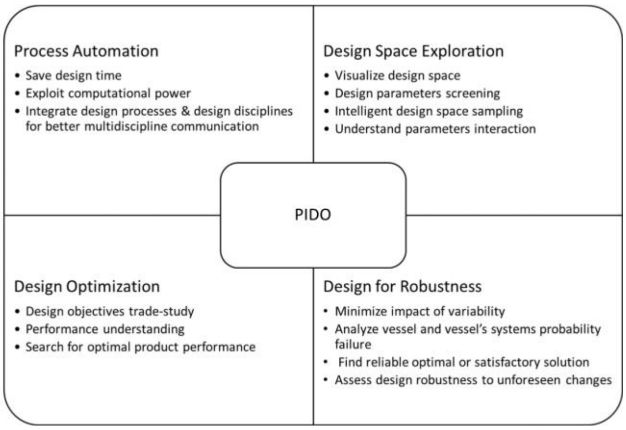


Fig.1: Diagram explaining the underlying rationale behind PIDO

Results from various simulations are then used in machine-learning or to construct RSMs. These models are then cross validated against or validated against few high-fidelity simulations, and then used as independent models for design optimization. Optimization is then carried out using global search evolutionary algorithm such as (MOGA, sPSO) for the first stage and gradient based algorithm for the final stage. Final optimal design configurations are then verified with the high-fidelity simulation.

Most of the aforementioned statistical methods, integration of processes from different disciplines and optimization are known in various scientific and engineering disciplines, however they are challenging to apply into practical ship design tasks due to difficulties in auto-generation and evaluation of precise design alternatives such as hull-form and propeller, or scaling the size of main engine and generators without careful considerations. These difficulties by no means depreciate the value and progress made by various tools for modeling and analyzing ship's subsystems. Furthermore, the nature of ship design means that design requirements, objectives and constraints often change during the design process based on new observations and results interpretations *Andrews (2004)* and *Gero and Kannengiesser (2004).* Lastly, there is a level of challenges that arises from communicating data between different design disciplines and the nature of the information flow. For instance, there is no specific format or approach or boundaries where one subsystem and its requirements and constraint can interact with the next subsystem with its objectives and constraints. That being said, theoretically challenges can be reformulated into opportunities where constraints can be shared and softened among subsystems or turned into objectives.

Essentially PIDO philosophy tries to bring about wider systematic design perspective, to utilize various statistical methods as aid tools in the design process, to improve on computational cost through smart experimentation, provide more precise models from simulation data with lower uncertainty instead of relying exclusively on approximate heuristic models, and finally to enable designers to consider wider system boundary at an early design stage.

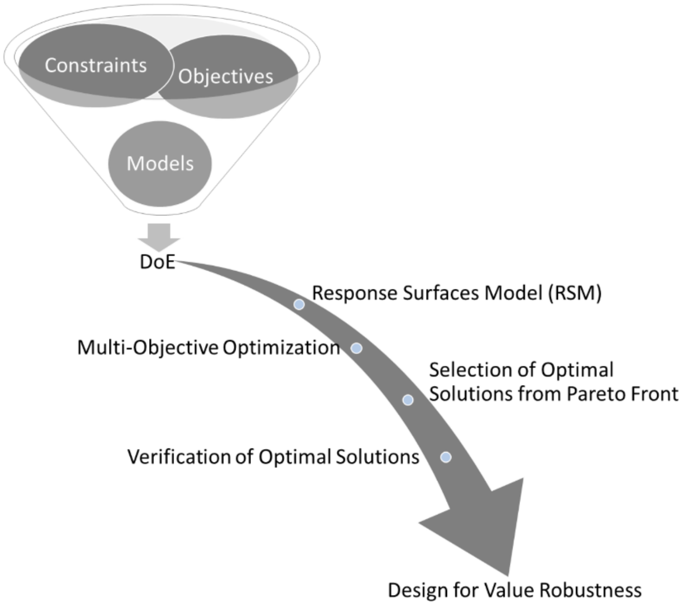


Fig.2: PIDO process follows from design models-constraints (hard/soft)-objectives to formal DoE study. RSM and/or supervised machine learning model is then constructed and validated with the initial models. Optimization is then carried out using suitable algorithm to examine large number of design alternatives. Optimal results are then verified with the initial models and tested for their robustness.

3. Simulation Models and Workflow:

The PIDO workflow utilizes machinery models and ship hydrodynamic aspects as proposed in *Yum, Skjong et al. (2016), Yum, Taskar et al. (2016)* as well as ship voyage simulation model for weather and transporter capacity. The PIDO workflow is based on Noesis Solutions Optimus software tool. This workflow essentially guides the simulation models and their parameters, and extract results for each run, then store and re-use knowledge acquired during each simulation including trends and relationships that lead to specific solutions.

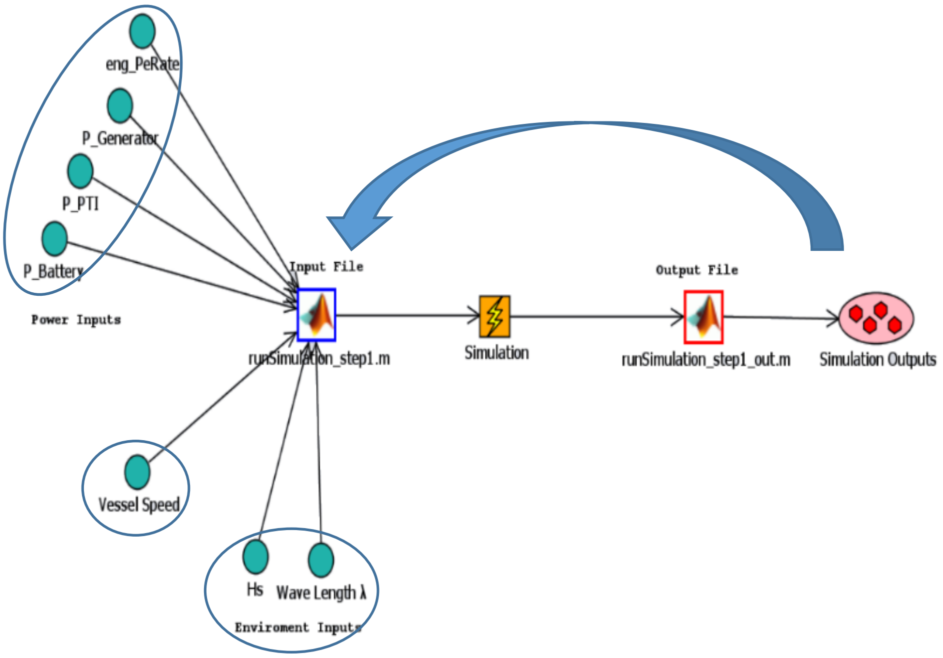
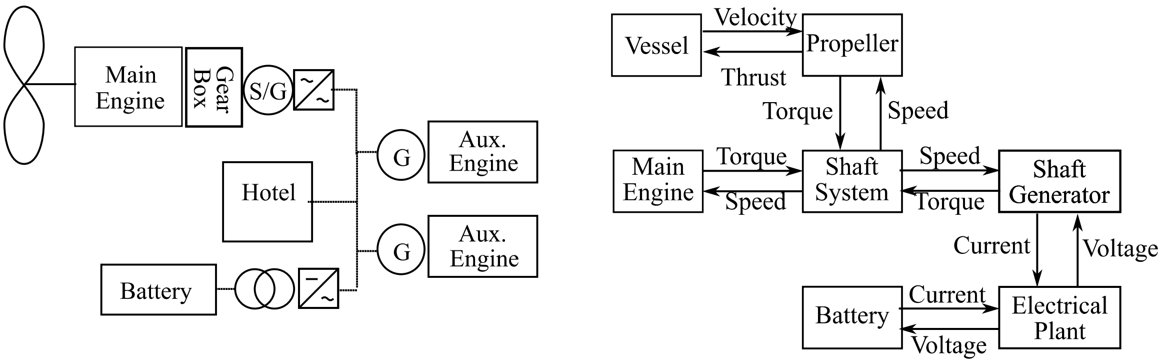


Fig.3: Simulation workflow that perform the virtual vessel design optimization (Created with Noesis Solutions Optimus software tool)

The vessel model in use based on the well-known KVLCC2 model where vessel particulars can be found in the appendix. Hydrodynamic coefficients were computed using the ShipX Veres module from SINTEF Ocean, which is using linear strip-theory *Salvesen, Tuck et al. (1970)* to compute the vessel motions. The added resistance is then computed according to the modified version of Gerritsma & Beukelmans as presented in *Loukakis and Sclavounos (1978)*. The ship propeller was based on the modified propeller design and open water propeller diagrams and wake estimation procedure as proposed in *Taskar, Yum et al. (2016), Yum, Skjong et al. (2016)*. Pre-processing simulation is then carried out and stored in a database for both regular and irregular waves with Hs (significant wave height) and T_p (peak period) according to the metocean model outputs.

The structure of the machinery and propulsion simulation model is presented in Fig.4, which only provides the model structure in the component levels. In addition to the component models, controllers such as an engine governor, a governor for PTI/PTO device and a power management system had been implemented order to run the dynamic simulations for different operating conditions. *Table I* shows the modeling framework used for the submodels.



(a) Hybrid propulsion system (b) System model

Fig.4 Schematic of the hybrid propulsion system and the structure of the simulation model

Table I: Modeling framework of the submodels

Submodel	Modeling framework	Submodel	Modeling framework
Electrical system	Dynamic model using dq-frame	Shaft system	Single rigid-body
Diesel engine system	Filling and emptying method 0D phenomenological combustion	Vessel	1D rigid-body Calm Water Resistance Curve Added Resistance Coefficient
Battery system	Capacitance and resistance model	Propeller	Quasi-steady based on propeller curve Mean wake variation model Ventilation model

However, the models had to be modified in order to be used in the design space exploration to overcome the two challenges: simulation time and robustness of simulation over various configurations of the power plant and operational conditions.

The average simulation time for the hybrid propulsion system in the previous work was typically 10~15 times slower than real time when the whole system was run as a single simulation on a high-performance computer. The main reason for the slow computational speed was to include both the electrical models and the diesel engine models that have very different time scales. Co-simulation could enhance the computational speed but not so drastically. In this regard, we decided to divide the simulations into three where the second and third part of the simulation is carried out in sequence. First, the vessel transport capacity is simulated for a given logistical network where vessel speed and carrying capacity are estimated, then metocean data from hindcast along the sailing route are computed into probabilities of occurrence and communicated to the rest of the simulation as an input. The second part of the simulation is the mechanical system which includes the coupled hull-propeller-machinery system. This is run first and the logged signals from the simulation are provided as inputs to the electrical system simulation. The interface between the second and third parts of the simulation is the PTI/PTO, which is modeled by a first-order transfer function in the mechanical simulation whereas it is modeled by its first principle physics model. The structure of the revised simulation model is presented in *Fig.5*. As a result of changing from the simultaneous simulation to the sequential one, the simulation runs approximately 30% faster than real time. Note that the electrical simulation is skipped in case that the PTI/PTO device provides enough electricity for the auxiliary loads so that the generators do not need to run.

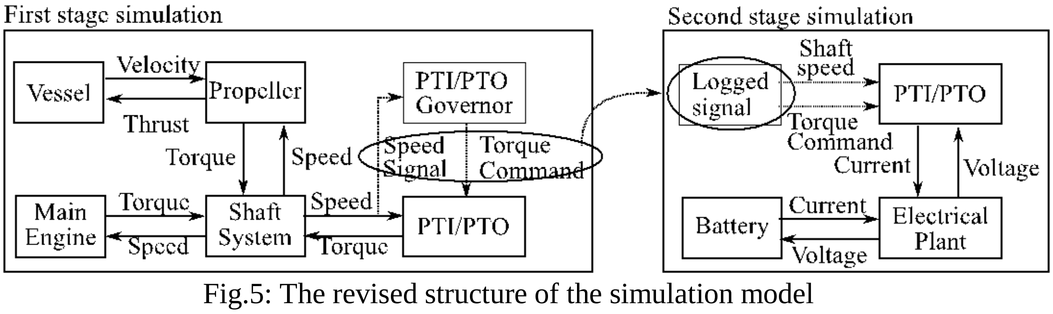


Fig.5: The revised structure of the simulation model

Regarding robustness of the simulation, the capability of the controllers had to be extended to enable the various operational modes depending on the power loads. The control objective of the PTI governor in the previous work was to regulate the shaft speed with minimum fluctuation for propulsion in waves. However, in order to simulate the performance in both the PTI and PTO mode, the mean power load on the shaft is to be shared between the main engine and the PTI/PTO device depending on the available power and the level of the power load. The control objectives for the PTI/PTO device for different powering modes are:

PTI mode ($P_{ME,Max} < \overline{P}_{Prop}$): While keeping the shaft speed constant, the device should provide the power to the shaft as much as possible so that the main engine does not operate above the torque limit for the given shaft speed.

PTO mode ($P_{ME,Max} > \overline{P}_{Prop}$): While keeping the shaft speed constant, the device should take off enough power from the shaft to provide the auxiliary loads. The torque of the main engine should be kept within the limit in any case.

It is however difficult to interfere the simulation manually as the number of simulations for the design study is too large for that. Introducing switching controllers depending on the mode may lead to instability in simulations for many combinations of different parameter sets. In order to tackle this challenge, we introduced load limiting droop control for the sharing loads between the main engine and the PTI/PTO device.

In general, a droop control is used for sharing the loads between the generators running in parallel. When the same droop curve is applied between two powering units, they share the load proportional to their rated power. This proportion can be regulated either by changing the slope of the curve or changing the reference frequency at no load. Usually the droop curve is defined for the power between 0 and 100%, but we defined the droop between -50 to 50% as PTI/PTO device can either be powering (positive power) or being powered (negative power). The droop curve for the main engine and the PTI/PTO device is shown in Fig.6. When the reference speed is given to the governors, it is multiplied by the value of the droop curve depending on the load to give the set point to the speed controller. From the defined droop curve in *Fig.6* for an identical speed reference, PTI/PTO will share the load of 20% of its capacity when the main engine is running at 70% load, or -20% of its capacity when the main engine is running at 30% load. The corresponding droop values are 0.99 and 1.01, respectively. The curve for the PTI/PTO device is flat outside the range because some power should be reserved for smoothing the power and speed fluctuations during propulsion in waves.

Furthermore, the proportions of load sharing can be adjusted by increasing or decreasing the speed reference value to one of the devices, which has the effect of lifting or lowering the droop curve of the device. As the speed reference is increased, the device has to work harder than the other that is controlled at the original reference, and vice versa. As shown Fig.6, when the speed reference for PTI/PTO is increased by a certain value, 1.5% in this case, the dotted line represents the new set point. In this case, while the main engine is running 70% of its power, the PTI/PTO will provide 50% of its rated power to the shaft, 30% increase compared to the identical set point in Fig.7. In the opposite case, decreasing the reference value by 1.5%, PTI/PTO will take off 50% of its rated power from the shaft while the main engine is running at 30%.

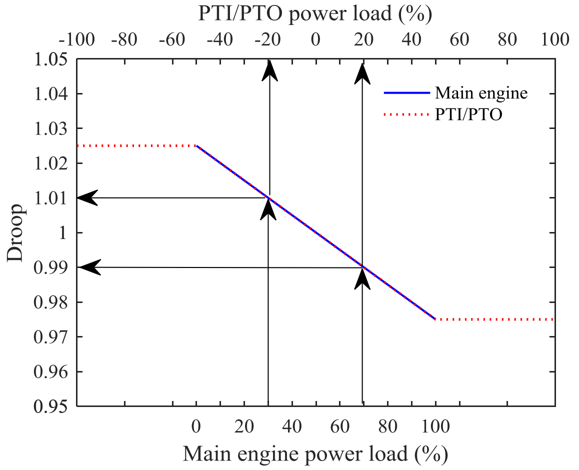


Fig.6: Droop curves for the main engine and the PTI/PTO

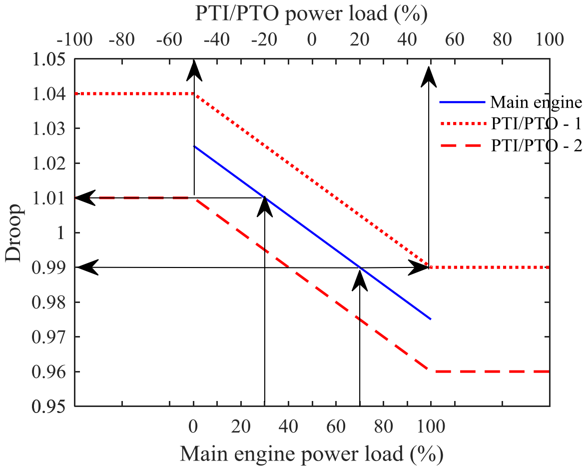


Fig.7: Adjusting the load sharing proportion by changing the speed

Using the principle above, the load sharing of the main engine and PTI/PTO can be controlled by adjusting the speed reference to the governor for PTI/PTO. This is achieved by the controller presented in Fig.8. PTI load control is the only active controller that regulates the load sharing. In case that maximum allowable engine load smaller than the average propulsion load ($P_{ME,Max} < \overline{P}_{Prop}$), which will be represented by the engine governor output greater than 1, PTI load control will give negative value so that the speed reference for the PTI/PTO device will increase, thereby, increasing the power load. In the other case, $P_{ME,Max} > \overline{P}_{Prop}$, the speed reference will decrease, reducing the power load and entering PTO mode eventually. However, the average power production from PTO mode should not exceed the power demand of the auxiliary loads. Therefore, if the average power production is greater than a certain portion of the auxiliary power demand, the PTO load controller becomes active which controls the power load of PTO to match the auxiliary power demand while the PTI load controller becomes inactive. The transition from PTI load control to PTO load control happens through the hysteresis type of switching so that they do not swing back and forth. This controller proved to be robust for all the variations of parameters and the operational conditions during the simulation.

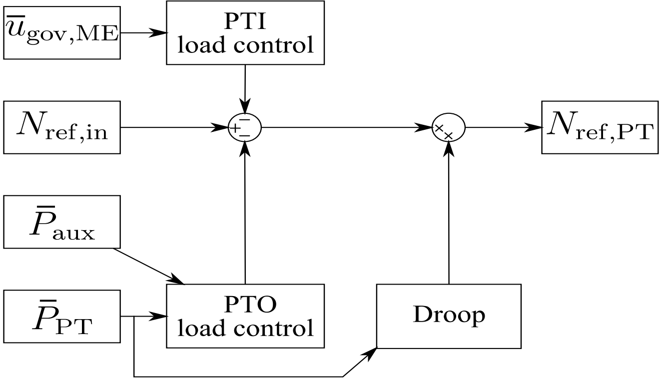


Fig.8: Schematic of PTI/PTO load sharing control

In addition to the operational variations in the simulation, the simulation models also have to cope with variations of the parameters in a large range for the design study. As most of the models are based on the first principles, there are large sets of parameters to be changed along the design parameters. It will be impossible to validate the models for each set of parameters in the process of performing design of experiments or optimization. To resolve this challenge, we decided to use the well-validated model and the parameters as is, and convert the power input/outputs only. For example, the interface with between the shaft model and the main engine model includes the information of the shaft and the torque. We assume the shaft speed will not be scaled as the propeller design remains the same, but the torque will be according to the ratio of the rated power of the new design to the original so that the power is properly scaled. The same will be applied for the gensets, batteries and PTI/PTO device.

4. Case Study: Environmental condition, operational profile and design constraints

4.1 Objective

This demonstration case based on the well-known KVLCC2 operating in adverse weather condition. The vessel's particulars, propeller characteristics and the machinery are provided in *Yum, Skjong et al. (2016), Yum, Taskar et al. (2016).* The objective of the optimization study is to find the set of the design parameters for capacity of the machineries that gives the minimum fuel consumption per miles for the given probabilistic operational scenarios (weather and speed) are calculated.

The particular values are for the nominal design where the parameters in *Table II.* will vary for the design space exploration and optimization. In addition to the high and low limit for the parameters, it must meet other constraints in order to ensure enough power for the propulsion and the auxiliary power.

$$P_{PT} + P_{ME} \geq P_{PropReq}$$

$$P_{Gen} \geq \frac{\left(P_{PropReq} - P_{ME} + P_{Aux}\right)}{2\eta_{Gen}}$$

where, $P_{PropReq}$ is a minimum power requirement for the vessel to survive under harsh weather and P_{Aux} is the auxiliary power load. In this study, they are assumed to be 25MW and 1MW, respectively.

Table II: Design parameters and their constraints

	Description	Range	Remark
P_{PT}	Rated power of the PTI/PTO	0 ~ 8MW	The same rate for PTI and PTO
P_{ME}	Rated power of the diesel engine	17.5 ~ 25MW	
P_{Batt}	Rated power of the battery	0 ~ 5 MW	The same rate for charging and discharging
P_{Gen}	Rated power of the genset	1.15 ~ 4.8 MW	

4.2 Operational profile

An evaluation of vessel speed to meet transport capacity and sailing through calm-to-rough weather conditions in the Northern Atlantic Ocean were performed with event-based voyage simulation. Results from this model were expressed in the form of probability distributions for equivalent Hs and vessel speed. The environmental conditions are stochastically independent while the vessel speed is a stochastic parameter influenced by markets from supply and demand between portal cities, and influenced by the environmental condition during voyage where voluntary speed reduction deemed necessary.

The probability of the equivalent wave condition along the sailing route P(W) is stochastically independent based on sample mean, rather than population mean, from hindcast open source weather data. Rationally, the vessel operating speed is a conditional probability. For a better speed and transport capacity estimation the vessel's maximum possible attainable speed can be pre-determined for a given weather condition and formulated in the below equation considering involuntary speed reduction from *Table 5* where T_p is the peak wave period and Hs is the significant wave height.

$$P(V \cap W) = P(V|\mathrm{W})P(W) \qquad (1)$$

Probabilistic operational profiles for vessel speeds (9, 11, 13 and 15 kts) and encountered environmental conditions (0, 1, 2, 3 and 4 m) for the sailing route were presented in 3 weather scenarios and 4 speeds as shown in Tables III and IV.

Table III: Five weather conditions with different frequency of occurrence from hindcast data along the sailing route.

Hs	Scenario 1	Scenario 3	Scenario 3
0 m	5%	5%	5%
1 m	10%	10%	12%
2 m	10%	20%	45%
3 m	55%	55%	28%
4 m	20%	10%	10%

Table IV: Combination of speeds with their frequency of occurrence to satisfy transport requirement.

Speed [kts]	Frequency Speed
9	15%
11	50%
13	20%
15	15%

Table V: Maximum attainable speed based on ship hydrodynamic calculation for different Hs & T_p.

Hs|T_p	5.66	8.00	9.80	11.32	12.65	13.86	14.97	16.01	16.98	17.90
1	14.97	14.96	14.96	14.95	0.00	0.00	0.00	0.00	0.00	0.00
2	14.99	14.96	14.90	14.57	14.45	14.35	0.00	0.00	0.00	0.00
3	0.00	14.54	13.47	12.52	12.33	12.09	11.88	11.97	0.00	0.00
4	0.00	0.00	0.00	9.63	9.25	8.84	8.54	8.85	9.15	9.44
5	0.00	0.00	0.00	0.00	0.00	4.47	4.42	5.04	5.59	6.37

4.3 Design of Experiment (DoE)

Design of experiment (DoE) was performed for each discrete operational point (combination of speeds and weather conditions) by sampling the list of design parameters from *Table 2* with Latin Hyper Cube Sampling technique. A total of 216 near-random experiments were produced for each operating point to explore the entire design space. Each evaluation of design combination is independent and therefore possible to carry out the simulation in parallel. In the DoE, we aimed at finding the influence of design parameters (inputs to the simulation) at the output response in terms of fuel consumption, torque and RPM fluctuation), which are the most dominant design parameters and at which condition, and finally how to predict outputs based on any set of design inputs. Correlation scatter matrices and bubble plots as presented later in results sections are used to screen out the least important design parameters and thus to focus the optimization resources on the most important parameters.

4.3.1 Response Surface Model

Using the results from LHC, a response surface model for each output is constructed. We used support vector machines (SVM) as a regression function that maps the inputs of design parameters to the output *Brereton and Lloyd (2010)*. While building the SVM models, it was found that the number of generators in operation causes some of our key outputs to be discontinuous. Therefore, the number of generators running that is an output of the simulation should be used as an input to estimate these outputs. Therefore, two layers of SVMs are used. Support Vector Machine classification (SVC) model was constructed to classify whether the inputs result in 0, 1 or 2 gensets in operation. Then a Support Vector Machine for regression (SVR) model was constructed to perform regression analysis and predict values of the continuous variables. The aim of this combined SVM is to provide a good prediction of fuel consumption per mile (SFCPM) for any combination of P_{ME}, P_{PT}, P_{Gen} and P_{Batt} as shown in Fig.9.

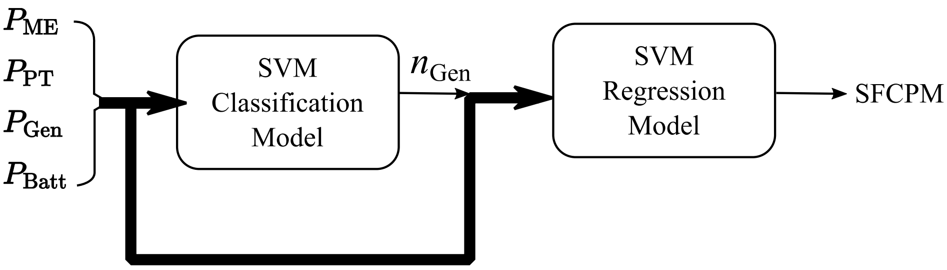
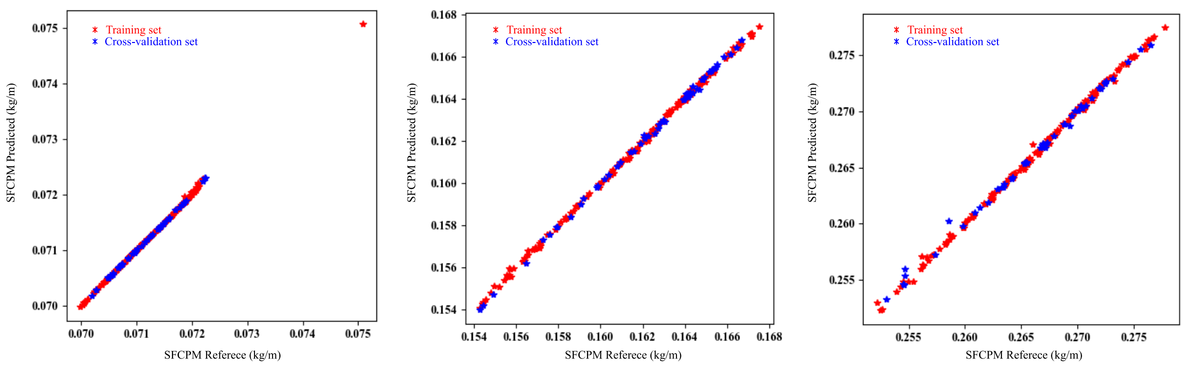


Fig.9: Schematic diagram for 2 levels SVC and SVR models constructed after the DoE study

Bayesian based optimization algorithm was used for training of the SVM parameters to get the best fit of the model. Lastly, cross-validation was performed using the dataset that is not used in the training in order to validate the SVMs for its generality. *Fig.10*, (A, B and C) show strong agreement between predicted SFCPM and computed (Reference) SFCPM from 3 different scenarios of weather condition and vessel speed.



(a) Vs 11kts, Hs 0m (b) Vs 15kts, Hs 2m (a) Vs 11kts, Hs 4m

Fig.10: Validation results from 3 randomly selected weather and speed scenarios

4.4 Study Scenarios

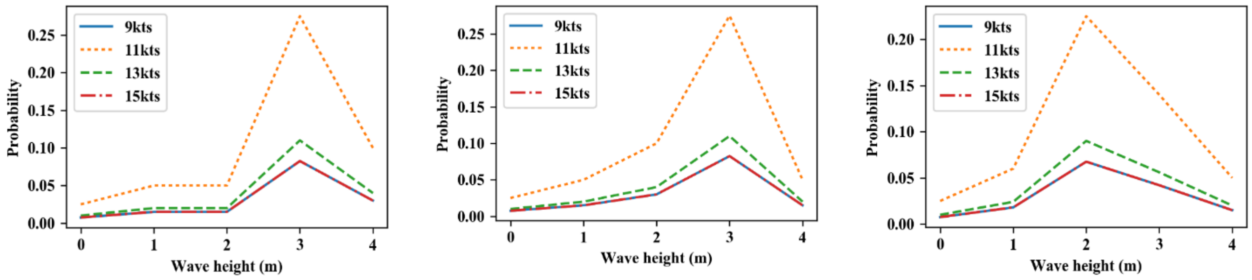
The main objective function of this case is to reduce the overall fuel consumption per miles for the given operational and weather conditions while taking into account the vessel dynamic response and feasibility of the machinery configuration. The focus was on finding the best configuration of the main engine, the PTI/PTO device, the auxiliary engine, and the battery where average fuel consumption per nautical mile for the given probabilistic operational scenarios (weather and speed) becomes minimum. The below equation of the objective function is used for consideration of the weather and sailing speed on the vessel's fuel consumption per mile.

$$Objective\ Function = \sum_{i=1}^{n} P_{v,i} \, . \sum_{j=1}^{m} P_{w,j} \, . SFC\ per\ mile_{\ (i,j)}$$

Where:

P_v is the probability of the vessel sailing at particular speed.
P_w is the probability of the vessel encountering particular weather condition.

A base vessel was provided with conventional propulsion and powering systems. An optimization problem is formulated based on the 3 scenarios as given in *Fig.11*. A comparison based on attainable speed and wave height was made, and therefore the objective function can be formulated with the assumption of two stochastically independent probabilities for the same attainable speeds and encountered wave height.



Case 1 Case 2 Case 3

Fig.11: 3 different probabilistic speed and wave height scenarios computed from voyage simulation at the sailing route in Northern Atlantic. Reference data are in Tables III and IV.

Combined optimization algorithms were used where global search algorithm finds the global minima, this was achieved using particle swarm optimization (PSO), and then local search was performed with Gradient Descent method. Both algorithms have their own advantage in finding the optimal solution and their own usage and convergence requirement. It was noted that PSO can find global solution but had difficulties in finding local minima. Gradient descent on the other hand was able to find only local minima and converge rather fast, therefore it required the assistance of other algorithm or multiple starting points in order to find global optimal solution.

5. Results and Discussion

In the first section of the results, the result from the simulations with various sets of design parameters are presented. 216 design sets were sampled for each condition of 20 combined cases of weather and speeds and simulated using the models presented in section 3. From the 20 cases a single correlation matrix is presented for a selected weather condition and operational speed (Hs = 1m and Vs = 15knt) as shown in *Fig.12*. Correlation matrices are used to find relationships between indirectly related design parameters and objectives. From *Fig.12*, it is evident that some parameters are highly correlated (+/-) while some are not. Many interesting hypothesis can be derived, for instance, SFCPM (kg/m) shows strong correlation with most design parameters and outputs with exception of P_{Batt}. This is vastly due to batteries are used for reserved power storage and damping speed fluctuation rather than fuel saving per se. Fuel reduction due to running the main engine at a more stable load is negligible in these simulations. As the value of SFCPM decreases, propulsion efficiency, P_{ME} increases with negative slope relationship. Also, it can be observed that SFCPM has discontinuities with all inputs and outputs due to switching between having a single generator and not having a generator in operation (PTO mode).

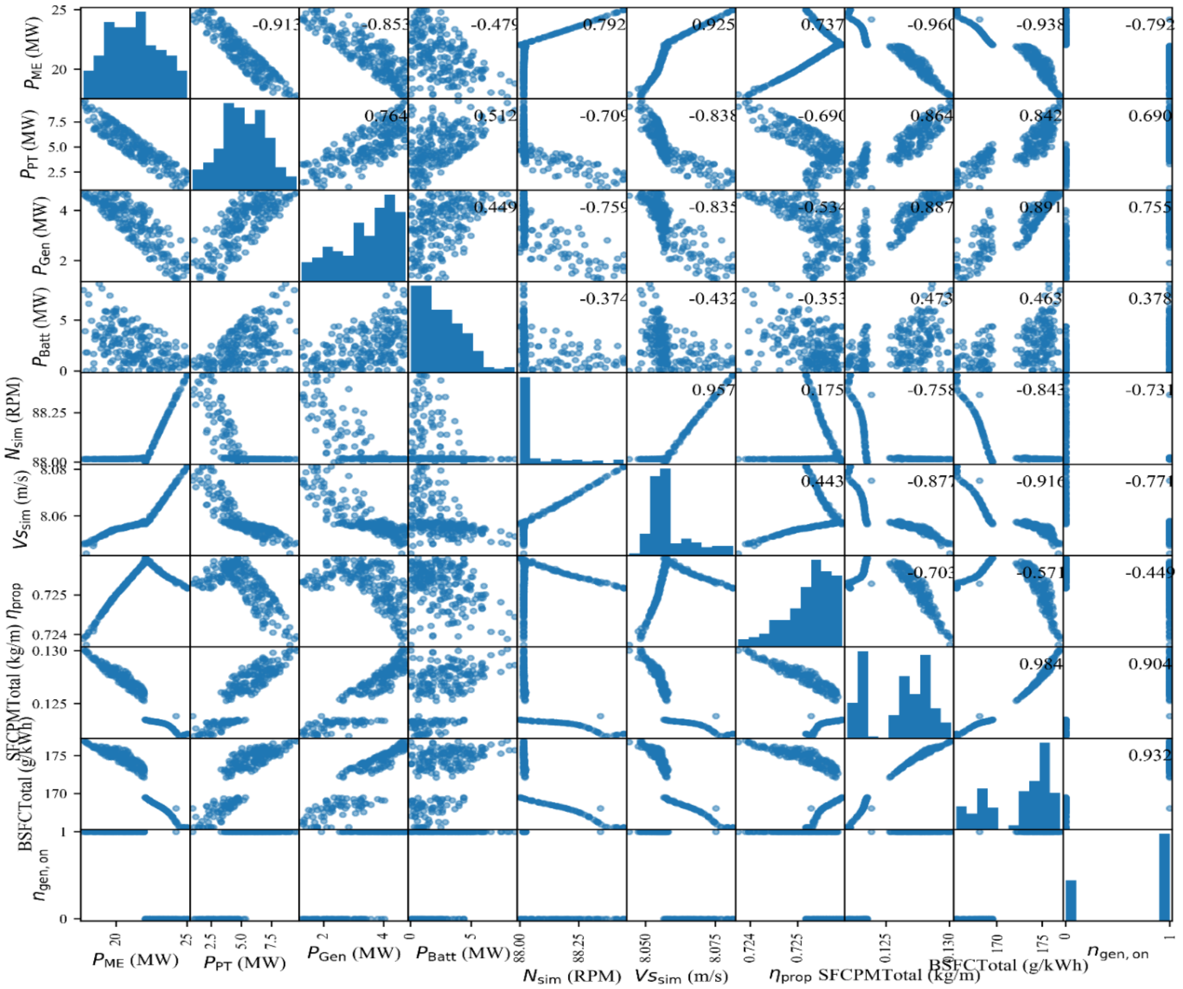
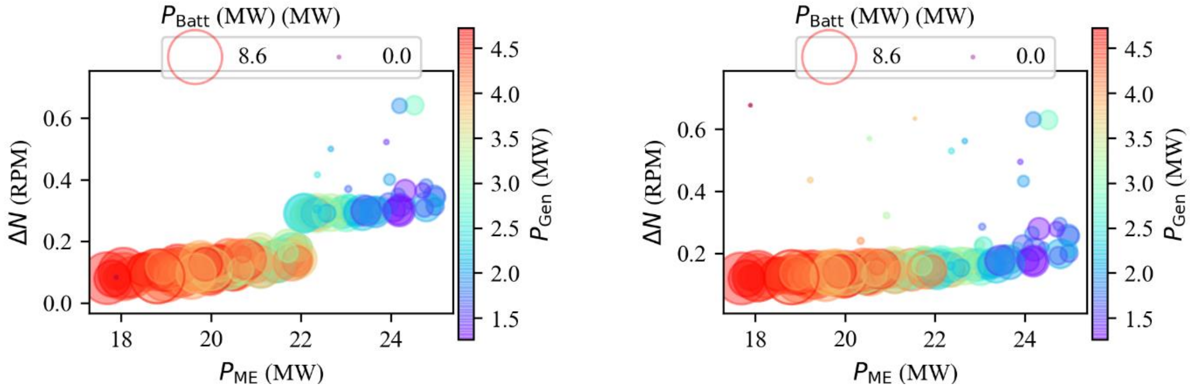


Fig.12. Scatter and correlation matrix for speed of 15 kts and Hs 1 m, generated from 216 high fidelity parallel simulations. Each box contain scatter which represents corresponding values (experimental set) between 2 parameters while the numerical values within the boxes represent the correlation coefficient of the two parameters calculated from the experimental set.

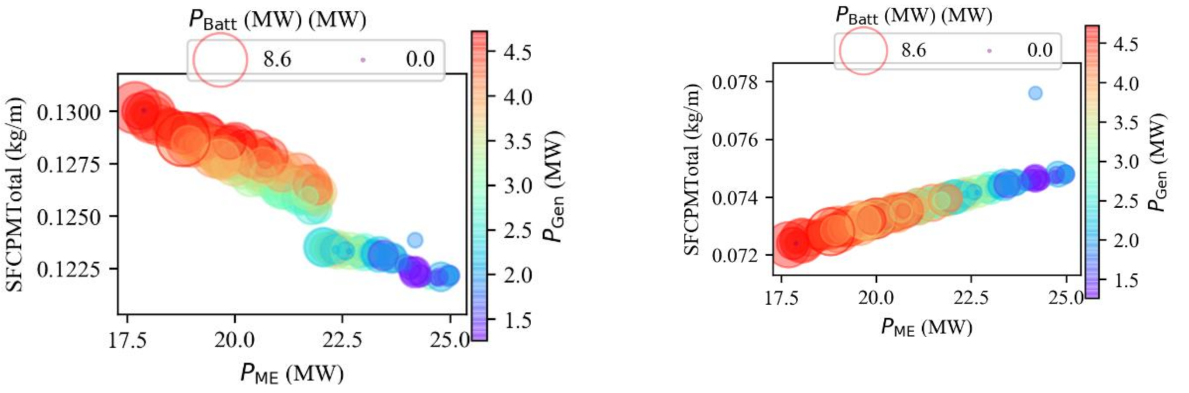
Further data visualization and analysis was performed on combination of design parameters with the system dynamic response and the vessel fuel consumption as shown in *Fig.13*. For this investigation, two sets of speeds at one weather condition was chosen [Vs 15 & 11 kts, Hs 1m]. This is also associated with discontinuities in experimental results in *Fig.13* [A & C]. In these cases, smaller main engine size is associated with higher SFCPM and lower RPM fluctuation. With reduction in vessel speed for the same environmental condition [B & D], results indicate that RPM fluctuation is rather constant for different values of P_{ME} and P_{Gen}, unless P_{Batt} is substantially reduced (small bubbles). Also, for this speed case and weather condition, fuel consumption is solely depending on P_{ME}. Note that the slopes for SFCPM for different speeds [C & D] are opposing each other. This is mainly because of the shape of the fuel consumption curve and the difference in the percentage load in two cases. In [C], the required propulsion power is higher than the main engines are highly loaded where the fuel consumption curve has positive slope. On the other hand, the required power is so low that the engine is loaded where the slope of fuel curve is negative. We can infer that the efficiency of the main engine is a main contributor to the overall system efficiency in a given ship design and the operation condition.

PBatt has rather low correlation values and does not exhibit any relation in the scatter plots with all important design parameters and objectives for this particular operational scenario. This means that it is safe to excluded PBatt from further parameter variation.



A) [Vs 15 kts, Hs 1m]

B) [Vs 11 kts, Hs 1m]



C) [Vs 15 kts, Hs 1m]

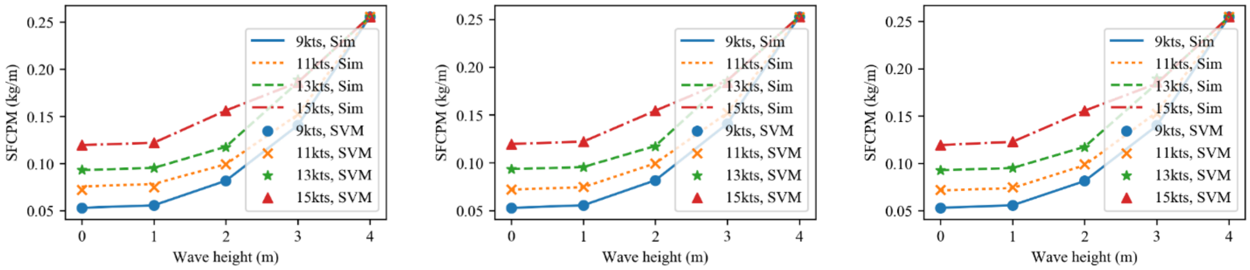
D) [Vs 11 kts, Hs 1m]

Fig.13: Bubble plots show relationship between 3 design parameters and 1 design objective. Parameters are SFCPM, PMe, PBat and generator rating.

Lastly, optimization results from the combined weather condition and vessel speed are presented in Table 6. Counterintuitively that case 3 where the vessel experience less severe weather and sails at the same speed benefits the most from the optimization. After the optimization, the obtained design parameters were verified against the high-fidelity simulation as presented in *Fig.14*. Results shows good agreement between higher fidelity simulation and trained SVM models.

Table VI. Results for stochastic optimization of machinery configuration based on the 3 scenarios

Scenario #	Base Results [kg/m]	HFS [kg/m]	SVM Optimization [kg/m]	Difference [%]	P_{ME} [MW]	P_{PTI} [MW]	P_{Gen} [MW]	P_{Batt} [MW]
1	0.1641	0.1631	0.1627	0.6094	24.93	1.884	1.802	1.079
2	0.1500	0.1491	0.1492	0.6000	24.41	2.375	1.641	1.266
3	0.1352	0.1334	0.1339	1.331	23.93	3.554	1.239	2.606



(a) Scenario 1 (b) Scenario 2 (c) Scenario 3

Fig.14: SVM prediction Vs simulation where SFCPM Vs Hs are displaced for different speeds. Results indicate very good agreement.

From optimization results performed on the metamodels in *Table VI.* for three weather scenarios, it was noted that scenario 3 has the highest potential of benefiting from finding the right design configuration with reasonable values of potential fuel savings. Also, this indicates that the trained metamodel is able to capture the behavior and fuel consumption of a complex system as a whole. Next stage is to include more degrees of freedom optimization routine from the vessel's hydrodynamic aspects such as propulsion system.

6. Conclusion

The study was set to examine the use of PIDO for hybrid marine power system design. Results indicate great potential to create a rapid design generation tool for testing multiple design alternative, sharing design constraints across subsystems and system boundaries, understanding parameters relationships between various subsystems and ultimately system level design improvements. However, unlike other aspects in ship design, hybrid marine power plant simulation is relatively new topic where tools are still developing. Therefore, after long period of testing the simulation tools for their robustness to optimization, eventually the right balance was found. Design automation and optimization has demonstrated great capability at finding many design alternatives, but well experienced engineers are needed to evaluate results as optimization algorithms work in a highly mechanistic fashion. Therefore, a combination of robust simulation tools and domain experience will assist greatly when using PIDO. Overall, DoE and RSMs demonstrated great capability of handling complex designs, decoding relationships between parameters, reducing computational cost from high fidelity multidomain models without compromising solution accuracy. Despite the design problem being highly constrained, it was possible to achieve relatively reasonable fuel saving and providing an understanding of the speed fluctuation in adverse weather conditions. Remaining work is to expand the optimization scope by including other design parameters from ship hydrodynamics and vessel operation.

Acknowledgements

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Annex A

Particulars of the Case Vessel and the Propulsion Plant

Propeller Geometry

Diameter (D) (m)	9.86
No of blades	4
Hub diameter (m)	1.53
Rotational speed (RPM)	95
A_e / A_0	0.431
(P/D)mean	0.47
Skew (°)	21.15
Rake (°)	0

Particulars of the electrical power plant

Number of generators	*2*
Capacity of each generator (kVA)	2000
Power factor of generator	0.9
RMS line-to-line voltage(V)	690
Number of switchboard	2
Mean hotel load during voyage (kW)	1000

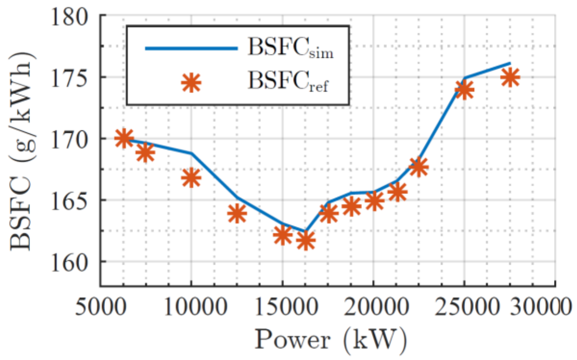

Fig.A-1: BSFC of the main engine

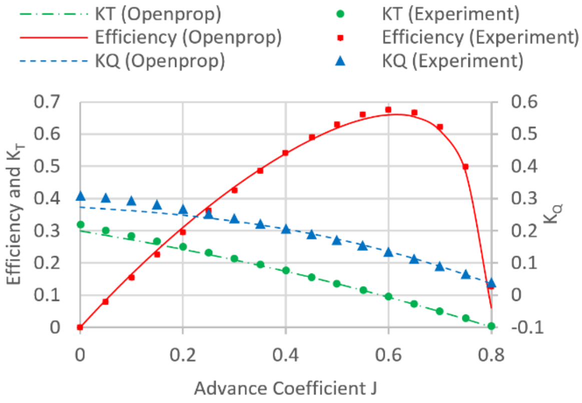

Fig.A-2: Propeller curve for the case vessel

Particulars of the main engine

Model	*Wartsila 8RT-flex68D*
Bore (mm)	680
Rated MCR (kW)	25,040
Speed at rated power (RPM)	95
Stroke (mm)	2720
Mean Effective Pressure (bar)	20
Number of cylinders	8
Turbocharger	2 x ABB A175-L35

Ship Particulars

Length beween perpendiculars (m)	320.0
Length at water line (m)	325.5
Breadth at water line (m)	58.0
Depth (m)	30.0
Draft (m)	20.8
Displacement (m^3)	312622
Block coefficient (C_B)	0.8098
Design Speed (m/s)	7.97

Specifications of the battery system

Energy capacity (MWh)	1.0
Maximum discharging current (kA)	5.6
Maximum charging current (kA)	5.6
Nominal voltage (V)	360

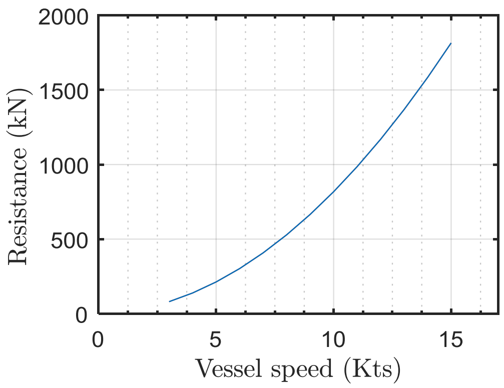

Fig.A-3: Resistance curve for the case vessel

Predictive Engineering Analytics for Shipbuilding - An Overview

Bart Van Lierde, Siemens PLM Software, Leuven/Belgium, bart.vanlierde@siemens.com
Wim Cardoen, Siemens PLM Software, Leuven/Belgium, wim.cardoen@siemens.com
Dejan Radosavljevic, Siemens PLM Software, London/UK, dejan.radosavljevic@siemens.com

Abstract

Modern ships operate increasingly autonomous through strongly interacting subsystems. Designing such ships requires an efficient development approach that can consider the mutual interaction between subsystems and the inherent multi-disciplinarity. Moreover, the overall vessel behaviour still needs to be optimal. Product design and use need to be coupled, requiring traceability through a performant data management system that spans the entire product lifecycle. Predictive Engineering Analytics combines engineering simulation and testing with intelligent data analytics, to develop digital twins that can predict real product behaviour throughout the entire lifecycle. This will help shipbuilders develop and maintain complex vessels faster and better.

1. Introduction

Modern ships operate increasingly autonomous through strongly interacting subsystems. These systems may be dedicated to a specific, primary objective of the vessel (such as special purpose, naval and more) or may be part of the general essential ship operations. Between them, they exchange sensor data and make coordinated operational decisions, ideally without any user interaction.

Designing such ships is complex, and requires an efficient development approach that can consider the mutual interaction between subsystems and the inherent multi-disciplinarity from the very beginning. Scalable simulation technologies must take the lead in this process. Whereas in the shipbuilding industry, virtual modelling was for a long time limited to point solutions for specific problems such as hydrodynamics and mechanics, it now must be applied on a much broader scale and drive development.

On top of that, the design of such ships doesn't stop after delivery. Through software updates or because of maintenance, subsystems can change. But the overall behaviour of the entire vessel still needs to be optimal. To make sure of that, product design and product use need to be coupled. That requires traceability through a performant data management system that spans the entire product lifecycle.

To deal with these challenges, Siemens PLM Software presents predictive engineering analytics (PEA). PEA combines engineering simulation and testing with intelligent reporting and data analytics, to develop digital twins that can predict real product behaviour throughout the entire lifecycle. This will help shipbuilders develop and maintain complex vessels faster and with greater confidence.

2. Industry challenges and research trends

In response of today's environmental and business challenges, companies across all manufacturing industries are coming up with increasingly sophisticated products. These are conceived by applying new design methods, new materials, combine mechanics with software, electronics and controls, behave multi-physical and include intelligent systems. The development, creation and maintenance of such products requires all stakeholders to dramatically change the way they do engineering. Digitalization will play a crucial role in this. The application of new digital technologies will at the same time enable a broad range of new product capabilities as well as disrupt how manufacturers work in order to deliver them. For transportation industries, many innovations have their origins in sectors with huge research and development (R&D) budgets, such as aerospace and automotive. But they could easily find their ways to the others. The marine industry cannot afford to lag behind. The industry challenges are similar, and so are the engineering trends and solutions to deal with them.

2.1. Increased pressure on energy efficiency and fuel economy

Together with safety and reliability, improved fleet performance and fuel economy are without question the most function-critical design aspects for marine products. Not in the least because they directly result in measureable economic added value for fleet owners and operators. But in addition to these commercial aspects, public interests play a role.

The pressure we put on our planet is huge. In response to the entry into force of the Paris Agreement on Climate Change, International Maritime Organization (IMO) regulations concerning emissions and fuel efficiency have become stricter. Authorities have committed to numbers and percentages, and are now counting on the industries to come up with innovations to make these happen. And as the entire marine sector consumes the equivalent energy of a small country, it plays a significant role in this matter. Showing social corporate responsibility (SCR) is becoming a must for companies that wish to secure their future.

All new ships since 1st January 2013 have to be designed in accordance with IMO set EEDI (Energy Efficiency Design Index). And all ships of 400 gross tonnage (gt) or more need to have an International Energy Efficiency Certificate (IEEC). This requires for example a Ship Energy Efficiency Management Plan (SEEMP) on board, incorporating best practices for fuel efficient operation of ships, such as speed management throughout a voyage.

Speed management comes down to finding the best balance between vessel speed and fuel consumption, taking into account operating environmental conditions such as the weather, sea state and scheduling requirements. All this just to stress the importance of the topic.

It is clear that requirements like these make energy efficiency and fuel economy top priorities for ship design. A good holistic vessel solution will need to have the most efficient individual components work together as an integrated system in an optimal way.

2.1.1. New powering methods for propulsion systems

Modern ship designers and builders put huge efforts in exploring new ways to generate energy, both on new vessels and for modernization of the current fleets. The typical large gas and diesel engines are being replaced by electrical and hybrid solutions. And companies also investigate how to make optimal use of natural resources like the sun or the wind on board.

Examples of new propulsion technologies are already in operation. In Norway for example, between Lavik and Oppedal, a fully electric ferry with a capacity for 360 passengers and 120 vehicles crosses the Sognefjord 34 times a day. On board, Siemens installed its BlueDrive PlusC system. It includes a battery and steering system, thruster control for the propellers, an energy management system and an integrated alarm system.

These types of intelligent systems combine mechanics with software, electronics and controls, and become increasingly important to make sure the complete vessel propulsion as multi-physical system performs in an optimal way. They obviously present a challenge during design, as they require simultaneous optimization of various subsystems and their interaction starting from the very early stage of concept design.

In future, new digital technologies will take the application of such systems to the next level. New sensor types or more precise ones, more powerful microprocessors, better algorithms, data mining capabilities and more will change the industry. These will allow intelligent systems to constantly improve, also after delivery, through updates. This will completely change the way shipbuilders work, as it will require a strong link between design and vessels in operation.

2.1.2. Optimizing performance of the vessel

Performance greatly depends on the fluid-structure interaction (FSI) of the entire vessel. Noise and vibration as well as durability are also largely impacted by how smooth a vessel can advance and for example how well peak loads on the propellers can be avoided. Optimizing this multi-domain behaviour should capture all operational aspects and should be conducted at various scales, from smallest component or equipment level, via various subsystem and system levels to a fully integrated holistic view on the entire vessel. Indeed, full ship-level FSI simulations should become a mainstream activity. And these should include real operating conditions. Doing so should eliminate the uncertainties related to the extrapolation of model-scale measurements, and allow finding the best design for a particular operating envelope. This will enable designers to achieve the most efficient design with the lowest environmental impact while satisfying a full range of often contradictory requirements.

Using real conditions at sea for behavioural prediction should also allow engineers to look much more accurately at extreme loading conditions. This will reduce uncertainties and improve the structural design and safety. Linking to this, it should allow better design of control systems to let them give the best possible response to these extreme conditions. As ships evolve towards ever more autonomy and less human interaction, this will become critical for future safe operation.

Ultimately, to really fully exploit the strength of such full-scale, multi-domain simulations, it should be possible to run hundreds of them at a time, in an automated way, to find the best compromise in design trade-off. Such a capability, which is called design exploration, will allow engineers to use their time and experience for selecting the best parameters for optimal vessel performance rather than for building simulation models, testing whether they work and starting all over again when the smallest design change is introduced.

Such multi-domain and automated vessel performance optimization will require a solid software infrastructure with powerful simulation tools that can handle for example hydrodynamics along with other physics such as structural integrity and acoustics. Even though some applications already reached sufficient maturity to be part of standard development processes, simulation technologies will still need to evolve during the coming decades to really reach digital design space exploration to its full extent.

2.1.3. Using new materials to reduce weight

The types of materials that are being used in the marine industry are rather diverse. Even though the main requirements, being strong, light and easy to maintain, are clear and common to all, the applicability of certain materials heavily depends on the vessel type, size and use. Nevertheless, there is a clear trend to try and reduce weight (and thus the payload) in view of energy efficiency by using new materials, of course without jeopardizing other priorities such as stability, manufacturability and reparability.

Composite materials are already widely used in recreational and commercial boat building, and gradually start to find their ways into the larger vessels like bulk carriers and containerships. The advantages of composites are many, including lighter weight, tailored layup for optimum strength and stiffness, improved fatigue life and corrosion resistance.

Fully composite large vessels will probably not be the standard as of tomorrow, but it can be expected that the amount of composite parts will dramatically increase in the near future. This will have a big impact on many engineering aspects: on design and development, on manufacturing, on maintenance, and on the relation between all of these phases of the product lifecycle.

2.2. Adding value to the entire lifecycle

Another major challenge is related to the economic reality of the marine business. Equipment orders are usually large investments that leave little margin after price negotiation. On top of that, late delivery can lead to expensive penalties. It is critical for business success to have effective processes to turn the demand into delivered products. This on itself already puts big pressure on product development and manufacturing.

Besides, the shipping business is cyclic. Recessions usually result in a business slowdown, which comes down to declined new vessel order rates and reduced maintenance, repair and operations expenditures. To remain successful in such a harsh economic environment, shipbuilders must come up with extreme value for money and with innovations that bring value to the fleet owners over the entire product lifecycle.

This is where digital technologies that allow analytics on big data, advanced automation and smart applications show enormous potential. In future, shipbuilders will offer fleet owners more than 'just' a vessel, but rather a complete solution that allows them to manage their fleet efficiently and safely. The development of a ship then won't stop after delivery, but will continue while in operation.

2.2.1. Condition-based maintenance

One of such applications will be the ability to schedule maintenance on equipment based on measured physical condition rather than on clock, calendar or runtime meters. This philosophy is called condition-based maintenance (CBM), and will bring fleet owners a significant amount of cost savings, as safety margins can dramatically be reduced. It will also allow to apply maintenance in a more targeted manner, focusing on the root causes of potential failures.

Applying CBM could be automated by collecting data from sensors inside the vessel to continuously monitor equipment performance, and sending it to an onshore center. Here, the data could be analyzed, used for simulations or compared to statistics. Based on analysis, maintenance could then be scheduled. This process will maximize the useful life and reduce cost by avoiding early replacement of functional components.

2.2.2. Autonomous vessels

The ultimate goal of such applications would be the fully autonomous vessel that can monitor and report on its own health, can gather information from its environment and use this information to make autonomous decisions such as navigating safely and avoiding collisions. Even though big steps still need to be taken to make this real, not in the least on the regulatory or legal side, this is most probably the direction in which the shipbuilding industry will be going during the coming decades.

In fact, on the technology side, most components are already more or less available. The question is rather how to combine various sensor technologies with operating and climatic conditions of a maritime environment? Or how to program the interpretation of maritime regulations in the control algorithms? And how to guarantee safe connectivity to and communication with a land based system at any time, from anywhere?

2.2.3. A changing vision on doing business

Such innovations will change the entire marine business landscape during the coming decades. Design engineers will need to stay much closer connected to the vessel after commissioning to follow-up on monitoring, maintenance and updates. Shipbuilders will develop their products from a completely new angle, making decisions based on an integrated view that spans the entire product.

Being able to deliver such lifecycle spanning solutions will require a different approach to engineering. A product sale will no longer be the primary and ultimate achievement, but rather the beginning of a long-term relationship. And in a market, that is typically limited to a finite set of customers, and where incidents can have huge consequences, there will be little room for failure. To be successful, shipbuilders must deploy watertight processes, first of all to bring their complex products to market effectively, and secondly track if the functioning of all vessels meets the requirements cradle-to-grave.

They will need to collect, manage and analyse huge amounts of data that lets them continuously improve their vessels and define the most effective, individualized plans that embrace development, manufacturing and operation/maintenance.

3. The Digital Twin paradigm

A way to deal with all these development challenges and deliver such lifecycle-spanning innovations, is to build a set of highly accurate models that help predict individual vessel behaviour during all lifecycle phases. These models, which as a collection are called 'the Digital Twin', come in multiple scales and instances for various applications, integrate multiple physical aspects, contain the best available physical descriptions and mirror the life of the real vessel, its manufacturing process and operation.

The ideal Digital Twin tracks information on all parameters that define how each individual vessel behaves over its entire useful life, including the initial design and further refinement, manufacturing-related deviations, modifications, uncertainties, updates as well as sensor data from on-board systems, maintenance history and all available historical and fleet data obtained using data mining. Using processes that involve a Digital Twin for marine engineering could present various advantages.

3.1. Reducing development time and production cost

The design of a vessel comes down to creating a solution that satisfies various, often conflicting, requirements. As many behavioural aspects and their mutual interaction need to be considered, there is no room for endless trial and error. Shipbuilders need a process that leads to the best possible solution from the first attempt. By providing an integrated view on the vessel's various physical and behavioural aspects, a true Digital Twin will allow simultaneous optimization of all functional performance requirements throughout the entire development cycle, from early concept to detailed engineering and commissioning. This will avoid several test-and-repair loops and greatly reduce the time that is required to have a vessel ready for delivery. Instead of having the physical world validating the digital world, the digital world will be defining the physical world, which is a great strategic shift with respect to the role of simulation. Whereas the industry already largely adopted simulation for validating exiting designs, troubleshooting design flaws, or predicting performance of a design in place of (or at least partially in place of) physical testing, most companies now look for capabilities where simulation is leveraged to digitally explore the design space with the purpose of realizing better vessels while achieving much higher returns. Fig.1 shows how innovative companies can add value to their products by implementing a Digital Twin vision, and assigning a new role to simulation.

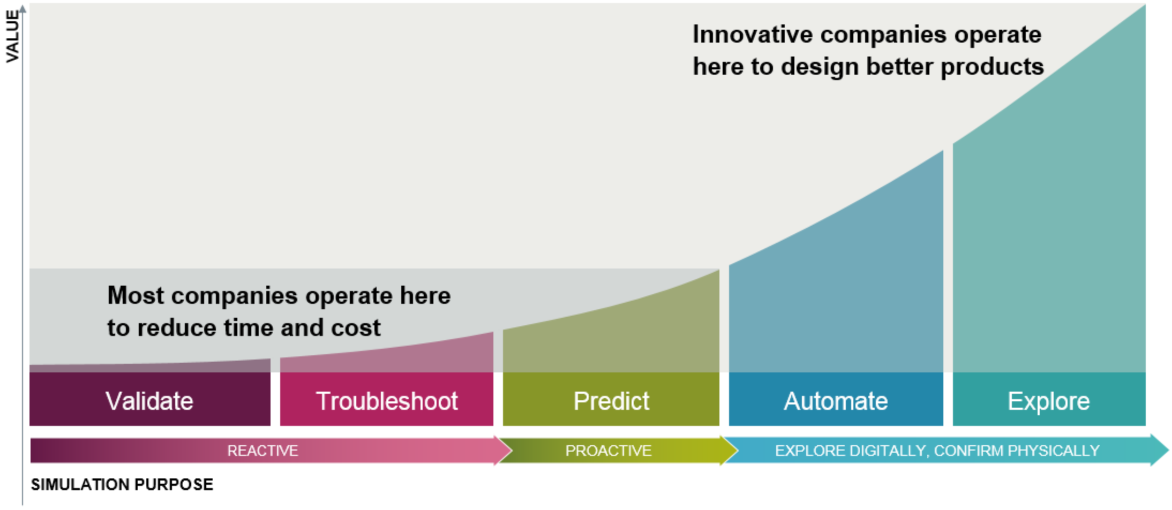

Fig.1: Digital Twin vision

3.2. Reducing risk and improving performance by prediction

The ideal Digital Twin could include all the required information to continuously verify and forecast the vessel's performance and health, or the remaining useful life. It could also predict system response to safety critical events and uncover previously unknown issues before they become critical by comparing predicted and actual responses. An ultimate goal could be that systems on board of the Digital Twin would be capable of mitigating damage or degradation autonomously. They could activate self-healing mechanisms and thereby increase the vessel's life span. Or they could suggests updates of intelligent systems to improve performance and reduce fuel consumption.

3.3. Reducing product and operational cost

The standard approach in vessel design is to assume appropriately severe operational conditions and subsequent usage, as well as rather large safety factors to account for deviations during the manufacturing process. Such an approach is very conservative and leads to vessels that may be heavier than they should be and require more frequent inspections than necessary. Thanks to the precision of the available models, using a Digital Twin could reduce design tolerances, manufacturing uncertainties and stochastic variabilities of vessel operation. This could result in a huge cost reduction in every respect, including the use of materials during manufacturing, fuel consumption as well as a better plan for inspection and maintenance.

3.4. Challenges to develop a Digital Twin to full extent

There is no such thing as a clear-cut and closing definition of a Digital Twin. It is rather a vision, a term that refers to the linking of all activities related to advanced simulation and prediction and their integration over the product lifecycle. If well-conceived, the Digital Twin should bring clear advantages to product development, manufacturing and after delivery. But the extent to which the concept is deployed still depends on what a company can or wants to do, and on what technologies are capable of. In the marine industry, a lot of work still needs to be done in the coming decades, even though various applications are already there. The industry looks forward to new methods and developments, especially in the fields of modeling realism, computation speed, data management and the integration between various activities that will enlarge the current scope of the Digital Twin.

3.4.1 Modelling realism

Current simulation processes are often still too separated. For example, there can be a computational fluid dynamics (CFD) model, a structural model, a stress analysis model and fatigue cracking model. And those can all be quite accurate for their specific use. But in reality, these physics are tightly coupled and that needs to be reflected in the Digital Twin. Ship designers and builders must invest more in developing parametrized multi-disciplinary models of their vessels. They should include all physics in a single, unified simulation model that also includes controls, and that tightly couples various disciplines. Ideally, these models come in various scales to allow both very detailed and very fast analysis, for some applications even real-time.

A lot of research should be done on simulating the implications of using new materials and manufacturing methods as well. Advanced modelling technologies should be able to capture the related micro-structural behaviour. And as this varies for every product depending on the individual manufacturing process and use history, the related parameters should be kept up-to-date for every individual product over the entire lifecycle. And finally also the loading and boundary conditions should become a lot more realistic than it is today. New FSI calculation methods and especially data measured on real structures should help to prevent over-dimensioning of new designs and allow better damage prediction. To successfully use a Digital Twin, it will not be sufficient to consult empirical load databases. The Digital Twin should experience exactly the same as the real structure, including transient events.

3.4.2 Calculation speed

While over the last decades computation technologies have really taken a flight, full-scale models that include all geometrical and physical details of entire vessels are still a pain. Simulations that involve tens of millions of degrees-of-freedom (DOFs) or cells require very smart solution schemes and solver algorithms, as well as very powerful high-performance computing hardware. And still, for a true Digital Twin that also includes fully coupled multi-physical behaviour, tens of millions of DOFs or cells are not enough. All transportation industries count on both simulation software companies and computer system manufacturers to join forces and come up with revolutionary improvements that will lead to an exponential increase of capabilities. In the coming decades, new modelling methods combined with exascale computing systems should allow simulations to stay ahead of the actual product use and enable true model-based prediction and decision-making

3.4.3 Data management

The Digital Twin concept requires a strong connection between all models that are used during the entire product lifecycle. Only a true digital thread can for example allow using the same 3D solid models from design to manufacturing for numerically controlled programming, tracking parameter changes for individual products during manufacturing and operation, or enable products in the field to provide feedback to design and engineering teams. In practice, this means that an enormous amount of data needs to be around for decades, constantly has to be updated and needs to be accessible for a large number of different user profiles, located around the globe and often even spread over various companies. To create and maintain a Digital Twin, ship designers and builders will need to deploy large data storage infrastructure, powered by a very robust data management system.

4. Siemens PLM Software solutions for Digital Twin

As a world-leading provider of product lifecycle management solutions, Siemens PLM Software helps thousands of companies across various industries and around the globe realize innovation by optimizing their processes, from planning and development through manufacturing, production and support. Converting the Digital Twin vision into an infrastructure with concrete solutions naturally fits these activities. Siemens PLM Software clearly displays the intent of being able to offer ship designers and builders the most comprehensive possible and state of the art solution set to build and maintain a Digital Twin. This manifests itself in acquisitions of companies that cover missing pieces and in ambitious development plans for more realistic simulation, accurate testing and powerful data management applications, as well as the integration between those.

4.1. Building a Digital Twin during product development

Siemens PLM Software offers manufacturers a holistic set of methods and technologies to support them during the entire development cycle and help them deliver innovations for complex products faster and with greater confidence. Such a collection of solutions will allow ship designers and builders to implement the Digital Twin philosophy, follow a more efficient design and commissioning process and reduce the acquisition cost for their customers.

4.1.1. Predict real product behavior

With this comprehensive offering, Siemens wants to let the traditional development process evolve to a new, predictive approach for systems-driven product development, called predictive engineering analytics (PEA). In essence, PEA combines the application of multidisciplinary simulation and test with intelligent reporting and data analytics in an integrated workflow with the ambition to build a Digital Twin. PEA achieves higher modeling realism and simulation performance by removing the boundaries between various development stakeholders. It integrates technologies such as 1D simulation, 3D computer-aided engineering (CAE) including computational solid mechanics (CSM), finite element analysis (FEA), computational fluid dynamics (CFD) and multibody dynamics, controls, physical testing, visualization, multidisciplinary design exploration, and data analytics in a managed context. Siemens has bundled all its solutions that underpin this vision in Simcenter™. This solutions portfolio combines decades of experience by putting well-known products such as LMS Test.Lab, LMS Imagine.Lab, NX Nastran, Femap, STAR-CCM+, Heeds and more under one umbrella. And it features Simcenter 3D as the combined successor of NX CAE, LMS Virtual.Lab and LMS Samtech. Besides these tools, PEA is also about a good alignment of processes. The following sections describe the essentials for a successful implementation of a PEA approach.

4.1.2. Deploying closed-loop systems-driven product development

PEA supports closed-loop systems-driven product development, the fastest path to turn a set of requirements into a vessel. In this multi-disciplinary simulation-based approach, the global vessel design is considered as a collection of mutually interacting subsystems from the very beginning. From the very early stages on, selected architectures are virtually tested for all critical functional performance aspects simultaneously. These simulations use scalable modeling techniques, so that components can be refined once the vessel configuration is defined and as data becomes available. This comes down to creating a Digital Twin starting from the concept stage and gradually adding details. Closing the loop refers in this context to concurrent development of mechanics with controls.

4.1.3. Increased use of 1D multi-physics system simulation

1D system simulation, also referred to as 1D CAE or mechatronics system simulation, allows scalable modeling of multi-domain systems. The full system is presented in a schematic way, by connecting validated analytical modeling blocks of electrical, hydraulic, pneumatic and mechanical subsystems (including control systems). It helps engineers predict the behavior of concept designs of complex mechatronics, either transient or steady-state. Manufacturers often have validated libraries available that contain predefined components for different physical domains. Or Simcenter also contains a complete set for various applications. Using those, the engineers can do concept performance predictions very early, even before any computer-aided design (CAD) geometry is available. During later stages, parameters can then be adapted. 1D system simulation calculations are very efficient. The components are analytically defined, and have input and output ports. Causality is created by connecting inputs of a component to outputs of another one (and vice versa). Models can have various degrees of complexity, and can reach very high accuracy as they evolve. Because of their inherent multi-physical nature, their scalability, their ability to become highly accurate and their outstanding computational performance, 1D system simulation models are excellent and versatile components of a Digital Twin. Some model versions may allow real-time simulation, which is particularly useful during control systems development. Or later in the product lifecycle, as part of built-in predictive functionality inside the product.

4.1.4. Multi-discipline 3D simulation technologies

3D CAE models can account for additional phenomena that naturally relate to 3D physics aspects, and typically become highly detailed, computationally intensive representations that are usually very application-specific. Over the last decades, various 3D CAE technologies have proved their value by speeding up development and avoiding late-stage changes. Within a Digital Twin vision however, 3D CAE will need to gain realism and performance, and be capable of pro-actively driving the decision-making process more than today. In current research, big efforts are being spent in making revolutionary improvements in this field. A lot of new capabilities arise on modeling, process and solver side. And many more are expected to come in the near future. Simcenter features the state of the art for every individual application, and bundles solutions for various functional performance aspects in a common platform to facilitate multi-discipline analysis. It also captures industry knowledge and best practices in application verticals. Simcenter includes very dedicated 3D solutions such as high-end CFD, structural analysis, powerful acoustics, fatigue crack propagation modeling, composite analysis and many more.

4.1.5. Strongly coupled 1D simulation, 3D simulation and controls engineering

As closed-loop systems-driven product development requires concurrent development of the entire multi-physical system, including controls, the processes for 1D simulation, 3D simulation and control algorithm development must be very well aligned. To achieve this, Simcenter offers various co-simulation capabilities for Model in the Loop (MiL), Software-in-the-Loop (SiL) and Hardware-in-the-Loop (HiL) simulations that combine various versions or scales of Digital Twin models in a coupled analysis.

4.1.6. Combined simulation and physical testing

Working with a Digital Twin does not mean replacing physical testing completely by simulation during vessel development. First of all because final certification still relies on sea trials. It will even become more complex and time-consuming with all these multi-physics and controls involved. And secondly, because lots of additional testing tasks will be required to reach the desired model realism, both during development and after delivery. To successfully create and maintain a Digital Twin, test and simulation engineers should collaborate and reinforce each other. Simcenter uniquely brings together a complete series of physical testing applications and a comprehensive set of simulation solutions in a common framework. This facilitates collaboration and data exchange between two traditionally very distinct engineering domains. On both sides, engineers will see lots of benefits. Test engineers can use simulation results to become more effective, whereas simulation engineers will have access to lots of data to validate and improve their models.

- **Use simulation for more efficient certification testing**
  As the number of parameters and their mutual interaction explodes in vessels that include control systems, efficiency is key during certification testing, both in terms of instrumentation and definition of critical test cases. Simulation can help to analyse upfront which locations and parameters can be more effective to measure a certain objective. And it also allows to investigate the coupling between certain parameters, so that the amount of sensors and required test conditions can be minimized. On top of that, simulation can be used as an observation tool to derive certain parameters that cannot be measured directly. Here again, a close alignment between simulation and testing activities is a must. Both 1D and 3D simulation models can give access to many parameters that cannot directly reached with sensors. In fact, that is a huge advantage of using a Digital Twin for product development.

- **Increase realism of simulation models using test input**
  Modal testing has for decades been a useful method to help improve structural finite element models via correlation analysis and model updating. It greatly contributed to the success of for example structural dynamics, vibro-acoustics and fatigue simulation analyses on mechanical structures, and will continue doing so in the decades to come. Within the Digital Twin story, modal testing will remain important, in particular for component validation. In addition to that, the required fidelity of Digital Twin models calls for much more test-based validation and input. Measurements also need to be capable of improving 3D CFD and 1D multi-physics models for example. And they have to help defining realistic boundary conditions, loads and all kinds of simulation parameters. In the Digital Twin context, a whole range of new testing capabilities (some modal-based, some not) will become essential for success.

- **Create hybrid models that combine test with simulation**
  Test results can even replace entire components during simulation. Complex products are usually combinations of subsystems which are not necessarily concurrently developed. As the Digital Twin always strives for the best possible combination of accuracy and performance, it can be beneficial during various development stages to create hybrid setups that include hardware, simulation and test models. This will obviously require dedicated technologies as well as a very good alignment between simulation (both 1D and 3D) and physical testing.

4.2. Maintaining the digital twin after delivery

To fully exploit the capabilities of the Digital Twin once the vessel is out in operation, and involve it in future applications such as activating self-healing mechanisms, pro-active damage control and history-based updating of intelligent systems, all parameters that define the complete behaviour should be traceable and kept in-sync. This will require a very powerful data management system that spans the entire product lifecycle. Nowadays, damage findings, repairs, replacements and modifications, if they are recorded at all, are usually maintained in an environment separate from the analysis models and in a totally different format. Using a Digital Twin will provide a visual database that directly displays both the analysis models and the physical vessel. This allows accurate life prediction, configuration control as well as better maintenance planning for every individual product.

4.2.1. Install a data infrastructure that connects all product lifecycle stakeholders

Teamcenter from Siemens PLM Software helps manufacturers share designs, documents, analysis and testing data, bills of materials, sensor data, maintenance reports and more within their organization, and with suppliers and partners. With Teamcenter, companies can standardize workflows and effectively manage the entire lifecycle of individual products by providing all stakeholders role-specific access to synchronized information.

4.2.2. Close the loop between design and product use

By connecting Teamcenter to Simcenter as its underlying data management system, a work that will be completed in the future, Siemens will be removing the boundaries that exist between design and the vessel life after delivery. This will transform vessel development from a process that delivers discrete units into a continuous process that keeps track of individual vessels and constantly updates them until end of life. That will allow applications that exploit the Digital Twin to its full extent. In such a process, sensors on the real product can easily feedback information to the development team. This will allow engineers to make predictions and plan updates or maintenance. They can decide to replace parts or components. Or they can use all this information as improved starting parameters or boundary conditions when working on a new project.

5. The Digital Twin today

Even though both tools as well as their mutual integration still have to evolve to exploit a Digital Twin to its full potential, many examples of successful applications already exist. State of the art technology today offers already the capabilities for a fundamental shift in the approach to design. A nice example is a case of energy saving by optimizing flow using a dedicated device, and involving both propeller and hull interaction. Becker Marine Systems designs and builds energy savings devices for marine vessels. One type of device is shown in Fig.2. It is the Mewis Duct, which is basically a flow-directing device positioned near the propeller.

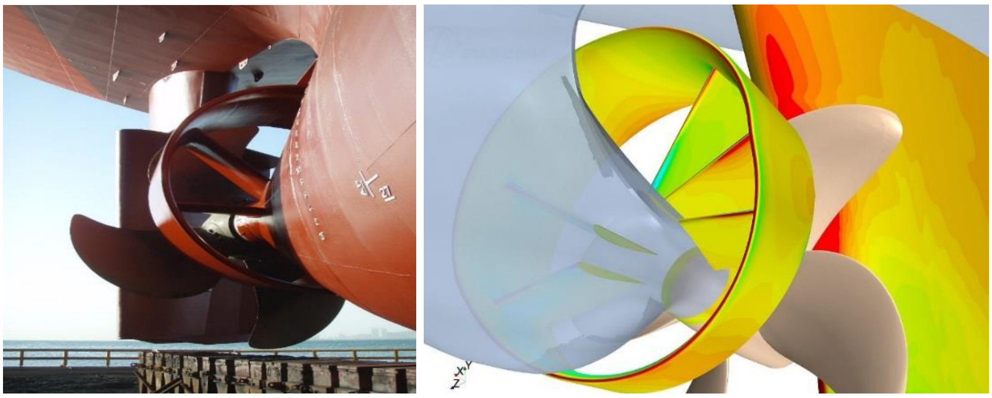

Fig.2: Mewis duct

Crucial to the success of this Becker Marine's product is to develop a particular shape of duct and fins that provides the most energy savings, which depends on both the hull geometry and the propeller. In order to do so, the engineers have created a process to calculate the flow field around the hull and propeller. Then they automated this process to explore the design space varying 40 design parameters that define the duct and fin geometry. They finally achieve a guaranteed 4.5% improvement in fuel savings, with a project turnaround time of only 6 weeks. This is just one example of how accurate simulation based on a holistic view that includes various subsystems can add value to a design, and via fuel savings, to the entire vessel lifecycle.

6. Conclusion

The objective of this paper was to demonstrate how a Digital Twin vision can provide an answer to today's environmental and business challenges in the marine industry, and to the transformation vessel designs will undergo in the decades to come. Even though both computational technologies and infrastructure still need to evolve to reach a state in which they can fully support all applications the ideal Digital Twin could allow for, state of the art solutions already bring lots of value in many aspects. Siemens PLM Software is collecting all the pieces to put the Digital Twin puzzle together. By combining product lifecycle management software, 1D system simulation, 3D CAE as well as physical testing, Siemens has a holistic offering for Digital Twin. During the coming years, further work will be invested in both integration between tools and extension and improvement of the individual applications.

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Expanding the Scope of Early Stage Computer Aided Ship Design

Rachel Pawling, UCL, London/UK, r.pawling@ucl.ac.uk
Nikolaos Kouriampalis, UCL, London/UK, n.kouriampalis.11@ucl.ac.uk
Syavash Esbati, UCL, London/UK, syavash.esbati.09@ucl.ac.uk
Nick Bradbeer, UCL, London/UK, n.bradbeer@ucl.ac.uk
David Andrews, UCL, London/UK, d.andrews@ucl.ac.uk

Abstract

Previous papers by the authors have described the need for more holistic approaches to the early stage design of ships, incorporating a wider range of aspects. This paper provides an overview of some ongoing PhD projects in the UCL Marine Research Group (MRG) to use ubiquitous desktop computers to apply methods from outside traditional Naval Architecture to further expand the range of ship design and performance aspects that can be addressed in early stage design by the widest range of practitioners. These include queuing theory, real options theory, on-line tools and Virtual Reality. Possible impacts on ship design education are briefly discussed.

1. Introduction

The Marine Research Group (MRG) is a subdivision of the Department of Mechanical Engineering at UCL (https://www.ucl.ac.uk/mecheng/research/marine). The MRG has a range of research interests in the areas of Naval Architecture and Marine Engineering, including computer aided preliminary ship design, and the use of computers in design education. The latter is related to the Department's MSc courses in both Naval Architecture and Marine Engineering. MRG interests encompass the use of high-performance computing (generally for CFD), but, primarily driven by both teaching requirements and involvement in ship design consultancies, there is a strong interest in methods and tools that can be widely deployed using desktop hardware.

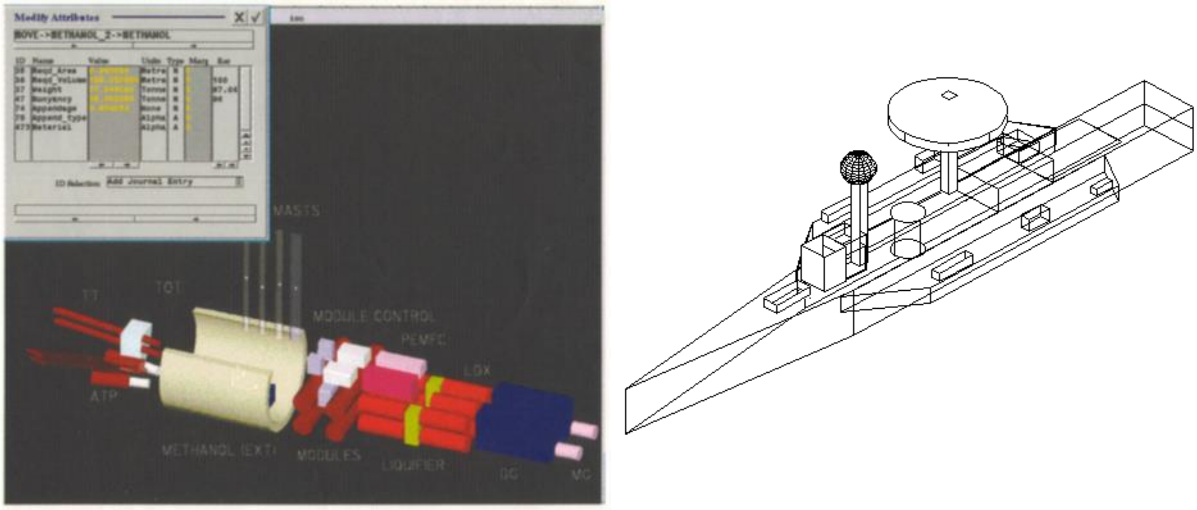
Computers have found application in all stages of ship design, and ship design has adopted a wide range of modelling and analysis approaches from other domains to solve the many decision making, design and engineering problems encountered in the design process. Some technologies are seeing increasingly wider application, such as CFD, *Bertram and Peric (2013*) or genetic algorithms for use in early stage design, *Burger and Horner (2011*), but still require some degree of dedicated computing hardware (or time) to use. The ongoing development of ubiquitous desktop computers has made other approaches far more accessible at the day-to-day level.

One example of this is the application of network science and analysis, first applied to ship design via bespoke research software by *MacCallum* (*1982*) but now incorporated in free software tools, such as nodeXL (http://research.microsoft.com/en-us/projects/nodexl/*)* and Pajek, *Mrvar (2016*). *Pawling et al. (2015,2016)* describe the UCL application of network approaches to problems such as: understanding drivers in databases of expert ship layout preferences (inspired by *Gillespie* (*2012)*); elucidating early stage ship sizing model structures; and internal blast vulnerability analysis. The combination of these readily available tools and the low computing overheads, required by network analysis, offers the potential to widely use this for ship design approaches incorporating network science.

2. Architecturally Centred Ship Design tools for Research and Education

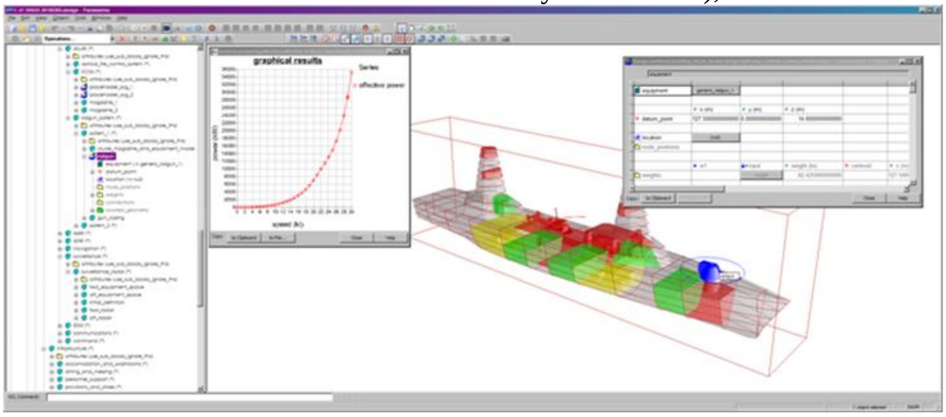
Previous papers by the authors have described the need for more holistic approaches to the early stage design of ships, incorporating a wider range of aspects than straightforward numerical performance analyses. This is particularly the case for complex service vessels, such as warships, survey ships and vessels associated with offshore infrastructures. One key aspect of such a holistic approach is the architecture or configuration of a ship and the fifth author proposed an approach, later termed the Design Building Block approach (DBBa) to address this in early stage design, *Andrews (1986*). This combines a flexible, interactive configurational model of the ship with numerical naval architectural analysis tools to ensure technical balance, while enabling innovative exploration during the formative design evolution. Demonstrated in PhD research, *Andrews and Dicks (1997)*, the Design Building Block approach was subsequently implemented as “SURFCON” within QinetiQ’s Paramarine Preliminary Ship Design System *Andrews and Pawling (2003)*.

The development of this architectural approach, and in particular the interactive graphical interface, has primarily been enabled by developments in consumer desktop computers and graphics cards. The earliest tools with Graphical User Interfaces (GUI) required expensive, specialist hardware, limiting their application, *Tan and Bligh (1998)*, *Yuille (1978)*. The DBBa was itself first implemented in a semi-bespoke software and hardware environment as the UK MoD SUBCON tool, *Andrews et al. (1996)* – shown in Fig.1a, then six years later a demonstrator for a surface ship application SURFCON was developed using a combination of commercial CAD tools, *Andrews and Dicks (1997)*, and a (then) high-end desktop PC, Fig.1b. Its latest implementation in Paramarine, Fig.1c, can be used on even low-specification Windows tablet PCs.



(a) SUBCON user interface, Andrews et al. (1996)

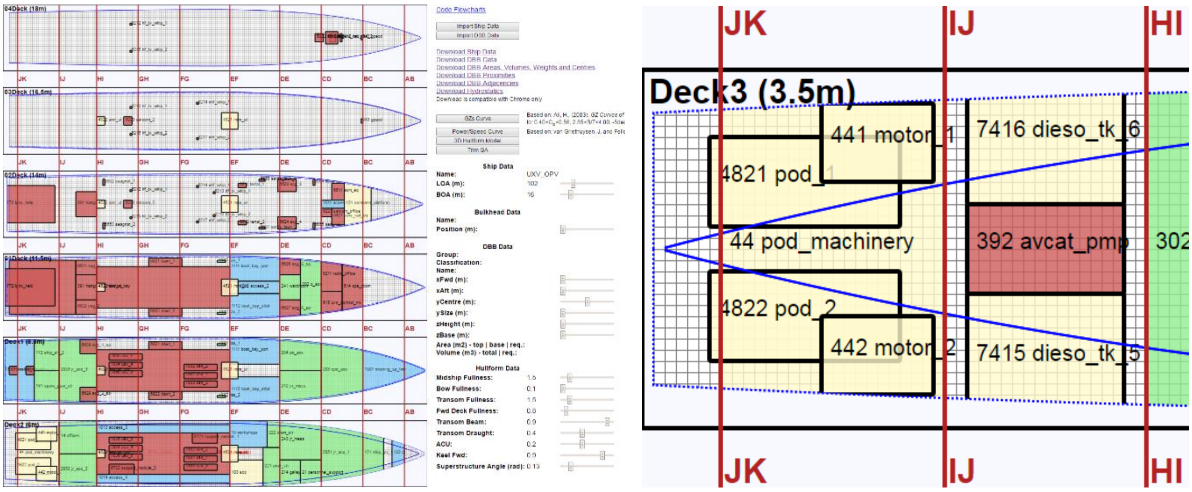
(b) SURFandON demonstrator GUI (upperdeck layout and EMI), *Andrews and Dicks (1997)*



(c) Paramarine implementation of the Design Building Block approach
Fig.1: Three figures showing the development of the DBBa GUI

Although Paramarine integration allowed the DBBa to make use of a highly capable naval architectural modelling and analysis package, it has been found that this high-fidelity, high-capability tool is not always appropriate for early stage design, and for teaching purposes, as described by *Pawling et al.* (*2015*). The Paramarine implementation is within a CAD GUI and modelling paradigm that offer great flexibility for ship design tasks, but can be overwhelming for new users. To address this, and additionally to provide a more open tool that can be edited and changed for research purposes, the MRG has developed an alternative implementation of the DBBa. The key features of a tool for teaching arrangements design were noted in *Pawling et al. (2015)* as: wide availability; low learning and familiarisation overheads; fast operation; flexible levels of detail; not type ship based; task focused and reliable; not automated; integration of early stage models, datasets and evaluation; appropriate levels of precision.

The initial version of the new tool, described by *Pawling et al. (2015)* was implemented in Excel, Excel was chosen because it is widely available, has a pre-existing Graphical User Interface (GUI), permits scripting and a limited degree of programming (via Visual Basic for Applications (VBA)) and inherently provides an addressable cellular model, albeit only in 2D. However, the VBA environment placed severe limitations on the speed of the tool and so it has been developed into an on-line JavaScript based tool, inspired by work presented by *Gaspar et al. (2014)*. JavaScript is a remarkably versatile scripting language, and, while running inside a web browser on a typical consumer desktop PC, the tool provides an interactive GUI (shown in Figure 2), including auditing of areas, volumes and centroids. Additional JavaScript modules have been added including: a scalable hullform; intact stability analysis (GZ and hydrostatics); and resistance and propulsion. The tool is currently limited to monohulls, as the current focus is on investigating applications of the on-line design tool concept.



Ship Data

Name: UXV_OPV
LOA (m): 102
BOA (m): 16

Bulkhead Data

Name:
Position (m):

DBB Data

Group:
Classification:
Name:
xFwd (m):
xAft (m):
yCentre (m):
ySize (m):
zHeight (m):
zBase (m):
Area (m2) - top | base | req.:
Volume (m3) - total | req.:

Hullform Data

Midship Fullness: 1.5
Bow Fullness: 0.1
Transom Fullness: 1.5
Fwd Deck Fullness: 0.8
Transom Beam: 0.9
Transom Draught: 0.4
ACU: 0.2
Keel Fwd: 0.9
Superstructure Angle (rad): 0.13

Overall GUI with controls at right Close-up showing cellular representation

Fig.2: Screenshots of the developmental JavaScript based implementation of the DBBa

The tool can also output matrices describing the proximity and adjacency of all spaces in the design. These relationships, which are simple to calculate using a cellular representation of the arrangement, were developed to support three application areas: the network analysis described by *Pawling et al. (2016)* the supportability analysis described in this paper; and the further development of simple early-stage arrangement evaluation methods described by *Andrews (1984)*. The latter is of particular interest as a teaching aid. As was noted by *Pawling et al. (2015)*, arrangements design is not currently afforded the same level of technical rigour in teaching as other aspects of naval architecture, such as resistance and propulsion, and the combination of an on-line JavaScript tool (which can be accessible to a large class) with simple evaluation and guidance metrics is being investigated as part of the solution.

3. Designing a System of Vessels and Craft

3.1 Designing Systems Rather than Ships and Craft

Uninhabited vehicles of various kinds are increasingly being used for both civilian and military tasks. The UCL MRG has previously examined the application of Uninhabited Aerial Vehicles (UAVs), *Pawling and Andrews (2009)*, Underwater Vehicles (UUVs), *Pawling and Andrews (2011)*, and

Surface Vehicles (USVs), *Pawling and Andrews (2013*). In each of those studies, the vehicles themselves were designed (to a preliminary level), in addition to the mother ship (or submarine) to carry them. A common point of all three studies was that future UXVs may be quite different in both operational capability and physical solution to those currently available. Comparison was drawn with the significant changes in the design of naval aircraft and carriers, with the note that the current generation of USVs in particular is constrained by short-term market forces, such as the availability of RHIBs for conversion to automation.

These considerations raise the question of how to perform the early stage design of a complete system of UXVs, with both the mothership and daughter craft. Such systems may consist of multiple types of UXVs and have been proposed for the RN, *MoD (2012)*. Existing ESSD tools and approaches, such as the Design Building Block approach used at UCL, have demonstrated their suitability to the early stage design of the vehicles in terms of their "conventional" individual naval architectural performance aspects (e.g. stability), but there is a need to add to this a method to evaluate the operational performance of different combinations of vehicles. This method should accommodate innovative solutions, such as large UXVs, http://www.naval-technology.com/, remote refuelling of UXVs, *Petersen et al. (2012*), "carrier" UXVs, which deploy smaller vehicles themselves, and even large uninhabited motherships.

3.2 Queuing Theory as a Possible Approach

Current research in the UCL MRG is examining the applicability of Queueing Theory (QT) to this problem. QT is a branch of Operations Research concerning the modelling of the flow of customers, passengers, goods and other entities through a network of servers, *Hillier and Lieberman (2001)*. It has been applied to a wide range of domains, such as transport, airport design, production lines, telecommunication and the design of computers, *Bhat (2008), Suri et al. (2007)*. Fig.3 illustrates how a physical entity, such as a crane, can be abstracted as a server node in a QT network. Such a model may be used to represent a number of customers (i.e. UXVs) that arrive at a waiting area (i.e. space requirement), where they queue up if all servers are busy and eventually get served from an available server (i.e. facility or resource) and leave after the required service (i.e. a list of tasks described in the fleet of UXVs overall operations) is obtained, *Bose (2002)*.

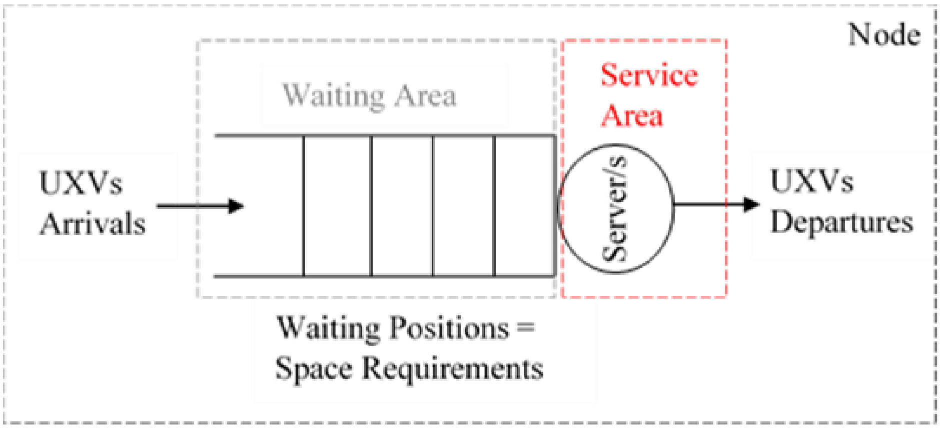


Fig.3: Single node using a simple queueing model (Adapted from *Bose (2002)*)

The time taken for the crane (the "server") to launch or recover the UXV (the "customer") becomes the service time, and metrics, such as the resulting queue length in the "waiting area", can provide the designer with information on the required mission bay size. In the current UCL research, the various stages of preparation, deployment, operation, support and recovery of a fleet of UXVs are abstracted as server nodes in a network, to be analysed using QT. The same basic methods of analysis can potentially be used to examine any system that can be abstracted into a network of customers and servers.

3.3 Representing a Network of Ships and Craft in QT

The research to date has focussed on a network of USVs and UUVs, which are themselves relatively conventional. However, more innovative concepts, such as refuelling USVs at sea, are being examined, and radical concepts, such as hydrofoil USVs, can easily be inserted into the analysis. Additionally, there is the potential to extend the analysis to the transmission and use of data received by the UXVs. The latter approach would make use of the QT model to represent different data and knowledge paths (the two being different), including: local processing on UXVs; data storage and burst transmission; and decision making times by a limited number of groups of human (or human-machine partnerships). A small section of an example network used in this research is shown in Fig.4. There is a significant degree of interconnection between the nodes, representing alternative possible outcomes for the same overall scenario.

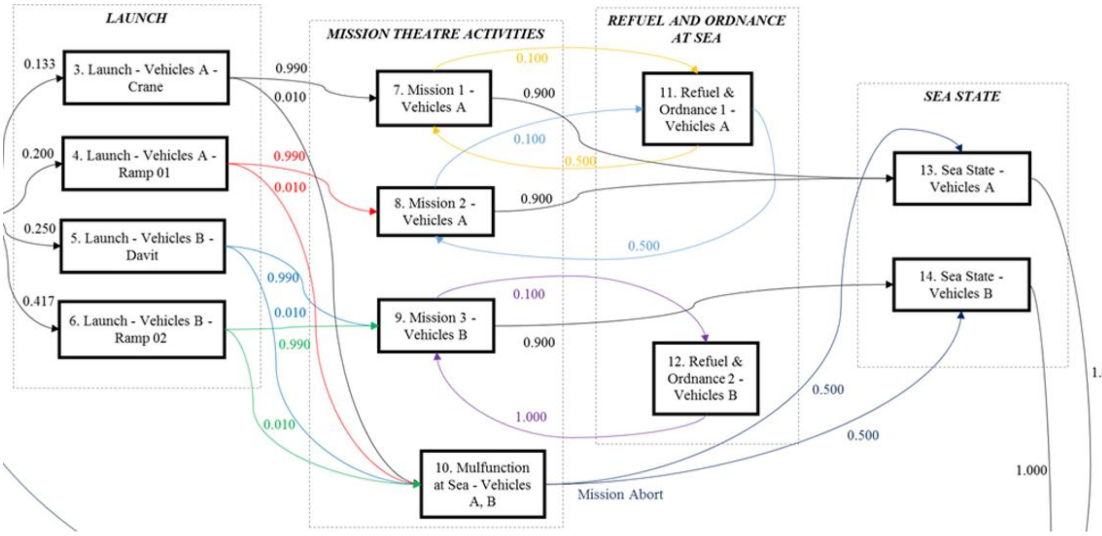


Fig.4: Section of an example network representing USV operations showing the ratios of vehicles heading to each node (Nikolaos Kouriampalis)

As indicated in Fig.3, a wide range of physical systems and operational activities can be represented using the same basic concept of a node serving customers, including the possibility of vehicles malfunctioning and different sea states – shown as two different server nodes on the right side of Fig.4. The numerical parameters representing the performance of individual servers are derived from the physical system design. For example launch time would be related to launch system type and specifications. These include winch speed, mothership aspects (such as freeboard and sea state, the latter of which can lead to a “wait time” due to temporarily unfavourable conditions.

The UXV networks have been modelled in FORTRAN and are analysed using the Mean Value Analysis (MVA) algorithm approach to solve the differential equations describing the queueing network. The complexity of the network requires numerical, rather than analytical, approaches to be used, plus a stochastic element, *Bose (2002)*. Numerical simulations allow flexibility in modelling the behaviour of complex network systems, as well as efficiently allowing the comparison of alternative solutions. The basic QT model developed for this research has been validated against a simple reference case, and a network representing a USV system has been built and analysed.

A key task in the use of QT for such analysis is the process of describing real-world systems and operations as nodes in the network, together with the development of procedures and models to reliably relate the physical parameters to input parameters for the QT model. Similarly, the output metrics from the QT analysis have to be related to UXV system performance. This is currently an area of development, as the numerical results may or may not relate directly to some real-world physical parameter, depending on the nature of abstraction used to generate the QT model. In such a case, the QT analysis may be more comparative than absolute.

3.4 Applying the QT Model in a Concept Exploration Design Phase

The QT model is very quick to execute and thus can be incorporated into concept exploration activities requiring the generation and assessment of a large number of design variants. To generate these design variants, an approach is being adopted similar to that previously described by *McDonald et al. (2012)*, where a large number of variant designs are generated for a limited number of fixed ship topologies. However, rather than attempt to numerically balance the design at every stage, a search and downselection process is used to remove those variants that could never meet the design requirements.

In this approach, each design variant will only be "partially detailed and partially balanced", so some aspects, such as the space and weight of machinery and the accommodation for the "basic" crew, will be calculated for each size and capability variant for each selected topology. However, other aspects, such as accommodation for mission specialists and mission bay space, will be examined by filtering the complete set of design variants to obtain those with sufficient area and volume remaining on the appropriate decks. This is similar to the approach developed by *McDonald et al. (2012)*, where each function of the ship was evaluated separately and a large set of possible variants refined by removing those not capable of supporting the required combination of functions. It also has similarities to the work by *Duchateau et al. (2015)*, where the very large set of layout variants generated by the TU Delft packing approach is reduced by downselecting only those sets of options with certain preferred features. It is important to note, however, that this is not a purely numerical sizing method, as the configuration of the vessel is incorporated in the topological models, with available areas and volumes being associated with selected locations in the vessel.

Fig.5 illustrates a (highly generalised) topological model and some of the methods for downselection that could be used. The primary reason for avoiding a fully iterative, numerically balanced model is that such tools are both complicated and complex, for example the Ship Impact Model (SIM) described by *Calleya et al. (2014)*.

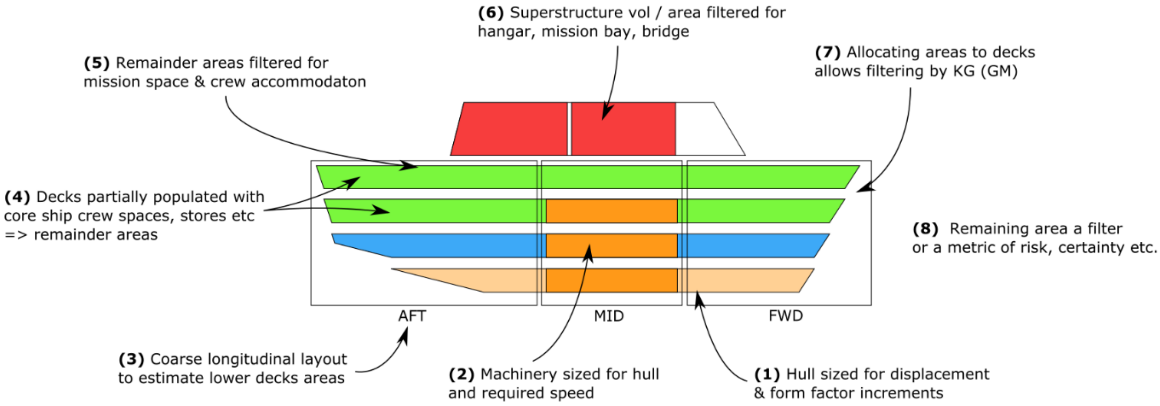


Fig.5: An illustrative example of a topological model

The output of this approach will not be a small set of completely numerically balanced designs, as the amount of numerical iteration in the ship design model will be limited. Instead, it is envisioned that the results of the exploration and downselection process will be a set of ranges of design variants for each topology (varying in dimensions, density, cost, stability margins, etc.), where an associated UXV system performance has been evaluated using QT. Analysis of such a set of variants will provide information on the type of solutions that might meet the requirements of the UXV system; aspects such as overall trends, diversity (or lack thereof) in possible approaches, divergence from historical trends or typical engineering rules of thumb (possible indicators of technical risk) could be investigated. The objective being to use the QT and concept generation tools together to refine the requirements for the UXV system, rather than to specify a detailed solution, in a similar manner to that used in the RN MARS Tanker Programme to generate a large set of variants to support the setting of requirements for the industry bidders, who subsequently undertook the actual design of the ships, *Burger and Horner (2011*).

4. Incorporating Supportability in Preliminary Ship Design

4.1 The Problem of Supportability in Preliminary Warship Design

Supportability is an important issue for all types of ships, but particularly for warships, with a combination of long service lives, changing roles, bespoke equipment, high outfit complexity and a complicated socio-technical support organization, made up of multiple groups of specialists. Although technical design solutions have been developed to improve the supportability of naval vessels, it remains a challenge to ensure that these are incorporated into the designs early enough to be used effectively.

The increased availability of CAD modelling and analysis early in design does not seem to have improved this situation by itself, with feedback from industry indicating that this is because the problem is in part one of modelling fidelity. Ongoing PhD level research at UCL seeks to address some of the many challenges in the incorporation of supportability into computer aided preliminary ship design, *Esbati (2016)*. The main aspects under investigation are;

- Representing and using expert knowledge and experience. Design practitioners will be familiar with the phenomenon that, upon being shown a proposed general arrangement, experienced builders, operators and maintainers will recount all manner of problems that occurred on previous, similar configurations. The use of layouts to provoke such responses has been used successfully to collect designer preferences for layout, *DeNucci (2012)*. Formal subject-specific guidance documents are also maintained by some organisations, but is usually oriented towards procedures, *MoD (2015)*.
- Linking supportability to the ship layout and architecture. A long-running aspect of UCL MRG research is the integration of the ships' layout and other architectural aspects (such as the functional connections between spaces) into ESSD. Although many areas of supportability relate to the ship's arrangement – both in terms of individual spaces and the overall layout – this is not explicitly captured in ship CAD models.
- Decision making under conditions of uncertainty. Design uncertainty in naval vessel design does not only refer to the possibility of the design changing as the programme progresses, or of an eventual failure to meet the performance requirements. It also refers to the uncertainty in the ship's role and the potential need for unforeseen refits and upgrades. An additional dimension that has recently been illustrated by problems with the RN's Type 45 destroyers, *Fallon (2016)*, is that, with naval vessels pushing the state of the art within a highly cost-constrained and politicized procurement environment, there is further uncertainty regarding the likelihood and consequences of some unforeseen class-wide technical issue.

4.2 The Research Area and Proposed Approach

It is acknowledged that warship supportability is a very broad topic, as indicated by the UK MoD guidance, *MoD (2015)*. Many aspects relate to detail issues, such as equipment selection and compartment arrangement (ergonomics). To constrain this research to a scope practical for a single PhD, the level of design definition has been limited to a typical early stage ship design: namely, general arrangement, selection and location of major equipment; and initial structural design. The approach being pursued is outlined in Fig.6 and some key points are described in more detail below.

1: Formulating and determining proxy supportability indicators. Direct and explicit supportability performance indicators have proven difficult to define. However, consideration of the type of experiential knowledge available on the subject has indicated that there are many features of the design that can be used as proxy supportability indicators, in that they have a known effect on supportability, and can be represented in a quantitative manner (albeit a simplified one).

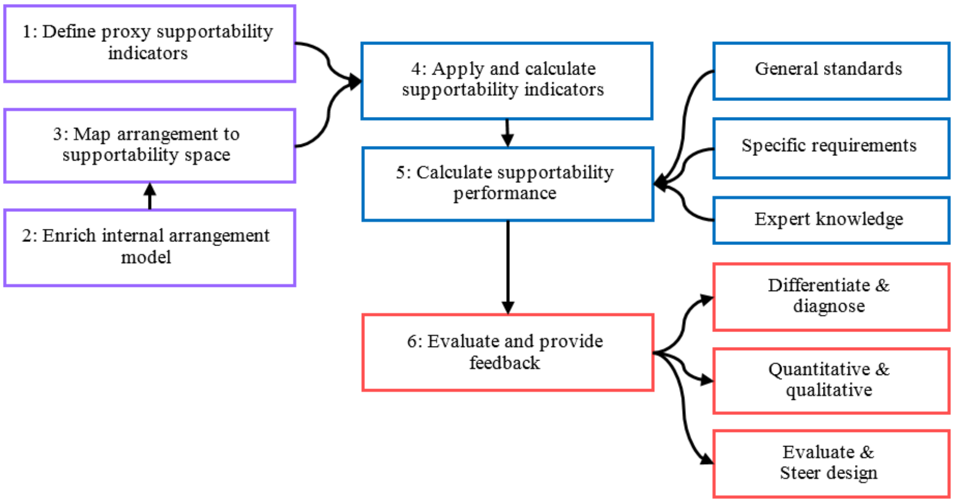


Fig.6: Outline of the proposed approach to supportability analysis in early stage design

Some simple example proposed indicators include: the travel distance and the number of physical boundaries (i.e. decks and watertight bulkheads) to pass through between a piece of equipment and the ship's workshop or removal route; the availability of naval stores and spare gear; and the degree of redundancy in key ship systems. It is important to note that, as these are proxies derived in some cases from expert judgement and experience, they cannot be treated in the same way as analytically generated performance indicators. They may, however, be used to compare options, to "steer" the design away from undesirable solutions, and to provide a framework for applying, discussing (and challenging) experience in future designs.

2 & 3: Mapping the ship's internal arrangement into the supportability space. This step involves enriching the model of the ship's internal arrangement, (geometry and topology) with characteristics required to evaluate the proxy supportability indicators. This is similar to the previous UCL work on the FIREPROOF project, where additional characteristics were added to an existing ESSD model to allow the evaluation of fire safety, *Pawling et al. (2012).* Examples of additional characteristics include: density of the space (which is usually not explicitly considered in CAD models but can indicate the difficulty of maintenance); adjacency to other spaces (as some types of space influence others e.g. vibration and heat); and vulnerability of the space to certain through life issues, such as corrosion (which can be considered as probabilistic and with consequences).

4 & 5: Calculating supportability performance. Some performance indicators will be directly useable, whereas others ought to be aggregated together. This is complicated by the fact that supportability considers future events, some of which may not occur. The objective of such a calculation is to provide a numerical representation of the performance of the design when considered against several criteria. These could include: General design standards; specific performance requirements for the project in question; and the past performance / expert knowledge based assessment.

6: Evaluate performance and provide feedback. The numerical performance indicators need then to be used in some decision making approach. This approach must be able both to differentiate between multiple options, but also be able to diagnose why they are different. As well as the subject-specific issues of evaluating supportability, this approach has to be sensitive to the fact that, the proxy indicators in particular, are quantitative representations of a largely qualitative assessment. One option for addressing this paradox is that the supportability evaluation will not simply be a pass/fail type analysis, but rather should be used to steer design development.

4.3 Decision Making for Supportability 1: Prospect Theory-Based Real Options Analysis

Regardless of the method used to generate a numerical performance indicator for supportability, there remains the issue of handling future uncertainty. One approach that UCL has investigated to address this is the use of Prospect Theory-Based Real Options Analysis (PB-ROA). This is a technique applied to investment appraisal, so originating in the financial industry with its strong interest in decision making for uncertain futures. PB-ROA was first applied to a maritime example by *Knight and Singer (2015).* The UCL application of the analytical framework, proposed by *Knight (2014),* was described in detail by *Esbati et al. (2015)* so will only be summarized here. In the case of a naval vessel, the application of investment appraisal methods is complicated by the fact that they do not generate cash flows, and naval operations do not necessarily map well to a conventional commercial market model. Three key changes were made to the PB-ROA approach to apply it to naval vessels:

- Utility Theory can be used to define value of assets in the absence of cash flows;
- Prospect Theory helps to model the loss-averse nature of navies, through risk-adjustment of the value of naval options;
- Game Theory is used to model the interdependencies of naval options and the resulting feedback to the operating environment.

The UCL application of PB-ROA investigated a simple change to the design; using a cellular concept in build to allow for future (possible) enlargement of a mission bay, with the use of a "design complexity metric" as defined by *Knight and Singer (2015).* Fig.7 shows one set of results of this analysis; if the probability of the mission bay requiring enlargement at some point is larger than 70%, it becomes more preferable to use the cellular option due to its higher defined utility.

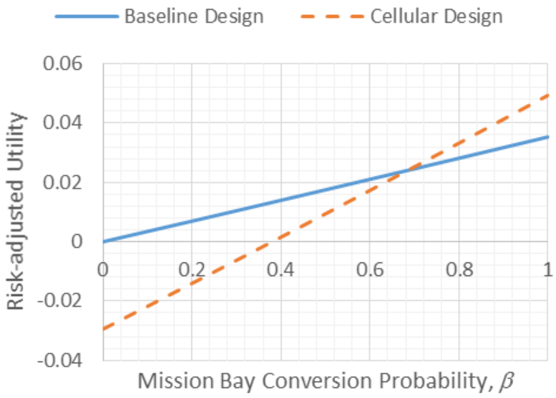


Fig.7: Variation of risk-adjusted utility with mission bay conversion probability

Ultimately, the PB-ROA method was found to be a useful approach for decision making under these circumstances of through-life uncertainty. However, it requires a significant amount of abstraction (and in the example, assumption) to translate ship design technicalities and naval operational concepts into the various mathematical components of the method. Given the level of assumptions being used in the examples, an alternative approach was investigated, which could better address the issues concerning expert judgment and past performance being highlighted by the definition of the proxy supportability indicators.

4.4 Decision Making for Supportability 2: Decision analysis

Although PB-ROA provides a method for comparing different designs with different supportability options, another approach was needed for steps 4 and 5 in Fig.6, and the techniques of Decision Analysis and Effectiveness Analysis have proved promising. Decision Analysis provides a framework to articulate and integrate the values and professional judgments of decision makers and experts. *Keeney (1982)* identified the lack of natural or direct attributes as a major difficulty in many Decision Analysis studies, and proposed employing proxy attributes that in practice would have the same role as the proxy indicators proposed for supportability analysis in the UCL research. Effectiveness

Analysis is another hierarchical approach to determine the (military) worth of design alternatives in performing mission tasks, *Office of Aerospace Studies (2013)*.

Multi-Criteria Decision Making approaches (MCDM) has a long history of application to ship design, with a summary of early work provided by *Andrews et al. (1997)*. Of particular interest in the supportability analysis is the Analytic Hierarchy Process (AHP), *Saaty (1987)*. The various supportability indicators identified to date allow the definition of Measures of Performance and Effectiveness (MOP and MOE), but AHP provides a mechanism for integrating the (potentially contradictory) preferences based on historical lessons and expert judgement. The novel aspect of this work is that the AHP analysis will be linked to the ship's general arrangement, via the various Supportability Metrics. Where many previous applications of MCDM to ship design have focused on comparing high-level capabilities, the application under investigation here seeks to apply these same techniques to detail issues in the arrangement and equipment selection.

5. Virtual Reality as a Design Tool

5.1 The Availability of Virtual Reality

The development to consumer level of several technologies, such as small high-resolution screens and accurate solid-state accelerometers, has seen Virtual Reality (VR) move from an experimental or specialist technology to one available to consumers at costs similar to desktop computers. VR has seen application to training and familiarization, *MacKinnon et al. (2016)*, and supporting construction, https://www.virtalis.com/blogs/casestudies/bae-systems-submarine-solutions-3/, such that it is frequently described as having potential for use in naval architecture and marine engineering design tasks. However, the main design applications to date have been focused on the ergonomic design of specific, highly user-centric spaces, such as bridges, *Nordby et al. (2016)*.

The UCL MRG has recently begun to incorporate VR into the MSc Ship Design Exercise and the CPD Submarine Design Course, *UCL (2017)*. The main technical teaching objective of VR in these contexts is to provide students with the sense of space on ships and submarines (or rather, the lack of it). Although many students will have some industrial experience, possibly including sea-time, prior hand-on experience is highly variable and VR is seen as having an important role to play in helping students internalise the issue of space demands and use that VR has over conventional lectures.

5.2 UCL MRG Experiments in VR

The most typical of these is helping the students appreciate the difference between a neat, seemingly spacious engine room, drawn in a 2D vector CAD package and populated with neat cuboid engines, and the crowded, busy space that results once the somewhat less neat actual engines and their many associated equipment and systems are added. This is particularly significant for submarines and Figure 8 illustrates a VR visualisation of a design produced by a student design team on the 2016 Submarine Design Exercise.

The success of these initial experiments, combined with the falling costs of the hardware, have raised the question of what else can VR be used for in early stage design and design education? Will it always be centred on the human factors / ergonomics field (which is vital) or are there wider applications? A three-year UCL MRG PhD project focusing on this subject is starting this year. Possibilities to be investigated may include the use of VR to assist in the exploration of complex multi-dimensional datasets that will be produced by future semi-automatic concept generation tools; application to hullform design; and improving the quality of ROV telepresence. From the educational perspective, the combination of high-end bespoke equipment, such as the HTC Vive, https://www.vive.com/uk/, and, less sophisticated but increasingly accessible, smartphone-based solutions (which can now incorporate position-tracked hand controllers) offers the possibility of on-line VR teaching and collaborative resources.

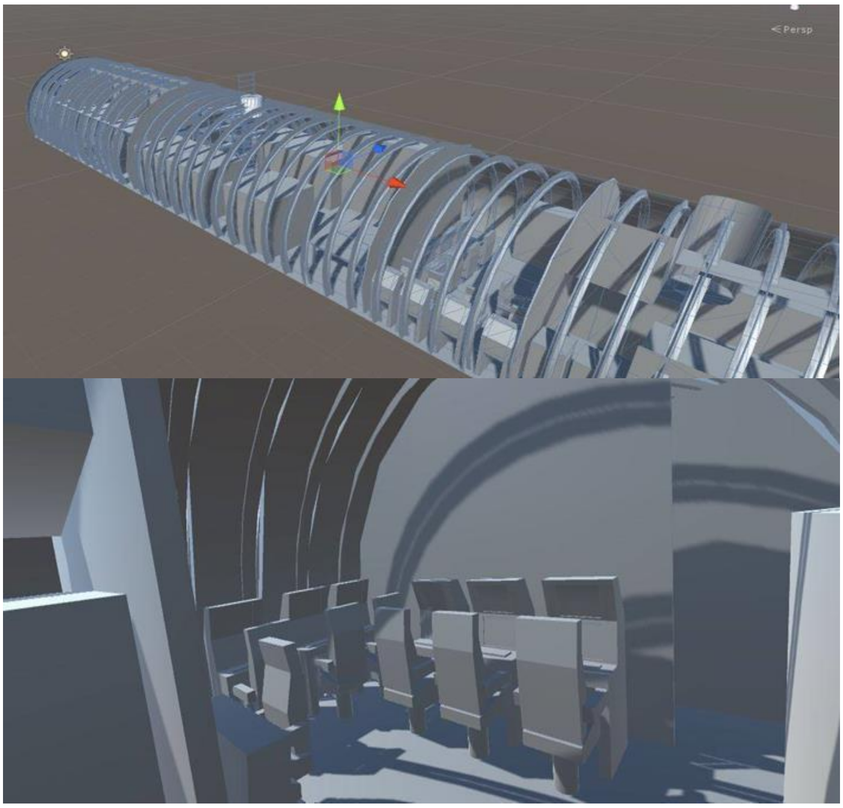


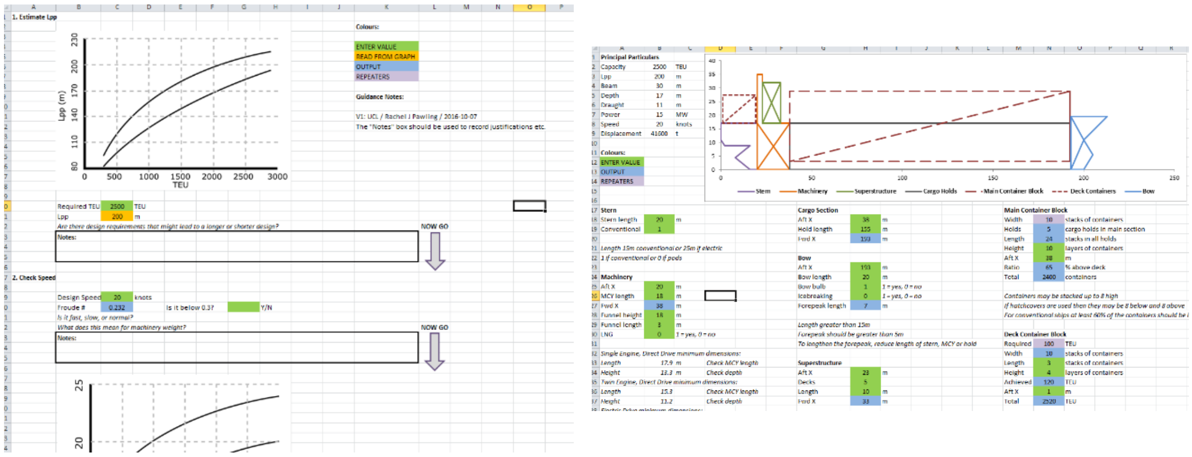
Fig.8: VR model of a student submarine design, showing the overall geometry in the editor (top) and a view from inside the control room (bottom)

6. Future Challenges: Teaching of Ship Design to Naval Architects

The combination of ever more capable computer tools, the widening of the scope of technical aspects that can be considered ever earlier in the design process, and the familiarity – almost from birth – of the new generation of students with computers, raises the question of how to teach ship design to future generations of naval architects. University courses rely on teaching and exam questions focused on the fundamentals of engineering modelling and analysis, and frequently the underlying science, sub-divided by subject area, but this may only lead to an ever greater divergence between what is taught at university and what is done in practice. It may also become increasingly problematic when faced with a generation who have always lived with Google, Wikipedia and the immediate availability of vast amounts of decontextualized information. This raises the question of what might be the new key fundamentals of engineering teaching.

The UCL MSc Naval Architecture and Marine Engineering courses are notable for the inclusion of a three-month Ship Design Exercise (SDE), carried out in small teams, which enables the student (and obliges them, if success is to be achieved) to apply the wide range of specialist subjects in a holistic, integrative manner, to produce a concept ship design. With the increasing capability of desktop ship design tools to perform the numerical calculations (for example, over the course of her undergraduate degree the first author moved from hand calculations of stability through two generations of PC-based NA CAD tools), one of the key fundamentals is proving to be decision making and justification. Within the context of the UCL course, an “Introductory Ship Design Exercise” (ISDX) has recently been introduced, which takes place in the first weeks of the first term, in contrast to the main SDE, once the naval architecture topics have been learnt. The ISDX makes use of a highly simplified Excel-based sizing tool, based on container ship data, a screenshot of which is shown in Fig.9.

The primary purpose of the ISDX is to introduce students to the need for engineers to make design decisions and justify them. The sizing relationships are all presented as ranges, rather than single lines or algorithms, and the students have to choose where in the range their design is likely to lie, based on the broad implications of requirements, such as icebreaking and high speed. Additional teaching objectives for the ISDX include providing students with some understanding of the nature, utility and limitations of historical and "type-ship" data in engineering design. The ISDX is short – a single morning – and is deliberately kept more casual than a conventional lecture, to encourage the students to explore the various design options and introduce them to decision making in a "risk-free" environment (as the full SDE involves design reviews with senior staff).



1. Estimate Lpp

Colours:

ENTER VALUE
READ FROM GRAPH
OUTPUT
REPEATERS

Guidance Notes:

V1: UCL / Rachel J Pawling / 2016-10-07
The "Notes" box should be used to record justifications etc.

Required TEU 2500 TEU
Lpp 200 m
Are there design requirements that might lead to a longer or shorter design?
Notes:
NOW GO

2. Check Speed

Design Speed 20 knots
Froude # 0.232 Is it below 0.3? Y/N
Is it fast, slow, or normal?
What does this mean for machinery weight?
Notes:
NOW GO

Principal Particulars		
Capacity	2500	TEU
Lpp	200	m
Beam	30	m
Depth	17	m
Draught	11	m
Power	15	MW
Speed	20	knots
Displacement	41600	t

Colours:
ENTER VALUE
OUTPUT
REPEATERS

Stern		
Stern length	20	m
Conventional	1	

Length 15m conventional or 25m if electric
1 if conventional or 0 if pods

Machinery		
Aft X	20	m
MCY length	18	m
Fwd X	38	m
Funnel height	18	m
Funnel length	3	m
LNG	0	*1 = yes, 0 = no*

Single Engine, Direct Drive minimum dimensions:
Length *17.9* *m* *Check MCY length*
Height *13.3* *m* *Check depth*
Twin Engine, Direct Drive minimum dimensions:
Length *15.3* *Check MCY length*
Height *11.2* *Check depth*

Cargo Section		
Aft X	38	m
Hold length	155	m
Fwd X	193	m

Bow		
Aft X	193	m
Bow length	20	m
Bow bulb	1	*1 = yes, 0 = no*
Icebreaking	0	*1 = yes, 0 = no*
Forepeak length	7	m

Length greater than 15m
Forepeak should be greater than 5m
To lengthen the forepeak, reduce length of stern, MCY or hold

Superstructure		
Aft X	23	m
Decks	5	
Length	10	m
Fwd X	33	m

Main Container Block		
Width	10	stacks of containers
Holds	5	cargo holds in main section
Length	24	stacks in all holds
Height	10	layers of containers
Aft X	38	m
Ratio	65	% above deck
Total	2400	containers

Containers may be stacked up to 8 high
If hatchcovers are used then they may be 8 below and 8 above
For conventional ships at least 60% of the containers should be

Deck Container Block		
Required	100	TEU
Width	10	stacks of containers
Length	3	stacks of containers
Height	4	layers of containers
Achieved	120	TEU
Aft X	1	m
Total	2520	TEU

(a) Sizing sheet showing historical data as ranges (b) layout sheet

Fig. 9: The UCL Excel-based ship sizing tool used to introduce students to decision making

From 2019, most first-year undergraduates will be fully "21st century students", however it could be argued that some universities are still teaching them using 20th century tools and 19th century methods. Activities such as the UCL research on VR, and the ISDX, are only two examples of attempts to address this, but it is a vital area for future development.

7. Summary and Conclusions

Computers have found application in all stages of ship design, including adopting many modelling and analysis approaches from other domains. Although there is ongoing development of methods best suited to specialist, high performance computing hardware, the continuous improvement in the performance of desktop personal computers has made other approaches more accessible at the day-to-day level. This paper describes research into the introduction of established or developing technologies in both ship design and education for naval architects and marine engineers. The research areas described in this paper have covered: an on-line implementation of the Design Building Block approach using the JavaScript programming language and libraries; the application of Queuing Theory to the modelling and analysis of a system of UXV motherships and uninhabited craft, enabling them to be designed in a coherent manner; the application of financial decision making methods and decision analysis to the problem of naval ship supportability; and Virtual Reality for ship design and education into it. In each of these cases, an initial implementation of the method or tool has been created and applied, with second iterations or alternative approaches under development. In keeping with the theme of education, the paper also briefly considered the question of how to educate future generations of engineering students, highlighting the use of simplified design exercises as one valuable tool.

Acknowledgements

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Secure Wireless Options in the Smart Ship

Scott Patterson, Babcock Analytic Solutions, Scott.Patterson2@babcockinternational.com
Peter Barton, Babcock Analytic Solutions, Peter.Barton@babcockinternational.com

Abstract

This paper presents a summary of the findings of a detailed study, conducted on behalf of the Ministry of Defence, assessing wireless technologies with the potential to support secure communications on-board Royal Naval platforms. Specific requirements and possible solutions were not in scope but the security and interference implications of implementation of such networks in RN warships and submarines were considered for a range of information types and classification levels. Design considerations to limit exposure to threats are also discussed.

1. Introduction

Previous work on behalf of the MoD developed a Smart Platform Vision Demonstrator which showcased a future state where on-board information (including equipment sensor data) was accessed remotely at the point of use using mobile technologies, delivered over a wireless network bearer with automated process flow and on-board analytics capability. This approach placed the Maintainer at the heart of the solution and also highlighted the potential utility of Augmented Reality (AR) in an In-Service support environment. The work presented how significant benefits could potentially be achieved in the supportability maintenance environment by the use of secure wireless technologies in a Smart Ship, including:

- Improved access and exploitation of information by Ship Staff;
- Improved feedback from the Platform to aid Design Authority and Waterfront decision making;
- More effective fault resolution and diagnostics, using digitally enabled equipment and sensors;
- Ability to deploy mobile applications and workflow automation, both shore side and within platform environments.

However, there will be security and interference implications of installing and operating a wireless communications system in an on-board platform environment. Wireless networks come with increased Cyber risk, noting that they are generally easier for attackers to access than their wired equivalents and can present an attractive, lower risk, path into a private network. If Cyber risks are not managed adequately, an attacker can potentially intercept or transmit data at long range from a position of safety, or deliberately jam the medium causing a network denial of service.

The selection of wireless technology solutions will be driven by specific requirements so, to avoid being proscriptive, this paper summarises an assessment of a broad range of personal and local area wireless communication technologies, particularly with respect to their potential utility in the maritime environment. The security and interference implications of installing such networks on an secure platform are considered for a range of information types and classification levels that may need to be accessed. Additionally, design considerations to limit exposure to threats, including those of the potential "Insider" to on-board systems, are discussed.

2. Background

2.1. Wireless Network Types

The evolution of wireless network communications has played a major role in shaping the ways in which we work, play, socialise, are entertained and communicate in general. They offer location flexibility, connectivity on the move, are scalable and can be adapted more easily than wired networks to meet changing business and technological needs. The diversity in these wireless networks is such that they are now categorised by the primary function or role for which they were designed to meet.

2.1.1. Wireless Personal Area Network

A Wireless Personal Area Network (WPAN) can be defined as a wireless network operating over very short distances (sometime known as the last metre) to provide interconnection between devices within an individual’s workspace, such as PDAs, headsets, keyboards, mice, printers, fitness trackers and others. WPAN is specified under IEEE standard 802.15 and includes technologies such as Bluetooth, IrDA, ZigBee and Z-Wave.

2.1.2. Wireless Local Area Network

A Wireless Local Area Network (WLAN) provides the means for connecting two or more devices within a limited area such as the home, a building or a compartment on board a submarine / surface platform. Most WLANs are implemented under IEEE 802.11 standards which have evolved over time to meet the demands for increased bandwidth, resilience and coverage. Connectivity between different access points on a WLAN, and between access points and external networks, can be wired, wireless or a combination of both. Wireless extension of a WLAN is known as a Wireless Distribution System.

2.1.3. Wireless Metropolitan Area Network

Wireless Metropolitan Area Networks (WMAN) provide network connectivity for devices in an area that is generally larger than that typically covered by a LAN, but smaller than that covered by a WAN. A MAN can cover a large city, town, village or military establishment such as a dockyard. Where coverage is across a large site, this may be referred to as a Campus Area Network.

2.1.4. Wireless Wide Area or Regional Access Network

Wireless Wide Area Networks (WWAN) or Regional Access Networks (RAN) describe the ability to access network services using mobile telecommunications technologies such as GSM (including 3G, 4G, UMTS, LTE etc) and Wi-Fi hot-spots (such as those offered by BT and other service providers).

2.1.5. Global Area Network

A Global Area Network, as the name suggests, is one that has access points across the globe. Broadband Global Area Network (BGAN) services are offered by companies such as Inmarsat using very small aperture satellite terminals from manufacturers such as Hughes, Thrane & Thrane, Cobham and Wideye.

2.1.6. Wireless Sensor Networks

Wireless Sensor Networks provide a means of exchanging sensor data information (area, health, environmental and industrial monitoring) in areas where wired solutions are not practicable, to meet emerging or temporary needs, or where the need was not identified during design and build and a wired Post Design Service (PDS) would be costly or impracticable. Sensor networks have evolved to include the control of end devices (including reconfiguration of parameters and control of actuators), known as SCADA (Supervisory Control and Data Acquisition). Sensor networks can be established in a variety of topologies and can include both wired and wireless devices.

2.1.7. Virtual Private Network

A Virtual Private Network (VPN) is a private network established across public or commercial networks to provide a level of security or protection to the data transiting the network and to provide a level of protection to the private network infrastructure. VPNs are used widely to extend corporate networks, to enable remote working and to provide levels of privacy for users of open networks.

A VPN is created by establishing one or more virtual point-to-point connections using tunnelling protocols or by encrypting the point-to-point links.

2.2. Tunnelling

VPN or encrypted tunnel networks can be structured in a number of different ways, each with its own merits dependent on a variety of factors, including the assigned protective marking of the environment in which the networks are deployed and the number of different security domains.

2.2.1. Simple Tunnel Network

The most common implementation makes use of open, unclassified networks as the main bearer. In very simplistic terms this can be implemented by tunnelling secure data over an insecure network. In this example, black UNCLAS devices access public network services (the internet) via the firewall and network access protection (NAP) router. Encryption devices establish an encrypted VPN to provide a secure connection between the two red LANs to create a red WAN:

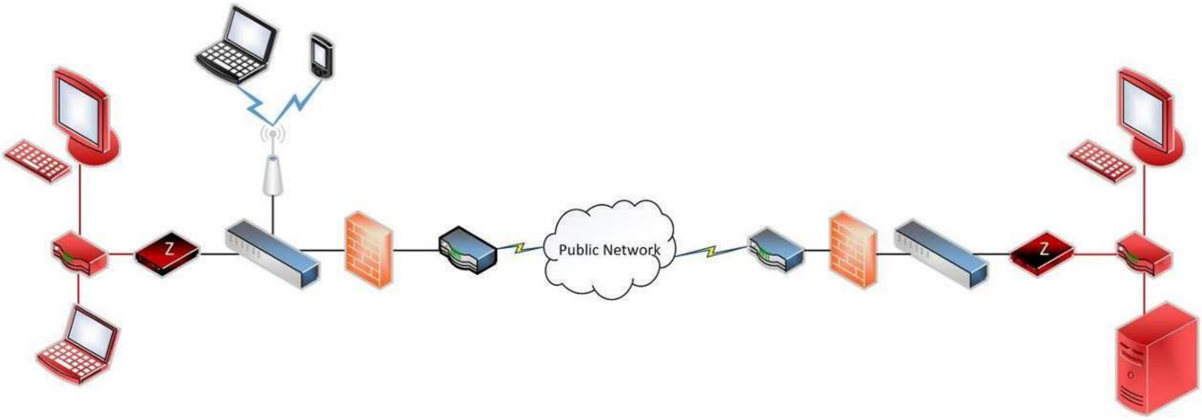

Fig.1: Tunnel Network

2.2.2. Reverse Tunnel Network

Where the predominance of network infrastructure is at a higher security classification (for example in a closed or compartmented environment shown here in red), it may be more practicable to reverse-tunnel the lower (blue) classification data:

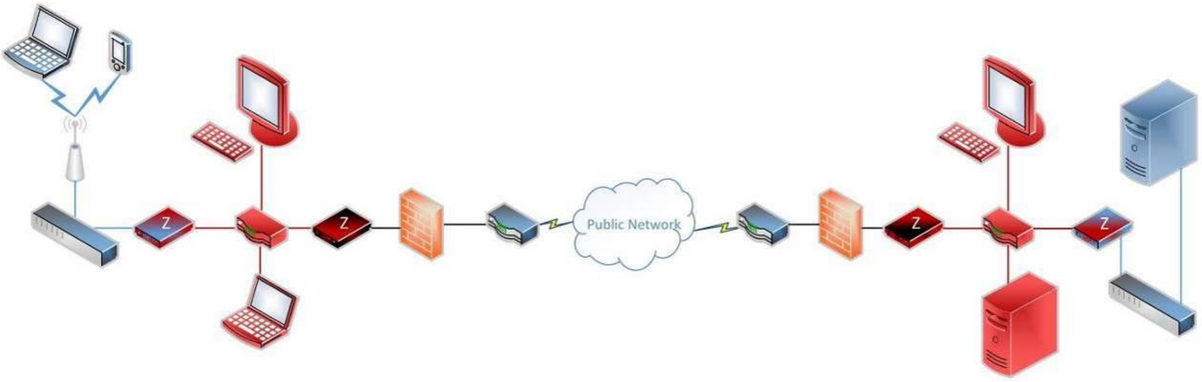

Fig.2: Reverse Tunnel Network

2.2.3. Multi-Tunnel Network

More complex networks can support the integration of multiple security domains using accredited cryptographic devices and/or VPNs to provide the required network separation. Fig.3 shows devices operating in three different security domains (red, blue and black), each with its separate encrypted tunnel or VPN:

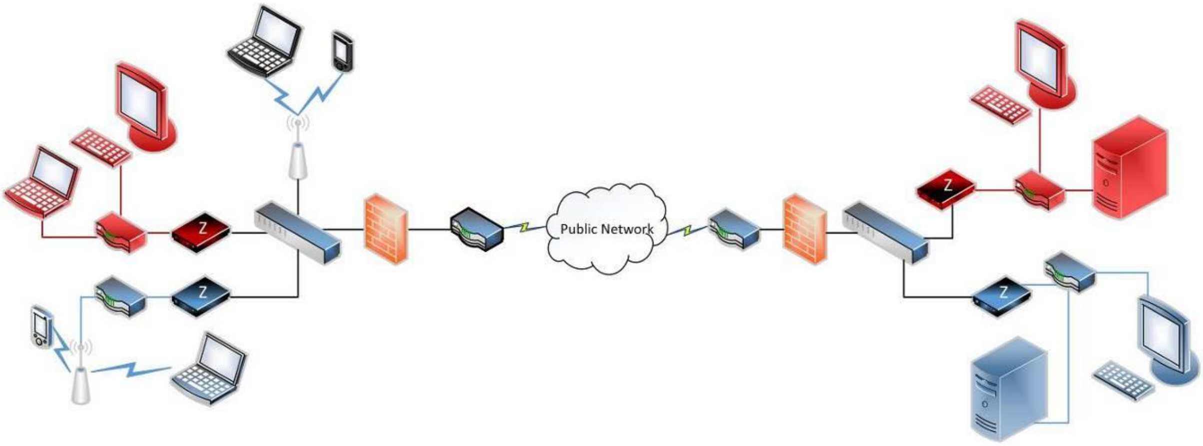

Fig.3: Multi-Tunnel Network

2.3. Internet of Things

The Internet of Things (IoT) is a collective term that encompasses the networking of devices embedded in homes, offices, buildings, metropolitan areas and vehicles, with remote access over the internet. Devices include smart meters, sensors, thermostats, domestic appliances, lighting, health monitors, traffic signals, traffic sensors, TV and Satellite receivers/recorders and many more. The concept is that by network enabling these devices, their data can be shared remotely and the devices themselves can be remotely configured and controlled (e.g. setting a Sky+ box to record a programme via an app, from a remote location).

In enabling IP connectivity for legacy electronics, the IoT has widened the attack surface of vehicles, homes and cities exponentially. As a result, new security issues for everything from fridges to cars have been identified, ranging from using a network of compromised fridges to crack passwords to stealing wireless passwords from kettles, security cameras and even toys.

An Internet of Maritime Things (IoMT) might include devices such as Wireless sensors, Applications, Analytics, Wearable technologies, Augmented Reality and Portable hardware (mobile devices).

3. Wireless Technologies

3.1. Introduction

Any solution design will need to consider how the information services are delivered to the platform and how they are distributed throughout the platform, both of which will be influenced by factors including available bandwidth, the protective marking of the system and the protective marking of the environment in which the system is deployed. Separation between security domains will be achieved using encryption, VPNs and tunnelling.

This paper summarises previous work to investigate the feasibility of using wireless networking technologies to extend wired networks and provide added flexibility in working on board military and Smart vessels. Delivery of services to the platform, and core distribution throughout the platform, were out of scope and not considered any further.

A broad range of wireless options were considered from across the electromagnetic spectrum, including the traditional Radio Frequency based technologies, such as Wi-Fi and Bluetooth, and those operating in the Infrared, Visible Light and Ultraviolet bands. Ultraviolet was discounted immediately as there are no developments for short range networks. Laser communications were considered initially due to previous implementations in campus network solutions, however these devices are no longer available and current developments are focused on space communications.

The remainder were considered to have potential utility in the maritime domain either now or in the future and were assessed with respect to performance, security and maturity, the findings from which are summarised below.

3.2. Wi-Fi

Wi-Fi is a technology that enables devices to connect wirelessly to Local Area Networks and is specified under IEEE standard 802.11 for operation in the 900 MHz, 2.4GHz, 3.6GHz, 5GHz and 60GHz bands of the RF spectrum. Since its first implementation in the 1990s, the Wi-Fi standard has undergone a number of revisions and developments; it is now a very well established open standard offering reliable and secure wireless network extension that is capable of delivering sufficient bandwidth to support most applications across multiple devices. Its popularity has ensured that generic devices are readily available and Wi-Fi capability is often integrated in to many domestic, industrial and commercial devices. This popularity does increase the risk of interference; however this can be mitigated by careful network configuration and management.

Use of the Advanced Encryption Standard (AES) protocol means that Wi-Fi can be accredited for use with some Government and military networks, but it is essential that robust key management is implemented for this to meet the requirements of system security accreditors.

Wi-Fi networks are well suited to the delivery of welfare services where Bring Your Own Device initiatives are supported, particularly as most service personnel will own Wi-Fi enabled smart phones and tablets. Within an operational environment, consideration should be given to access point siting in order to reduce the risk of targeted, standoff attacks. Solutions should also consider configuration options that allow network access devices to be controlled in accordance with Emission Control (EMCON) policies.

This type of network extension on board a platform could provide added flexibility and improve efficiency of some working practices; however the structure of vessels is such that platform wide coverage would require a considerable number of wireless access points. The use of PowerLine technologies may help address this on existing platforms, however these would also need to be assessed for Radio Frequency Interference (RFI), Electromagnetic Compatibility (EMC) and Security Accreditation.

Wi-Fi standards have continued to develop in order to address emerging needs. The release to market in 2016 of the first 802.11.ad devices, operating at 60GHz and offering significantly increased bandwidth, may present opportunities for the employment of Wi-Fi in more sensitive and/or bandwidth hungry environments.

3.3. Bluetooth

Bluetooth offers a suite of very well established, open standards which are used extensively in modern communications and information systems (CIS) solutions to provide short-range connectivity (typically less than 10m) between devices: including computers and their peripherals (keyboard, mouse & printers), hands-free headsets, wireless speakers, media players and media centres, fitness devices, remote controls, test equipment, medical equipment, bar code scanners and many modern applications previously served by RS232 and other wired protocols. Governance by the Bluetooth Special Interest Group (SIG) has helped ensure interoperability between different vendors' devices and developed user trust in the technology. Classic and Low Energy (LE) implementations of the standards are well suited to applications requiring modest data rates (up to 3Mbps and 1Mbps respectively) over relatively short distances (up to 10m). Later versions of the standard offer greater throughput but rely on a hybrid Bluetooth/Wi-Fi solution to achieve this.

Bluetooth uses a frequency hopping standard which helps minimise the risk of interference with other devices in the Industrial, Scientific & Medical (ISM) band and has the option to form mesh networks which can be attractive for some applications such as sensor networks. The Bluetooth standards include strong 128 bit AES encryption, however robust key management is critical to ensuring connection integrity is maintained. Many low end devices, such as some headsets and keyboards, employ weak pairing procedures and use fixed keys which can leave devices vulnerable to intercept or cyber-attack.

The low transmit power levels of Bluetooth Classic and LE lends the technology to employment in areas where minimising RF signatures is desirable and the risks of eavesdropping or interception are concerns. Bluetooth headsets are currently used in operational environments where ease of movement and freedom from wired devices is desirable. Current policies preclude the use of wireless devices at higher classification levels, however where a suitable operational imperative can be justified and trials results are able to demonstrate suitable risk mitigation (for example when deployed in metal clad compartments providing sufficient RF screening) accreditation of such devices may be possible in the future.

Bluetooth standards continue to develop, with V5 recently announced in December 2016. Despite these progressions, Classic and LE versions continue to fill specific needs that V4 and V5 will not and therefore device availability and support will not be affected.

3.4. ZigBee

ZigBee is an open specification, based on IEEE 802.15.4 for low-speed (250 kbps), short range (10m) wireless personal area networks. ZigBee was conceived in 1998 and initially targeted at sensing and control functions in the industrial and commercial sectors. Since then it has been adopted more widely and is now also found in domestic and residential ‘smart home’ devices. Certification of ZigBee products is undertaken by the ZigBee Alliance. ZigBee provides a meshed, small area network capability, underpinned by predefined command libraries that could be adapted to meet many needs. ZigBee delivers relatively low bandwidth of up to 250kbps at individual link ranges of up to 10m, extendable up to 100m in a mesh.

The standard defines use of AES 128 bit encryption which, if correctly implemented, will provide sufficient levels of security for use in most sensor networks. There are many development options which make implementation of the standard for niche low bandwidth requirements a possibility. Easy development of bespoke solutions, coupled with user definable options for key management and ZigBee’s low power consumption, make it attractive for solutions which may need to be left unattended for long periods, or where detection or the possibility of generating RFI with other devices is a concern.

3.5. Z-Wave

Z-Wave was established by a small Danish start-up (acquired by Sigma Designs in 2008) as a home automation wireless communications protocol intended to provide simple remote control functionality for lighting, heating, air conditioning, security systems, windows, garage doors and access controls. Z-Wave is a proprietary standard that operates outside the congested 2.4GHz ISM band, reducing the risk of interference with other devices. Employing a mesh network topology provides a degree of resilience which, coupled with AES 128 bit encryption, could make Z-Wave attractive for very low bandwidth applications such as sensor networks.

The proprietary nature of Z-Wave is such that solutions rely on the use of chips that are only available from a single manufacturer. AES encryption is not available on all chip sets and where it is, the implementation is not generally very robust. This does not preclude Z-Wave from consideration for future development options, but these would likely prove costly and require tie-in with a single chip vendor. It is also likely that a requirement for which a Z-Wave solution might be implemented could be met using an open standard based technology, such as ZigBee.

3.6. IrDA

The Infrared Data Association (IrDA) presents a mature set of standards for short range communications (less than 1m) that were popular in the late 1990s and early 2000s to provide connectivity between Laptops, Desktops and PDAs. However, a key limitation was the need for a line of sight between the IrDA ‘ports’. The evolution of Wi-Fi and Bluetooth, which do not require a clear line of sight, overtook IrDA in this application and its inclusion in new devices has largely fallen by the wayside. Legacy support is still available for IrDA devices on some platforms, however research was unable to reveal any vendor that incorporates IrDA ports or capability on their current devices. Despite the IrDA association establishing Special Interest Groups for development of Giga-IR and IR-USB there does not appear to have been any further development since 2012.

This lack of any development, market presence, or inclusion of encryption within the standards, precludes IrDA from any recommendations for employment on military platforms or in any sensitive environments at this time. Despite this, Infrared is used in PureLiFi’s LiFi-X solution and the ongoing existence of the IrDA and its Special Interest Groups looking at developing speeds in excess of 1Gbps may lead to the publication of new IrDA standards and a resurgence in the development and production of IrDA devices.

3.7. LiFi

LiFi is a form of visible light communications theoretically capable of delivering full-duplex bandwidth in excess of 200Gbps. It is intended to work by modulating the light emitted by common household LED bulbs, which is picked up by photoelectric cells positioned within the beam of that light. The aim is to provide easy access to computer networks in areas where Wi-Fi is not practicable or where Wi-Fi bandwidth is insufficient. LiFi is a relatively immature technology which, although underpinned by an IEEE standard, has so far only been implemented by individual vendors using proprietary standards. Laboratory testing is reported to be achieving levels of performance that far exceed those of RF based wireless solutions, however the small number offering commercial solutions have failed to replicate this performance in the real world and none have achieved the throughput that is available with Wi-Fi. LiFi offers advantages in presenting no EMC or RFI issues, however performance in a range of different operating environments, with differing ambient light levels can only be truly assessed with longer term independent testing.

LiFi does not yet offer any encryption or authentication on the air interface currently and is therefore potentially vulnerable to intercept, denial of service and offensive cyber-attack. Interoperability testing with other vendor solutions has not been conducted, however as each vendor’s solution is proprietary, it is likely that a solution implemented using today’s technology would require single vendor tie-in. Both factors present significant security and business risk to any solution.

LiFi is a technology in the very early stages of evolution; however despite the listed reservations it has the potential to deliver significant increases in bandwidth, with utility in areas where RF solutions are impracticable on safety, security or technological grounds. Significant progress has been made in the 5 years since the IEEE 802.15.7 standard was defined. Should commercial and private sector buy-in start to escalate, now that products are becoming available, it seems likely that performance levels will continue to increase rapidly in the coming years, providing a viable alternative to other wireless technologies without the disadvantages of RF. Testing in controlled environments will provide opportunities for technical authorities to have an early look at proposed solutions whilst also enabling structured feedback that could aid rapid development of the technology to a stage where employment in sensitive environments becomes feasible.

3.8. Summary

These technologies are at varying maturity levels and have a range of performance and security characteristics to support and deliver a breadth of requirements in the maritime domain. Basic performance metrics for the above standards are in the table below for comparison.

Table I: Wireless Technologies Performance Summary

	TECHNOLOGY	**SPECIFICATION**	**MAX SPEED**	**TYPICAL RANGE**
RADIO FREQUENCY (RF)	**Wi-Fi**	802.11a	54 Mbps	35m
		802.11b	11 Mbps	38m
		802.11g	54 Mbps	38m
		802.11n	600 Mbps	70m
		802.11ac	800 Mbps	35m
		802.11ad	7 Gbps	2-10m
	Bluetooth	Classic	3 Mbps	30m
		Low Energy	1 Mbps	10m
	ZigBee		250 Kbps	10m
	Z-Wave		100 Kbps	30m
FREE-SPACE OPTICAL (FSO)	**IrDA**	SIR	115 Kbps	1m
		FIR	4 Mbps	1m
		VFIR	16 Mbps	1m
		IrSimple	16 Mbps	1m
	LiFi*		40 Mbps	10m
* LiFi Theoretical Max Speed >200 Gbps				

4. Assurance, Security & Design Considerations

4.1. Information Assurance

Information is a valuable asset that must be appropriately controlled and protected against threats which can affect it. Information Assurance (IA) is about protecting and defending information and information systems and it focusses on the management of risk to the information’s Confidentiality, Integrity and Availability (CIA).

4.1.1. Accreditation

In the UK Accreditation is a mandatory business process for all official information systems that hold protectively marked information. It is an independent assessment of the information risks and the degree to which they are mitigated and managed in line with the business requirement. The principle of accreditation is to ensure risks associated with information are properly managed, with the aim of protecting the CIA of information to a level acceptable to the business. A key component of the accreditation process is the Risk Management and Accreditation Documentation Set (RMADS). This document, or set of documents, provides a comprehensive picture regarding an information system and its risks. An Accreditor uses the RMADS as the primary source of information in assessing whether a system is suitable for operational use. HMG IA Standard Numbers 1&2 provide a framework for the production of an RMADS; however it should be recognised that the documentation required for accreditation of an information system should be proportional to the information being processed and impact to the business if the information is compromised.

4.1.2. Architecture

CESG Architectural Pattern No. 12 proposes a number of architectures that are aimed at managing the security risks of wireless networking. Two architectures have been selected below as representative examples of implementation in maritime platforms.

4.1.2.1. Managed Endpoints and Access Points

For classified domains, and assuming that network access points and endpoints will be managed by the Authority, the architecture suggested in CESG Architectural Pattern No. 12 is as follows:

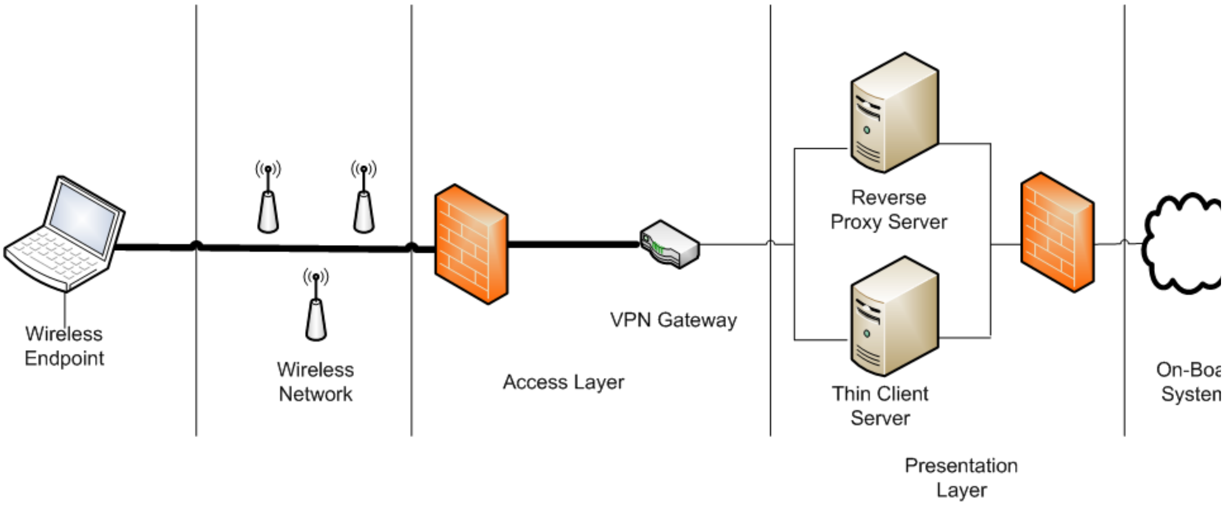

Fig.4: Managed Endpoints - Suggested Architecture

Any managed endpoint can associate with a wireless access point of the infrastructure; credentials are not required to associate with an access point under the control of the Authority. Users wishing to access existing on-board information processing systems must be in possession of the credentials required to pass through the VPN gateway. The confidentiality and integrity of the data transiting over the wireless network relies on a VPN tunnel between the endpoint and the VPN gateway which should be appropriately assured and configured for the traffic being passed in accordance with the available CESG guidance (current CESG guidance is focused at OFFICIAL).

The Access layer and Presentation layer provide a ‘Walled Garden’, as described in CESG Architectural Pattern No.2 to enable access to a sub-set of business services from remote endpoints. The reverse proxy is used to defend the internal services by authenticating remote users and ensuring they can only access appropriate web based applications, the thin client server is used to make internal, non-web based applications accessible.

This architecture is dependent upon the assurance of the firewalls and VPN solution. Currently the majority of government assured VPN solutions are certified at the OFFICIAL level and so, to enable the transfer and separation of higher impact level data, additional controls will have to be put in place (e.g. pre-encryption) or the development of a VPN solution that can be certified at higher standards.

4.1.2.2. Managed Access Points and Unmanaged Endpoints

For unclassified Welfare Internet Services, and assuming that network access points will be managed by the Authority but that the endpoints will be unmanaged and support Bring Your Own Device, the architecture suggested in CESG Architectural Pattern No. 12 is as follows:

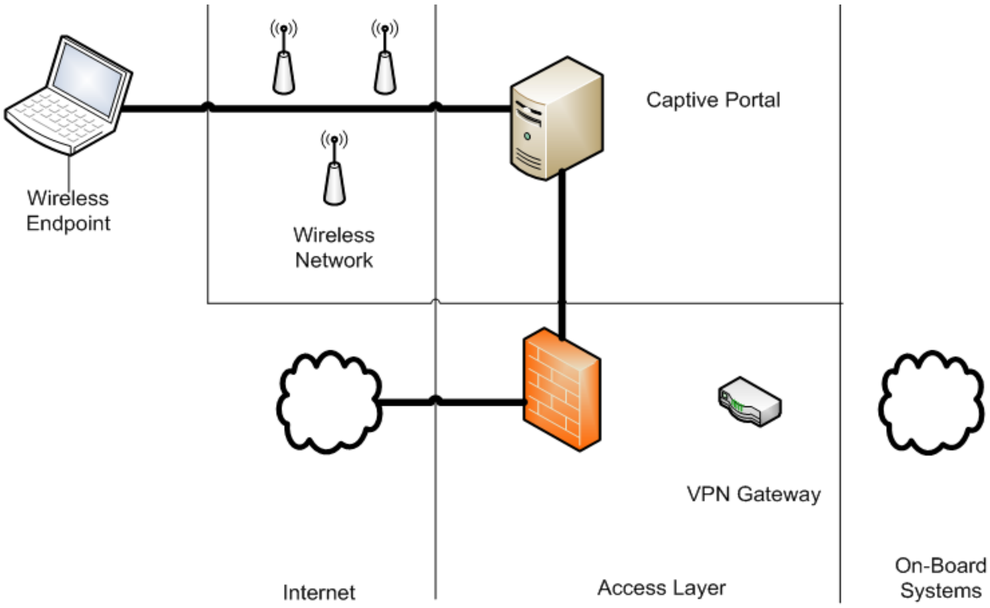

Fig.5: Unmanaged Endpoints - Suggested Architecture

Endpoints will need to authenticate to a captive portal before being granted access to internet services. Endpoints that are authorised to use the managed wireless infrastructure should obtain the required credentials from a credential provider.

The architecture illustrated does not provide for confidentiality of traffic transiting the wireless infrastructure, however Wi-Fi Protected Access - Pre Shared Key (WPA-PSK) provides a mechanism to protect the confidentiality of wireless traffic. It should be noted that on maritime platforms access will be required to on-board systems for communications off platform.

4.2. Communications Security

4.2.1. TEMPEST

In addition to intended emissions, all items of electrical and electronic equipment produce unintentional emanations, which can be intercepted by a receiving device at some distance from the radiating source. TEMPEST is the general term for naturally occurring and unintended emanations from electronic equipment and systems which can be intercepted and analysed to reveal compromising information. Basic TEMPEST countermeasures to reduce or control compromising emanations focus on the use of accredited equipment, good installation practice and the use of screening / screened rooms.

4.2.2. TEMPEST Threat

Short Range wireless Devices (SRDs) have low RF power output (< 100mW / 20dBm) for a variety of functional reasons such as conserving battery life and minimising interference with adjacent protocols; particularly those operating in the limited Industrial Scientific Medical (ISM) spectrum. Developments in Digital Signal Processing (DSP) have enabled RF transmit power levels for SRDs such as Bluetooth Low Energy (BTLE) and the proprietary ANT+ to be reduced to as low as 1mW (0dBm).

The same developments that have enabled the SRD market to develop have also enabled their interception at much greater ranges, particularly when used in conjunction with high gain antennas. SRDs should not, therefore, be considered as safer from SIGINT interception than other devices as low power devices, designed to work within the confines of a room, can be intercepted over the horizon with the right antenna.

4.2.3. Environmental Noise and Ducting

These substantial ranges do not account for the busy nature of the 2.4GHz ISM band which is normally oversubscribed in populated areas with many overlapping signals. These signals interfere with one another, especially if they are of the same protocol, e.g. 802.11g, which results in irrecoverable bit errors. If enough bit errors occur, information recovery becomes impossible for the receiving party (and intercepting sensors) but they do not stop the signal propagating and being detected at range.

Conversely, in an open sea environment with a typically low noise floor, the intercept range is not only more realistic but is a conservative estimate due to favourable propagation conditions over sea water (the most conductive of all radio terrains) and tropospheric ducting. Ducting is an anomaly whereby an emission is carried well beyond its normal attenuation parameters by refracting within a duct of warm air, similar to the way a beam of light bounces along a fibre optic cable.

4.2.4. Hatches and Windows

In a ship largely made of metal, the effects of Material Path Loss will contain SRD emissions within compartments whilst the hatches are shut. A small amount of RF may still be able to leak out of a compartment through rubber or ceramic seals covering pipework but this would only be practicably detectable in the adjacent compartment.

With hatches open, an SRD signal could travel for a considerable distance without relying on line of sight propagation. A wireless router in a cabin with an open door for example could radiate out, be reflected around a corner and out of an external open hatch. At the point of egress from the ship the signal may retain enough power for it to be intercepted at a substantial range. This risk can be mitigated through proper hatch discipline, careful siting of the router, or with an automatic kill-switch (inter-lock) circuit on each hatch.

The highest risk of intercept will be when a wireless device is used above deck or even on the bridge with only a pane of glass for suppression. With the height gain advantage, a low power device like a fitness tracker wristband could be intercepted at over a mile.

4.2.5. Automatic and Unintentional Transmissions

Many modern digital systems transmit management frames constantly to maintain the channel, even when not in use. A dormant 802.11 Wi-Fi network for example will send a beacon frame every 100ms to advertise its presence. Most low power devices beacon continuously to enable them to be found, they are promiscuous by design which carries risks. A wireless network will also transmit packets without human involvement due to services running on the network’s clients. Modern devices are tightly integrated with online cloud services as well as automatic updates and will generate traffic when idle. A failsafe to protect from this has been present on laptops and phones for some time in the form of wireless micro switches or ‘aeroplane mode’. These will stop the client device transmitting but will have no effect on the access point’s automatic transmissions.

4.2.6. Transmitter Siting

The location of a transmitter is key not only in determining its functional service area but in minimising unintentional leakage beyond the intended service area. For example, a transmitter in a compartment which has a line of sight view out of a door, and beyond into another compartment, would not be ideal. If it was moved adjacent to the door, such that it did not have a view out of it, unintentional leakage would be greatly reduced. Some RF leakage would still occur due to reflection within the metal compartment but the distance the signal must travel before exiting the area would be much greater and the chance of intercept reduced. These indoor propagation models show the modelled propagation of an access point.

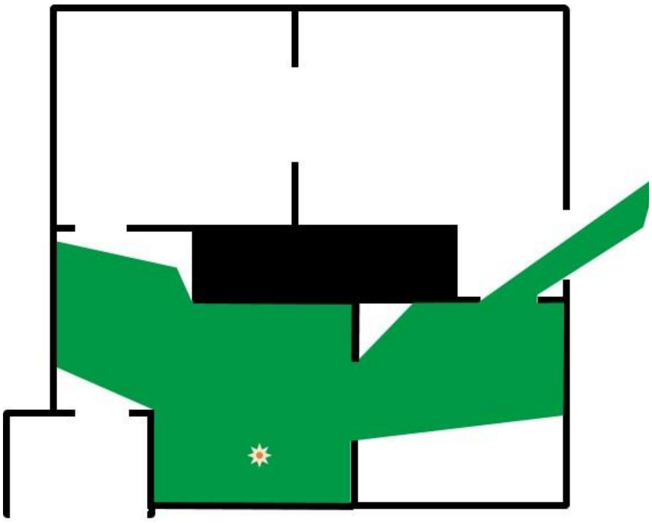

Fig.6: Indoor Propagation with Leakage

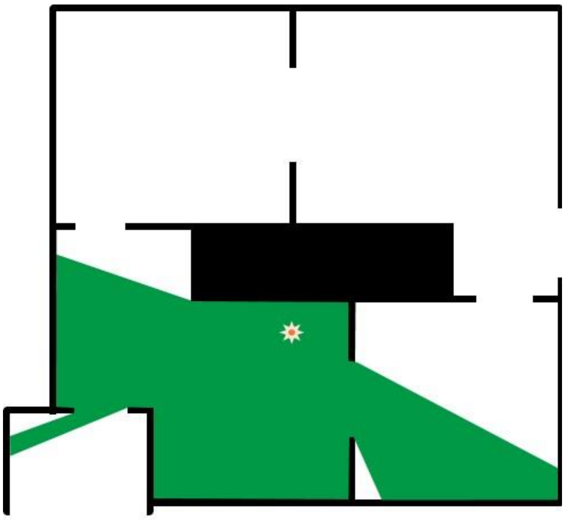

Fig.7: Indoor Propagation No Leakage

In the first image the AP is radiating beyond the compartments through three open hatches but in the second image it is positioned tactically so as to serve the compartment and not leak out - via its direct ray at least.

4.3. Cyber Threat

4.3.1. Radio Attack Surface

As well as previously discussed SIGINT risks, wireless networks are vulnerable to remote exploitation and deliberate denial of service. Wireless networks are especially attractive from an attribution and risk point of view as an attacker can explore them from a position of relative safety. Even if the channel encryption is strong enough to defeat an attacker, they can still gain a rich source of intelligence from low level framing information to enumerate networks and hosts to prepare them for an alternative approach.

A recent trend to make every gadget wireless has increased the attack surface of networks exponentially. Many gadgets like fitness bracelets support the Internet Protocol and have multiple interfaces, so even if one is secured well it might be compromised through another poorly secured or even undocumented interface. Most wireless products with a CPU are exploitable in one form or another, either through poor implementation of security features or software bugs in the driver itself.

Despite products supporting recognised industry encryption standards such as AES-256 or WPA2, a common theme noted by security researchers is for product manufacturers to use poor keys which can either be guessed, brute forced or stolen via undocumented interfaces.

4.3.2. Removable Media

USB sticks are infamous in information security circles as sources of infection due to their small and convenient nature. Developments in USB malware have seen hidden memory, belonging to the USB stick's own controller, used to store and deliver malware which cannot be detected or erased via conventional methods, including full disk formatting of the stick. Mobile devices including phones, wearables and media players are increasingly dangerous as many charge from a 500mA USB port as standard (as well as being powerful computers in their own right). Despite not being permitted, their owner's will eventually give in to human nature and charge them discretely from the nearest available USB port, even if that belongs to a classified system.

4.3.3. Bypassing USB Restrictions

Many secure hosts have USB disabled in the BIOS by policy. Some may accept only pre-approved whitelisted devices for commercial or security reasons. A whitelist for a USB device will use its idVendor and idProduct fields; however, these can be spoofed to bypass restrictions.

A single USB gadget can have multiple interfaces which it can present to the host; this is how a smartphone is able to be reconfigured to perform multiple roles over a single USB interface. This principle has been exploited by penetration testers to make a benign USB device appear to the host computer as a trusted Human Interface Device (HID), such as a whitelisted keyboard from an approved vendor. The fake 'virtual' keyboard can then issue keystrokes from a script, despite USB whitelisting, and then re-role as a (trusted) USB storage device to receive the stolen data.

Any USB powered device, no matter how innocuous or basic is a threat.

4.3.4. Dormant Wireless Bridges

Classified computers do not historically have active wireless interfaces but do, increasingly, have dormant adaptors on their circuit boards. These can be disabled at the hardware level by interfering with the circuitry. However, this is made increasingly difficult due to miniaturisation and is thus typically software disabled in a restricted menu like the BIOS. Any configuration change such as this is not guaranteed to persist after software/firmware updates, or an unexpected power/memory failure. Hence, there is a very real risk that a disabled (and accredited) wireless interface may become active again in the future and expose the host to attack. Avoiding software updates as a strategy to protect tightly configured secure networks is not recommended for obvious reasons.

4.3.5. Supply Chain

In a world of white labelled electronics where most vendors use common black-box components, supply chain security is a huge problem. A secure system may be built by a contractor who employs a sub-contractor who cuts corners and introduces counterfeit electronics into the supply chain; a largely accidental problem, driven by a desire to maximise profit through cheap components where possible. The risk to availability caused by counterfeit electronics is obvious, but if the weakness is known by an adversary it could be remotely triggered. In the case of fake components in a US helicopter programme, this could have allowed an adversary to blind a helicopter's night optics permanently.

A greater concern is where hidden functionality is deliberately introduced into the supply chain. This concern can be mitigated through very thorough and laborious reverse engineering, but the nature and pace of modern technology means that code and computer chips are being minted faster than they can be practically reviewed. There is a genuine risk that a computer chip on a secure computer may contain a backdoor.

4.3.6. Software Bugs and Backdoors

On average, software applications have 10-20 bugs per 1000 lines of code. If a wireless device's circuit board is composed of a third party core, a network controller and a Digital Signal processor (DSP) chip, with a total of 10,000 lines of code in their (proprietary) firmware, there will be at least 100 bugs before the manufacturer's firmware is added on top. Most will be benign but some, when triggered, could result in a denial of service or arbitrary code execution. A backdoor doesn’t have to be a secret password or additional code; it could be a very subtle engineered vulnerability such as a lack of bounds checking on an input buffer.

4.3.7. Insider Threat

The human is the weakest link in computer and network security. It must be accepted that there is always a risk that a trusted individual will interfere with or exploit a (wireless) network for a variety of reasons. Insider threat is defined as the risk of attacks to or security breaches of an organisation or system from people within it. These could be permanent or temporary employees or even part of the supply chain, but people who generally have access to critical systems, assets and information. Insider attacks or breaches are complex events, influenced by a number of psychological and socio-cultural drivers, which may be triggered by individuals with malicious intent or as an unintended consequence of their actions.

The malicious insider is a real and prevalent threat and their deeper knowledge of the organisation's systems allows them to better exploit known weaknesses and act 'under the radar' for longer periods of time. Unfortunately, many industries do not have an insider threat programme in place and are critically under-prepared for dealing with the threat. Similarly, there is too often a drive to solve the issue purely with technology, when a more holistic approach that focusses on understanding the human psychology and behaviour that underpins it is much more appropriate.

Unintentional insider threat is defined by harm to an organisation that is conducted or facilitated by an unwilling, unknowing and non-malicious employee. Unintentional insider threat relates much more closely to human error than it does to malicious behaviour. Whereas malicious behaviour is clearly the fault of the person doing it, human error must be treated as an inherent human condition and therefore not always the fault of the human. This can be mitigated through better system and organisational design that supports the human in the system. Dealing with malicious and unintentional insider threat in different ways shows an added appreciation and understanding of the risk and avoids an inadequate ‘one size fits all' solution being rolled out.

The greatest risk to wireless networks comes from the unintentional insider threat and can take many forms, including:

- Unauthorised devices introduced onto the network (such as USB memory sticks, mobile phones and smart jewellery) allow a malicious application to survey, intercept and exploit local wireless networks, without the knowledge of the device’s owner.
- Network security keys and certificates are compromised by the loss of a client device, such as a tablet or laptop.
- A confined signal could be unintentionally leaked out above deck, leading to unintended interception and exploitation.

4.4. Electromagnetic Compatibility

Electromagnetic Compatibility is the ability of a device, equipment or system to function satisfactorily in its intended operational electromagnetic environment without adversely affecting anything else in that electromagnetic environment. It should also be able to operate without intolerable electromagnetic disturbances, degradation of performance or malfunction. This is best achieved by equipment being designed and built to meet a pre-determined electromagnetic environment.

A major concern with introducing new wireless technologies in to a sensitive environment is EMC and harmony with international and MoD allocated spectrum, as well as other technology already on-board the platform such as SCADA devices. The EMC characteristics specific to individual wireless standards vary but, in general, co-located wireless networks should be on different channels separated by a guard channel to avoid interference. For 802.11, a channel has an overlap of 2 channels either side.

5. Summary

5.1. Wireless Technologies

A broad range of wireless options were considered from across the electromagnetic spectrum, including the traditional Radio Frequency based technologies, such as Wi-Fi and Bluetooth, and those operating in the Infrared, Visible Light and Ultraviolet bands. Ultraviolet was discounted immediately as there are no developments for short range networks. Laser communications were considered initially due to previous implementations in campus network solutions, however these devices are no longer available and current developments are focused on space communications.

The remainder (Wi-Fi, Bluetooth, ZigBee, Z-Wave, IrDA and LiFi) were considered to have potential utility in the maritime domain either now or in the future. The technologies are at varying maturity levels and have a range of performance and security characteristics to support and deliver a breadth of requirements in the maritime domain.

5.2. Accreditation

Accreditation is a mandatory business process for all information systems that hold protectively marked information. It is an independent assessment of the information risks and the degree to which they are mitigated and managed in line with the business requirement. The principle of accreditation is to ensure risks associated with information are properly managed, with the aim of protecting the Confidentiality, Integrity and Availability (CIA) of information to a level acceptable to the business. A key component of the accreditation process is the Risk Management and Accreditation Documentation Set (RMADS). This document, or set of documents, provides a comprehensive picture regarding an information system and its risks. An Accreditor uses the RMADS as the primary source of information in the assessment as to whether a system is suitable for operational use. Identification of information assets is fundamental to successful assurance; without understanding the information, the risks to the information cannot be assessed and nor can the impact to the business of any compromise. Without an understanding of the risk inappropriate controls could be implemented either leaving vulnerabilities that could be exploited or, conversely overkill which would waste time and resource.

5.3. TEMPEST

Basic TEMPEST countermeasures to reduce or control compromising emanations focus on the use of accredited equipment, good installation practice and the use of screening / screened rooms. However, modern technology enables the interception of relatively low power signals at significant ranges and environmental noise, platform structure, transmitter siting and automatic / unintentional network transmissions will all be important design considerations for future wireless projects.

5.4. Cyber Threat

In addition to SIGINT risks, wireless networks are also vulnerable to remote exploitation and deliberate denial of service. Wireless computer networks are especially attractive from an attribution and risk point of view as an attacker can explore networks from a position of relative safety. Even if the channel encryption is strong enough to defeat an attacker, they can still gain a rich source of intelligence from low level framing information to enumerate networks and hosts to prepare them for an alternative approach. Removable media, software vulnerabilities, dormant wireless bridges and supply chain weaknesses are all important considerations in threat assessment and design.

5.5. Insider Threat

The human is the weakest link in computer and network security and insider threat is defined as the risk of attacks to or security breaches of an organisation or system from people within it. Insider attacks or breaches are complex events, influenced by a number of psychological and socio-cultural drivers, which may be triggered by individuals with malicious intent or as an unintended consequence of their actions. The greatest risk to wireless networks comes from the unintentional insider threat and can take many forms; unauthorised devices being introduced onto the network, network security keys and certificates being compromised by the loss of a client device or a confined signal being unintentionally leaked out above deck, leading to unintended interception and exploitation.

5.6. Electromagnetic Compatibility

A major concern with introducing new wireless technologies in to a sensitive environment is EMC and harmony with international and government allocated spectrum as well as other technology already on-board the platform such as SCADA devices. This is best achieved by equipment being designed and built to meet a pre-determined electromagnetic environment.

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Marine 4.0 - Condition Monitoring for the Future

Patrick Müller, Siemens AG Marine, Hamburg/Germany, patrick.pm.mueller@siemens.com

Abstract

This paper presents the challenges of designing and operating marine facilities in a digitally optimized, competitive and sustainable way by using Big Data, Data Mining and Digital Twins. The main focus of the application presented is the condition based maintenance of ship machinery.

1. The challenge: Preparation of ship data for process analysis and management decisions

Digitalization is essential for every business, especially marine. Nowadays increasing the efficiency and performance of a vessel is mandatory, referring to laws & regulations. But this is not an easy task, neither for the crew nor for the owner or operator. Remote support systems are becoming state of the art and a default integral system on new buildings. Furthermore, remote access from onshore facilities is mandatory for prosperous fleet management.

Currently, ships use numerous sophisticated installations and systems on board. Each one delivers data on its status, performance, and efficiency. However, the collected data cannot be used for process optimization due to their protective and inconsistent nature. Comparability between the performances of peers is impossible since different circumstances cannot be guaranteed. Drawing conclusions for the entire fleet is difficult.

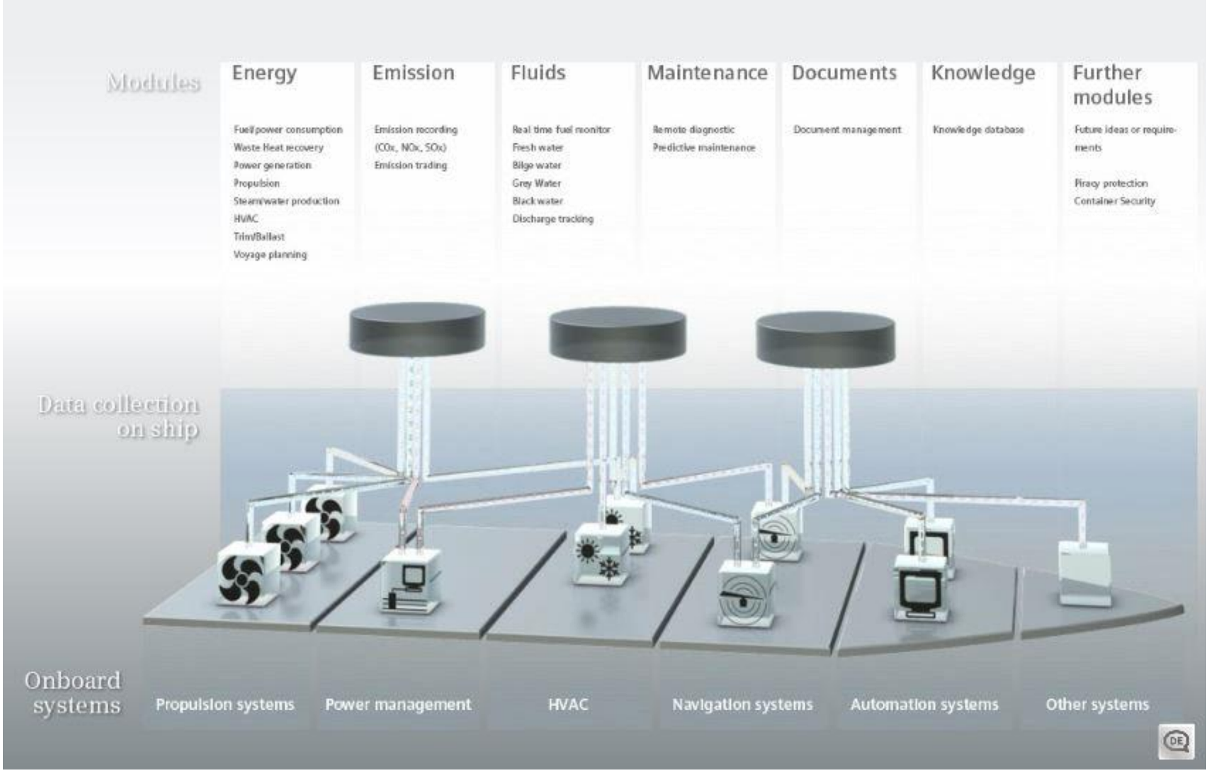

Fig.1: Status Quo

To wipe out mentioned challenges it is crucial to collect and provide all information in a consistent manner. Therefore, the collection, consolidation and storage of gathered data is mandatory. Two challenges coming along with the needs of the described data acquisition. First there is a wide range of different interfaces to be handled, second is the large quantity of accumulated data.

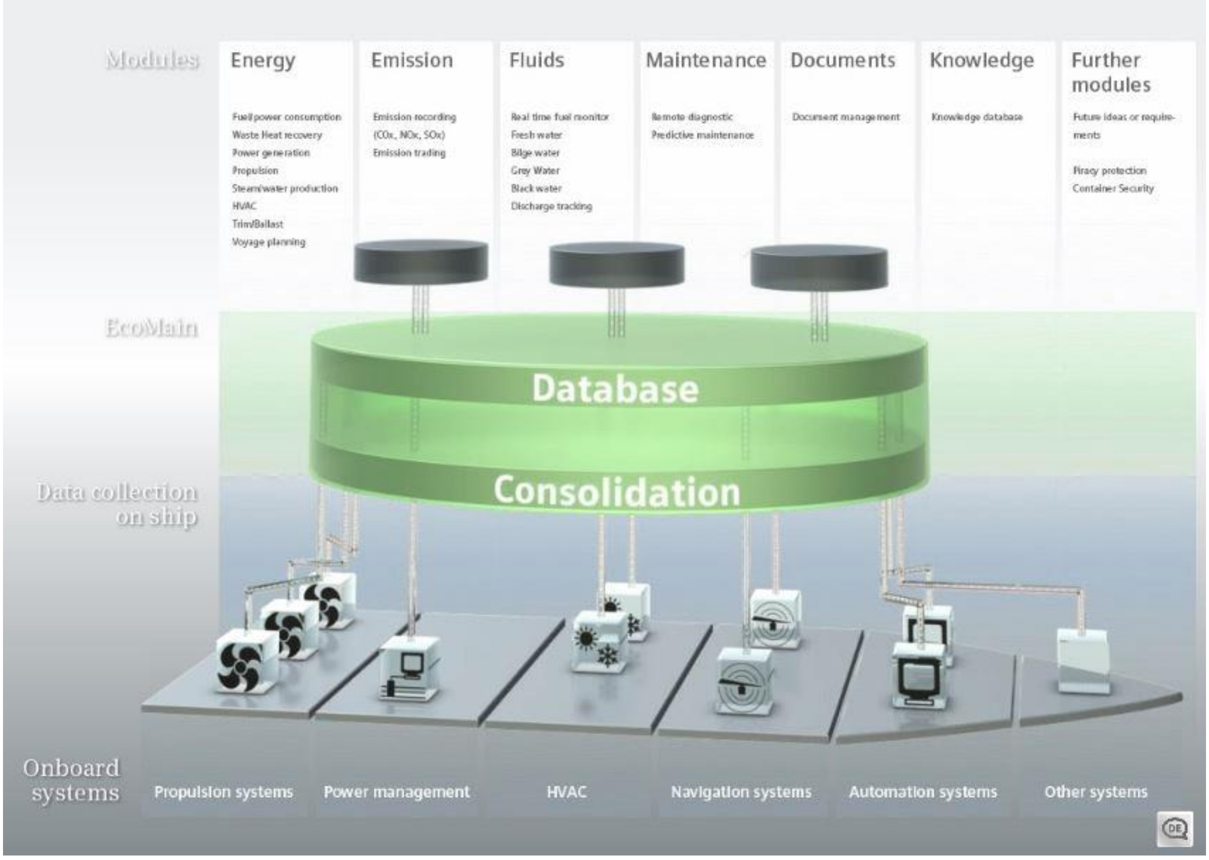

Fig.2: Approach

For instance, it is functional to name some background information and figures based on a real case. In 2016, Siemens delivered a cruise liner project with the following key figures:

- More than 80.000 data points,
- including all relevant technical on-board systems e.g. power management, propulsion, engine room automation, cabin automation, HVAC and navigation,
- fast acquisition cycle – one second for approximately 2000 data points,
- on-board storage of data for 18 month.

In simple terms, the shipping industry is already dealing with “Big Data”.

2. Big Data, what does it mean?

One common keyword in the context of digitalization is Big Data. But what does it really mean? What is the challenge? How could Big Data support the shipping industry? In general, Big Data is the description of operationally generated data volumes which are complex, fast moving, not or less structured and after all, with a vast quantity. Volume, velocity and variety are defining the three dimensions of Big Data.

The mass of information respectively content of Big Data is more or less unreadable and unmanageable. The question is for what purpose the Big Data shall be acquired? Couldn’t it be sufficient to collect and manage only the ordinary operating information from the on-board systems? But this is not enough to meet the daily needs of marine business anymore.

The answer is given by Big Data itself. If each available information is collected and stored it is impossible to miss important data. This generic view and description is a simplified statement, but valid for the industry and especially for the shipping industry in terms of the challenging environment of marine business.

Fig.3: Big Data, where is the information?

3. Data Mining – How to extract useful information from Big Data

The huge variety of different data sources requires algorithms in order to fulfil the tasks humans are not able to. These tools and methods automatically handle large quantities of data to extract previously unknown patterns and are known under the term “Data Mining”. Neither the data collection or the data preparation, nor the result interpretation and reporting are parts of the Data Mining step. Additional applications are necessary to process the data towards the operators.

Fig.4: Data Mining - Finding the information you need

4. “Digital Twin”, the virtual asset

Another vital keyword in this context is Digital Twin. Generally, the naming itself, explains its function. The Digital Twin is a virtual copy of a real asset. This includes all mechanical and electrical construction data, as well as its physical behavior. In addition, environmental conditions which are subsequently added to the Digital Twin influence its behavior. To build up a complex ecosystem like vessels, lots of specific Digital Twins assemble a complete copy of the whole system. They influence each other by interaction, like the assets are performing in the real plant.

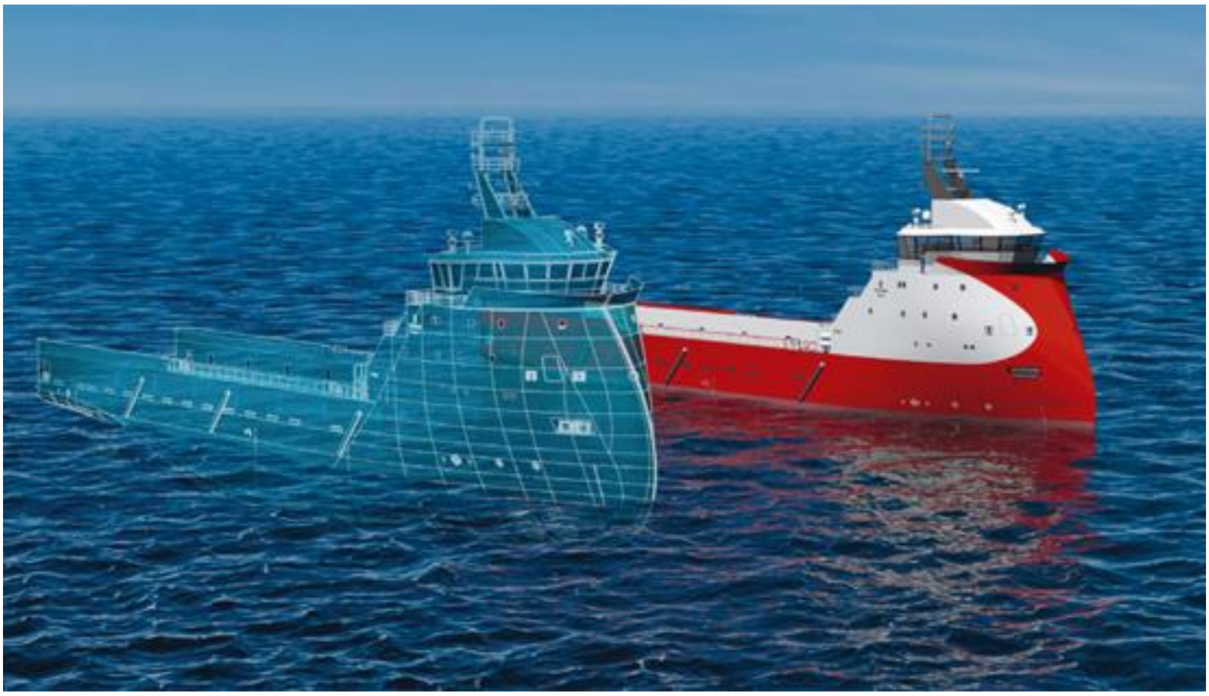

Fig.5: Digital Twin, the virtual copy of the reality, source: DNV GL

All steps between vessel design throughout operation, maintenance and service benefits from Digital Twins. Consistent real time replicas of equipment and systems in all imaginable device states, for instance construction progress, working conditions or positions, can be used for monitoring diagnostics and prognostics based on individual applications.

5. The EcoMAIN approach

Increasing complexity of on-board systems results in a wide variety of technical tasks for the staff onboard. Troubleshooting in complex systems requires deep knowledge about the installed technologies and interdependencies. Crews are changing frequently and the time for vessel handover is decreasing due to cost reduction. On top of that it is not possible to permanently have experts for all technologies available on every vessel.

Siemens Marine developed an economic and ecologic multi-application infrastructure to face those challenges, called SISHIP EcoMAIN. This platform helps with ship management decisions by delivering data from all relevant on-board systems and equipment on a joint platform that can also be accessed from onshore. This functionality allows it to compare important operating parameters across an entire fleet, which is mandatory to identify optimization potentials and implement best practices that will significantly reduce operational costs. These potentials are based on the areas of energy efficiency, environmental compliance and maintenance support.

The system also allows data exchange between different proprietary applications, becoming an integrated part of SISHIP EcoMAIN. No matter if they are third-party or Siemens based. The standard interface for all applications is able to return output data to the database which can be utilized as input for other applications. If required this enables smart data handling and improvements beyond pure basic analysis, e.g. energy optimization, waste heat recovery potentials or electronic logbook. These are examples for further extended analysis, done by applications to create real customer value up to optimized fleet management.

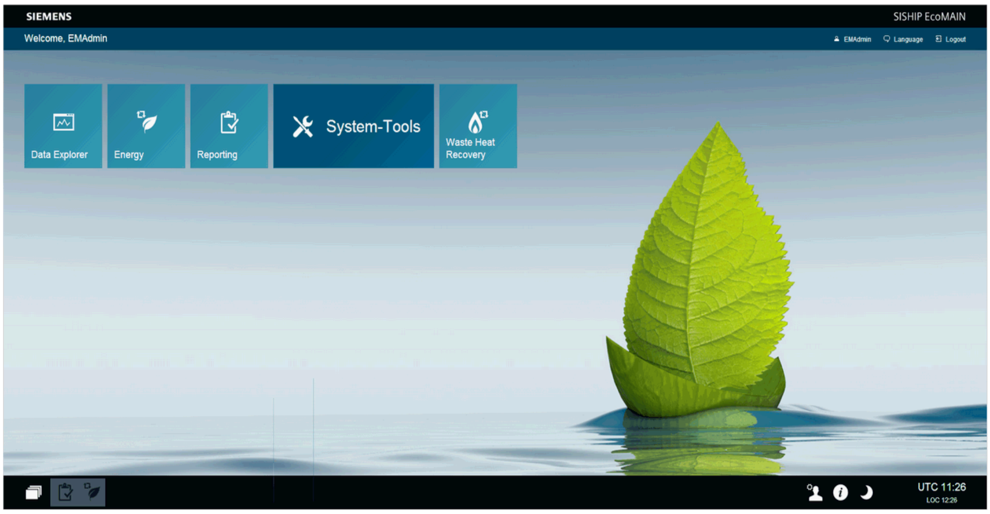

Fig.6: EcoMAIN – web-based home screen

6. Condition based monitoring with EcoMAIN as an example for digitalization

The usage and value of digitalization can ideally be described by an example related to real life: The condition based monitoring application of SISHIP EcoMAIN for the podded propulsion system SISHIP eSiPOD. As cargo and passenger space is essential valuable on board, it is necessary to find a replacement for the conventional diesel-mechanical shaft line arrangement in certain types of ships. The SISHIP eSiPOD has been developed by Siemens as a low-maintenance and space saving propulsion solution that provides an optimum of maneuverability and high efficiency, meeting highest safety standards. No other propulsion system provides as much flexibility when it comes to the design of the hull and the engine room combined with 360° maneuverability. The space-saving design of the propulsion system allows an increase in availability of cargo and passenger space, which fits perfect to the requirements of cruise ships, large ferries, passenger ships, midsized freighters, tankers, icebreakers and so on. The reduction in noise and vibration enhances comfort, especially on board of all kind of passenger vessels.

Fig.7: SISHIP eSiPOD

A complex system, like the SISHIP eSiPOD, has many sensors installed to ensure safe and frictionless operation. In addition, many subsystems, subassets and auxiliaries are essential parts of a podded propulsion plant. The installed control systems are mainly focusing on a safety and comfortable operation.

Maintenance is another major field of activity that comprise opportunities for high cost savings by transparent and efficient management. Condition monitoring systems (CMS) will become more and more important for ship and fleet operators. Remote access systems assure system availability and uptime in case of disturbances. Thus, early warnings can be utilized for short time technical support and speeds up e.g. response time for change of components and software updates. It allows sending specialists, split from necessary spare parts, to the next stop-over.

The condition based monitoring application of SISHIP EcoMAIN for the podded propulsion system SISHIP eSiPOD gives the operator on board an overview of all system relevant measurements, from generators to switchboards, transformers, converters and all other components. All figures are stored in the database of SIHIP EcoMAIN.

As continuous monitoring for propulsion systems generates Big Data, Data Mining becomes essential. To validate the collected data from the real life propulsion system, a Digital Twin is substantial. It provides a calibrated model which can give real time values for double checking the current situation of the plan. Comparing simulated and real values, systematic analysis of the system can be maintained in order to provide a valuable condition based monitoring system. This is crucial for a high availability of the whole plant by enabling predictive maintenance.

For the operator it is essential to get clear messages from the system: What is the problem? Where is the problem? How can it be solved in the best way? The answers can be derived from the specific Digital Twin. By using it as 3D-model with markups of the affected area, the operator gets a general idea of the issue. With additional clear text messages the problem will be described and a possible solution will be mentioned. In addition, it is possible to virtually walk inside the 3D-model to get a feeling about the location and the requirements of the maintenance task. Guided training scenarios in the model support the repair or change of the effected part of the plant. A spare part list with all relevant information, like supplier and order numbers, leads the application to a powerful condition based monitoring system and provides high potential benefits for the customer.

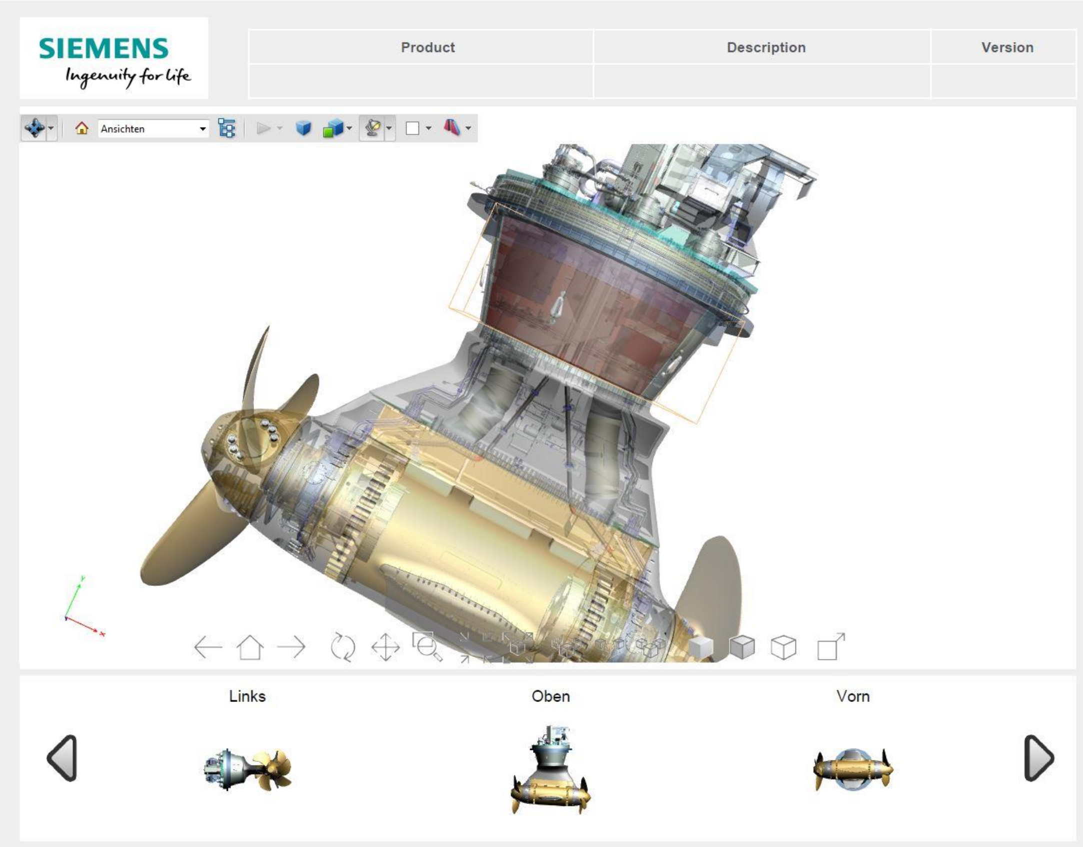

Fig.8: 3D Model

The established CBM mechanism could be extended to the entire vessel. Due to this SISHIP Eco-MAIN lays the foundation for efficient ship management on-board and supports green fleet management over the entire fleet.

7. Conclusion

Together with the increasing digitalization of the whole vessel with more complex and higher sophisticated equipment, like podded drives, the future of marine will go digital with the approach of all-electric ships. Such solutions require incorporation of digital engineering over the whole lifecycle: from design to construction to operation including training, maintenance and service – all over the whole life cycle. Siemens is prepared for this by providing the fitting systems and solutions.

Generic Control Strategy
for Future Autonomous Ship Operations

Martin Kurowski, University of Rostock, Rostock/Germany, martin.kurowski@uni-rostock.de
Agnes U. Schubert, MATNAV e.V., Rostock/Germany, agnes.schubert@matnav.de
Torsten Jeinsch, University of Rostock, Rostock/Germany, torsten.jeinsch@uni-rostock.de

Abstract

This paper describes a generic concept to control diverse marine vehicles. The approach is based on a hybrid model of the vehicle motion while transiting, manoeuvring or station keeping mode, consisting of modules of the propulsion and steering gears, the vessel dynamics as well as the disturbances. The hybrid scheme was refined further by generalisation of the transition between two motion states within one mode and between distinguished modes. The hybrid control structure is composed of the feedforward and feedback control including allocation corresponding to the active model. The strategy was applied to different marine vehicles; an ocean-going unmanned surface vehicle (USV) and a ferry model in a ship handling simulator. The developed control structure belongs to the first results of the cooperative project 'GALILEOnautic'. By using satellite-based navigation and sensor data fusion, the project contributes important tools for assisting safer and more efficient ship operations especially in limited fairways with the vision to autonomous shipping.

1. Introduction

The maritime sector is facing substantial technological changes. Due to the ongoing globalisation, maritime trade is steadily growing despite the fluctuating sales of the oil and gas industry as well as of the shipbuilding sector. Besides that, the ship traffic is growing because of the increasing offshore activities. The key drivers are the alternative energy industry, especially by expanding offshore wind farms, and the exploiting new mineral deposits in the deep sea. The result is a higher traffic volume in harbours or narrow waterways with equivalent higher coordination effort. Additionally, the technological progress in the shipbuilding industry causes increasing size of vessels and operative changes such as fairway and passing limitations. Significant disturbances as wind, current or fog enhance the risk of collision or other hazardous situations. Statistics show that the number of accidents rises and therewith in principal the costs within the shipping industry. The largest percentage of accidents (75 - 96 %), was due to human failure including vehicle loss, collision or grounding, *Fields (2012)*. The majority of these accidents could avoid by application of assistance systems in the nautical decision making process, *Porretta et al. (2016)*.

The subjects of recent research projects focus on unmanned ships to demonstrate the feasibility by application of common technologies, *Burmeister et al. (2014)*. Primary, the transiting motion mode is investigated because the established methods of automatic control offers sufficient control quality in this speed range and there is enough space to solve encounter situations. However, the automatic manoeuvring is excluded in limited and safety-critical areas. Optionally, the unmanned vehicles will be remotely operated by land-based radio or satellite communication systems, *Levander (2017)*. But, the autonomous systems are the future topic in all fields of global mobility. The investigations include assistance systems, innovative sensors and environment recognition systems, as well as a progressive digital interlinking to develop the basic infrastructure of safe and effective autonomous transport.

2. Problem formulation and related works

The joint project *'GALILEOnautic'* especially aims to develop control systems for fully automated vessels cooperating with each other in areas with high safety and efficiency requirements, such as harbours, harbour entrances or narrow waterways. The particular institutions compile methods to coordinate autonomous vessels centrally as well as to ensure a safe automatic or closed-loop control of the vessels in different operation modes, also in error cases. The complete system includes modules for fusion of data from standard ship sensors with the highly precise Global Navigation Satellite System (GNSS) information to allow safe and reliable positioning and navigation. The European global navigation satellite system GALILEO can support the automatic ship guidance by integrity information. The system implements features for continuously monitoring of the ship functions, active safety systems using fault diagnosis and proactive, fault-tolerant closed-loop control of the ship motion.

In general, there are two classes of ship guidance, navigation, and control systems (GNC), which were developed temporally parallel. On the one hand the complex systems for dynamic positioning (DP) with defined components by IMO respectively IMCA, *IMO (1994)*, and on the other hand the classical systems for heading control and path following applied to ferries, cargo or cruise vessels, *CENELEC (2014)*. The two systems differ substantially in the working mode respectively the velocity range and the implemented methods. From the control-technological point of view, it will be distinguished between interference variable control during dynamic positioning and follow-up control at cruising speed. Special, highly dynamic propulsion systems are a technical requirement to dynamic positioning. The heading control and path following control systems were developed for conventional propeller rudder combinations used in classic transport vessels.

Furthermore, the technological implemented and scientifically reported ship GNC systems differ essentially. In technological applications, linear control methods are used based on linearised models of the ship motion. In scientific solutions, nonlinear methods dominate verified by scaled ship models, unmanned vehicles or simulations. What they have in common is that they are always designed for a restricted working range, for cruising speed or dynamic positioning. Tendentially, there are single developments to realise the two functions by one system. The modern DP-systems can be used also in transiting mode and are supplemented by further functions like auto heading, auto area, autopilot (course control) or auto tracking for defined way points.

The requirements of each function significantly differ in working range and dynamic behaviour. Therefore, each function needs a different control approach combined in a hybrid control scheme with linear and nonlinear controllers. According to the current process and environmental conditions, a supervisor switches to the suitable controller from the given set. The switching bases on the performance comparison of the current and the next relevant controller. Similar to an adaptive structure, the performance is evaluated by measuring the manipulated and controlled variables in a separate feedback loop. In contrast to adaptive structures, the adaption between process and controller is not continuously but a discrete switching between various controller structures as shown in Fig.1, *Morse (1995)*.

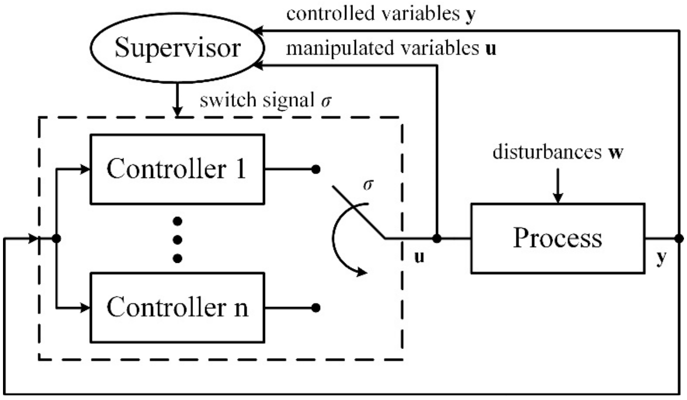

Fig.1: Scheme of a switching control system based on *Morse (1995)*

3. System concept

In this paper, an elementary new hybrid control approach applied to manoeuvring vessels is presented. As shown in Fig.2, the motion of the vehicle is modularised and divided into different operation domains. Each motion mode is characterised by its velocity range. In that way, various modes like transiting, manoeuvring or station keeping can be defined. However, the parameters of the motion models can continuously change within one motion mode and between two different motion modes. Independently from the motion mode, the disturbances affect the process in varying degrees by wind, current and other environmental factors. This hybrid concept provides the possibility to use generic simplified model structures valid in all motion states of any marine vehicle. Therefore, all effects of resistance generated by hull of the vehicle and its attachment parts as well as by variability of the propulsion and steering devices or by the effects of the motion through the fluid as restoring, Coriolis and centripetal forces are modularised. There is no restriction to linear or nonlinear description in the single modular structure. The effects by negative longitudinal velocities are described separately because of the significant changes in effectivity of the propulsion unit and in the hull resistance, especially in case of higher negative velocity beyond the DP operation. Based on the linearisation in operating points, the transition between two operating points can be generalised solely depending on current state and difference to the next commanded state. The new commanded state is calculated from the forces and torques generated by the propulsion and steering units.

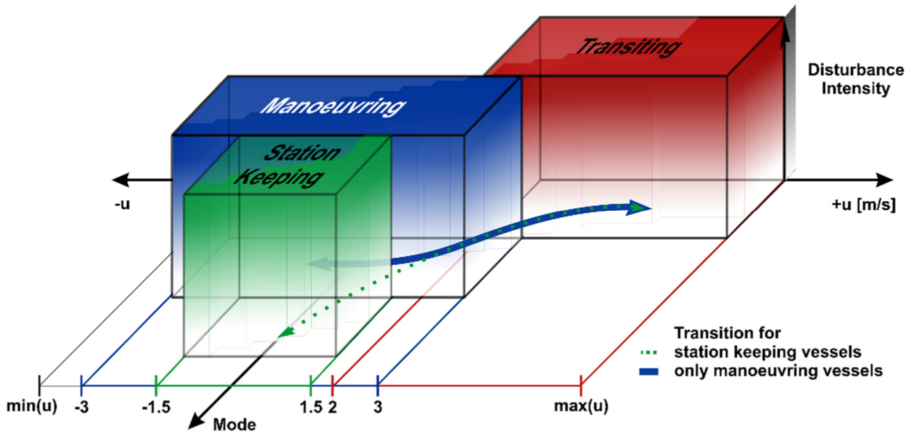

Fig.2: Generic hybrid concept with continuous description of different motion modes

Finally, the feedback control objective is to keep the marine vehicle on a given path, to follow heading or velocity changes and to compensate disturbances. According to actual disturbances and motion modes, different controllers have to be provided in a controller bank switched by a supervisor as suggested in Fig.1. Therefore, a modular control concept is considered using a unified inner loop and a variable outer loop, as introduced in *Kurowski et al. (2015)*. The inner loop is designed as multiple input multiple output (MIMO) velocity control system, which is a substructure of the variable outer control system. These primary controllers generate the desired velocities for the velocity control loop. The inputs of the primary control system are generated by the vehicle guidance system and consist of different desired values like heading, bearing and position as well as the error values. The states of the vehicle on the velocity level and the position and attitude information in the earth-fixed frame are calculated by the vehicle navigation system, which has been shown for USV in *Kurowski et al. (2015)*.

4. Model approach

4.1 Notations and marine modelling basics

The motion of marine vehicles is described in two reference systems. The movement on the earth's surface is given in an earth-fixed frame, which is defined as inertial north-east-down (NED) frame. Additionally, a body-fixed frame is defined, which is fixed to the vehicle. Fig.3 shows the defined frames and notations, where

- $\mathbf{v} = [u\ v\ w]^T$ are the linear velocities: surge (x-axis), sway (y-axis), and heave (z-axis) in the body-fixed frame,

- $\boldsymbol{\omega} = [p\ q\ r]^T$ are the angular velocities: roll, pitch, and yaw about the axes of the body-fixed frame, and
- $\mathbf{x_0} = [x_0\ y_0\ z_0]^T$ is the position of the vehicle according to the earth-fixed frame.

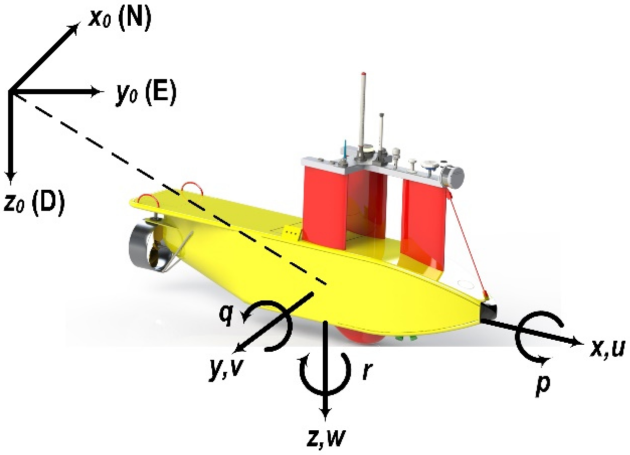

Fig.3: Definition of frames and notations

Additionally, the attitude of the vehicle is defined by the Euler angles $\mathbf{\Omega} = [\Phi\ \Theta\ \Psi]^T$, which represent the relative angle between the body-fixed and the earth-fixed frame. Finally, the transformation from body-fixed to earth-fixed frame is done by using standard rotation matrices given in the literature.

The dynamics of marine vehicles are described as slim rigid-bodies moving in the earth-fixed frame under the influence of forces $\mathbf{F} = [X\ Y\ Z]^T$ and torques $\mathbf{M} = [K\ M\ N]^T$, which can be described by Newton's laws. Assuming that the origin of the body-fixed frame coincides with the center of gravity, the motion equations of a body in a fluid is transformed to the body-fixed frame using the so-called Kirchhoff equations, which lead to matrix representation of the equations of motion

$$\mathbf{M_h}\dot{\mathbf{x}} + \mathbf{C_h}(\mathbf{x})\mathbf{x} = \mathbf{D_h}(\mathbf{x})\mathbf{x} + \mathbf{S_h}(\mathbf{x_e}) + \mathbf{H_a} + \mathbf{H_d}, \tag{1}$$

where $\mathbf{x} = [\mathbf{v}^T\ \boldsymbol{\omega}^T]^T$ is the state vector of the nonlinear model. $\mathbf{M_h}$ describes the hydrodynamic inertia matrix, which consists of the vehicle mass and moment of inertia, and $\mathbf{C_h}$ is the Coriolis and Centripetal matrix including added inertia effects. On the right-hand side, the sum of external forces and moments acting on the vehicle presented by damping matrix $\mathbf{D_h}(\mathbf{x})$, stiffness matrix $\mathbf{S_h}(\mathbf{x_e})$, using $\mathbf{x_e} = [\mathbf{x_0}^T\ \mathbf{\Omega}^T]^T$, actuators $\mathbf{H_a}$, and disturbances $\mathbf{H_d}$.

In practice, it is a cumbersome task to identify the unknown parameters of the nonlinear model, due to strong couplings of the motion variables, measurement noise and unknown disturbances. Hence, the dynamics can be divided into different subspace models, e.g. uncoupled planar motion, roll motion, etc., which complies with the modular system concept.

4.2 Planar motion models

Due to the modular design approach, the planar motion model of a marine surface vehicle consists of three essential modules, the static gear, the disturbance and the dynamic module as shown in the model components of Fig.8. In static and dynamic modules, the vessel motion is described in a simplified form in three degrees of freedom (DoF) for the longitudinal (u), lateral (v) and rotational (r) velocity depicted in Fig.4.

Eqs.(2)-(4) define the accelerating forces using the oriented masses and the inertial torque as the simple sum of actuator forces and moments (X_p, Y_p, N_p) as well as the overall resistance forces and moments (X_r, Y_r, N_r) in the respective direction. The actuator forces and moments are the sum of resulting forces of each propulsion and steering gear unit of the vehicle. The resistance forces result from the incident hydrodynamic flow as well as the friction forces. The steady state of the vehicle motion is characterised by constant velocities respectively no acceleration so that the left site of the equation will be zero. In consequence, the actuator forces are equal to the resistance forces for the current settings of the actuating variables in the steady state. To identify a specific actuator force, the definition of the resistance force in Eq.(5) can be used, where ρ is the density of water, A the submerged area in the motion direction, and c the shape factor of the vessel body in the respective direction. These constants are aggregated in constant k.

$$m_x \dot{u} = X_p - X_r \tag{2}$$

$$m_y \dot{v} = Y_p - Y_r \tag{3}$$

$$J_{zz} \dot{r} = N_p - N_r \tag{4}$$

$$X_r = \frac{\rho}{2} \cdot A_x \cdot c_x \cdot u^2 = k_{xr} \cdot u^2 \tag{5}$$

In the static gear module, the identified forces of the propulsion and steering units in each combination and separated according motion direction are summarised by lookup tables. For example, the effectivity of the steering gears depends strongly on longitudinal velocity. Simultaneously, a rudder deflection or an active thruster reduce this velocity. For a complete signification of the model, all effects have to be systematically analysed.

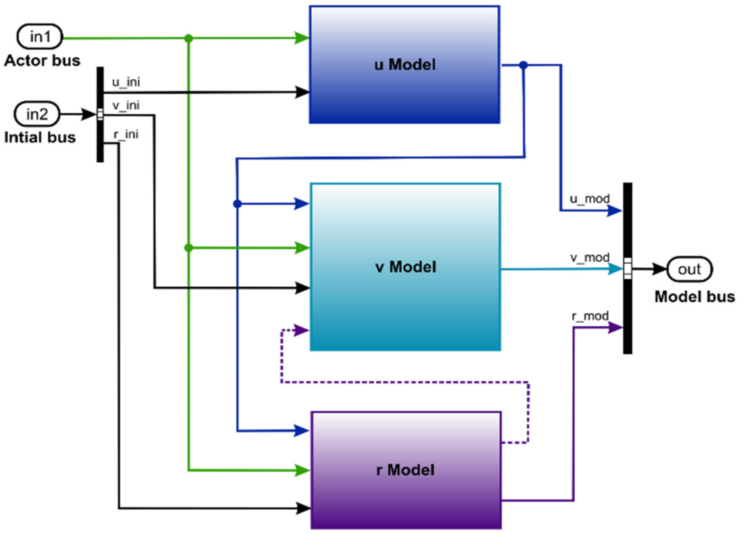

Fig.4: The model structure in 3 DoF with inputs, outputs and interconnections

4.3. Example model ferry ‘Mecklenburg-Vorpommern’

The ferry ‘Mecklenburg-Vorpommern’ disposes two variable pitch propellers (*EOT*) each with rudder behind (*Rud*) and a bow thruster (*Thr*). For the highly complex model of this ferry in the ship handling simulator, a control-oriented model was developed. In Eq.(6), the components are summarised that make a contribution to the longitudinal force. The main force results from the synchrony applied propellers X_{2EOT}. This force will be reduced by activating the rudder $X_{diffRud}$ or the thruster $X_{diffThr}$. Both functions depend on the current velocity u. A further nonlinear reduction arises from asynchrony application of two propulsion units $X_{diffEOT}$. These force terms of the u-component model can be found in Fig.5a) in the static part on the left site. The new steady velocity will be calculated from sum of forces and serves as an input to the dynamic u-module on the right site of this figure. In Fig.5b), the lookup table for $X_{diffThr}$ is shown as a function of the current velocity u and the thruster value. It is clearly recognisable that for $u = -2\ m/s$ and the thruster value of *100%* the largest difference force is reached.

Eq.(7) gives an example how the force components will be identified. The synchrony-applied propellers generate a steady-state velocity *u*. The rudder activation with defined angles reduces this velocity to a new steady state and the force difference can be calculated. The Eqs.(8) and (9) show the components of *Y* force and *N* torque. As a function of the current velocity *u*, these mainly depend on the degree of application of the steering units. The components *X*, *Y* and *N* for the rudder or the thruster application are identified by the same measurement. Additionally, only few equal distant supporting points are needed to create an interpolated lookup table with sufficient accuracy.

$$X_p = X_{2EOT} - X_{diffRud}(u) - X_{diffThr}(u) - X_{diffEOT} \tag{6}$$

$$X_{diffRud} = k_{xr} \cdot [(u^2{}_{2EOT}) - (u^2{}_{2EOT+Rud})] > 0 \tag{7}$$

$$Y_p = Y_{Rud}(u) + Y_{Thr}(u) + Y_{diffEOT} \tag{8}$$

$$N_p = N_{Rud}(u) + N_{Thr}(u) + N_{diffEOT} \tag{9}$$

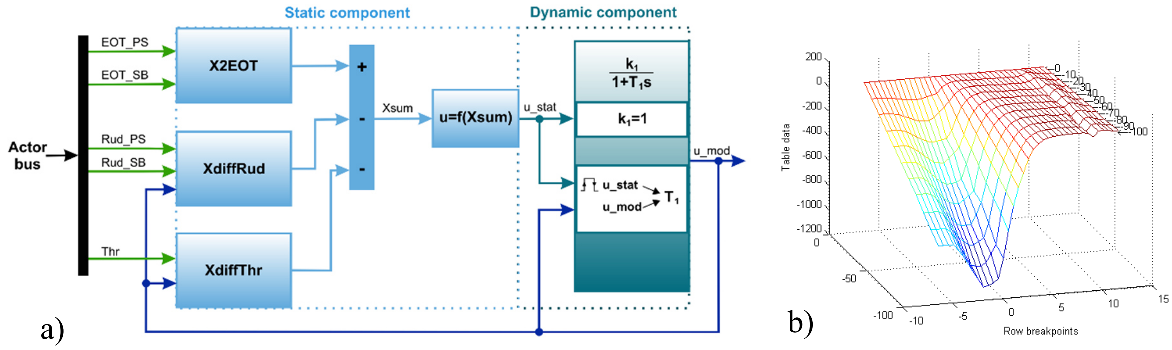

Fig.5: a) Structure of the *u*-component model with static and dynamic components; b) $X_{diffThr}$ lookup table as a function of velocity *u* and thruster value

The dynamic module describes the dynamic transient behaviour respectively for *u*, *v* and *r* between two steady states. To simplify the model structure and to reduce the model to essential characteristics, the transient behaviour is defined by first-order delays for all input steps initialised by current velocity and the difference value to the next steady state. For large sections of the velocity range, a first-order delay shows a model behaviour with sufficient accuracy. The delay was identified by Nelder-Mead Simplex Method for convergence problems. This dynamic approach is based on models with linearisation in the operating point as shown in Eqs.(10)-(13).

$$\dot{u} = \frac{1}{m_x}(X_p(t) - k_{xr}u^2(t)) \tag{10}$$

$$\Delta\dot{u} = f(X_{p0}, u_0) + \left.\frac{\partial f}{\partial X_p}\right|_{X_p = X_{p0}, u = u_0} (X_p - X_{p0}) + \left.\frac{\partial f}{\partial u}\right|_{X_p = X_{p0}, u = u_0} (u - u_0) \tag{11}$$

$$\Delta\dot{u} = \frac{1}{m_x}(X_{p0} - k_{xr}u_0^2) + \frac{1}{m_x}(X_p - X_{p0}) - \frac{2k_{xr}}{m_x}u_0(u - u_0) \tag{12}$$

$$\frac{\Delta u}{\Delta X_p} = \frac{\frac{1}{k_{xr}}}{1 + \frac{m_x}{2k_{xr}u_0}s} = \frac{k_1}{1 + T_1 s} \tag{13}$$

The gain k_1 of the first-order delay is presented in each working point by the continuously forces and moments in the static module lookup tables according to the propulsion and steering values as explained above. The delay T_1 is defined continuously in each working point of the velocity as a function of the current velocity and the degree of changing to the new commanded force respectively velocity. In this model approach, the operating point model is generalised for all degrees of changing. In the result, the continuous nonlinear model can be used for the complete velocity range and all motion modes of the vessel. The identification and modelling for other vessels with other propulsion and steering units will be executed very similar to this example because the basic structure of the model is the same. In that context, Fig.6 shows the results for a complex berthing manoeuvre of the ferry ‘Mecklenburg-Vorpommern’ comparing the designed and parameterised hybrid model with the motion of the ferry in the ship handling simulator. Despite of the major impact of different parallel working actuators, the results are convincing. Even in cases where the longitudinal velocity passes through zero the model shows excellent compliance with the nonlinear simulation of the ferry.

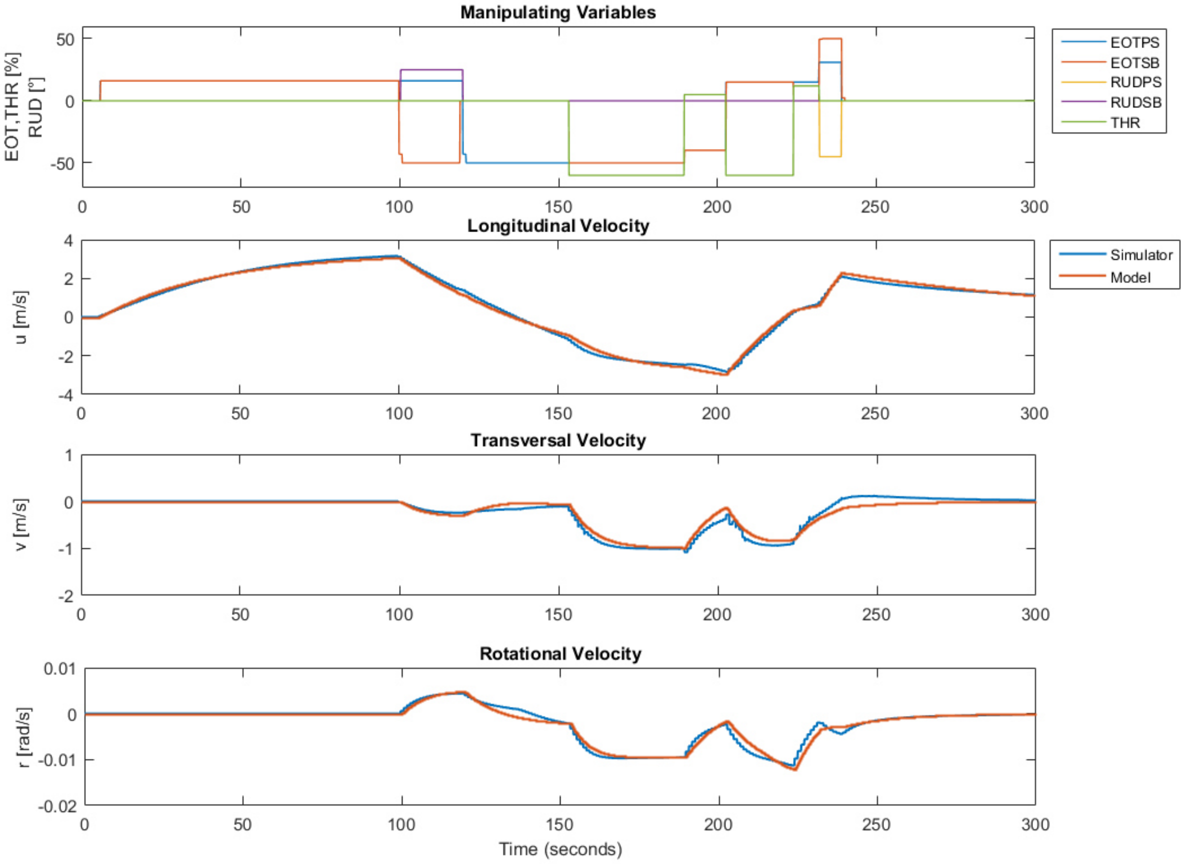

Fig.6: Modelling results for a complex berthing manoeuvre

4.4. Example unmanned surface vehicle SMIS-USV

The planar motion model of the SMIS-USV consists of a 2DoF subpart combining surge and yaw dynamics introduced in *Kurowski et al. (2016)*. The sway motion is negligible as it cannot be controlled directly and is quite small due to the vehicle size and shape. Due to the operation mode, the vehicle operates from nearly zero speed to maximum USV operation speed of 4 knots. Hence, the parameters of the nonlinear surge dynamics have to be considered. In order to estimate the damping characteristics of the hull, towing tests have been performed in the towing tank of the Technical University of Berlin. In context of the hybrid model approach, the nonlinear surge dynamics have been divided into an operation mode defined for higher surge velocity and propulsion force differences as well as a mode where the nonlinear behaviour predominates. For clarification, Fig.7 shows the damping characteristics of the already introduced first-order delays mapped to the SMIS-USV surge dynamics. Areas with high gradients around zero vehicle velocity u show major damping differences, where a nonlinear model is preferred. However, linear models can describe the flat areas at high vehicle velocity or in cases of significant propeller force steps with sufficient accuracy.

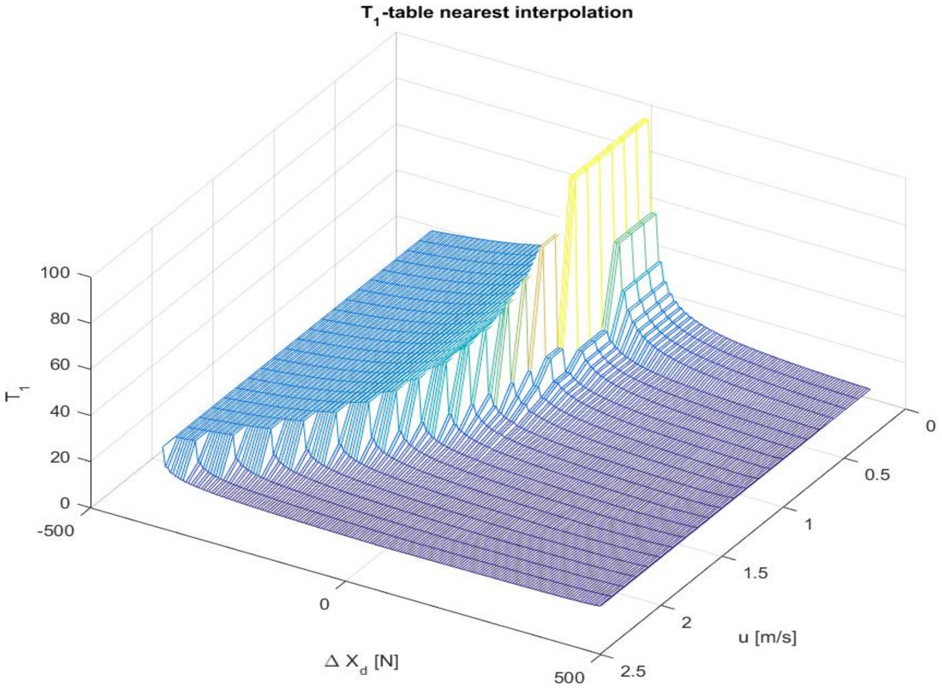

Fig.7: Surge damping characteristics of the SMIS-USV

The steering dynamics have been modelled in compliance with the ferry model by first-order, where the damping behaviour and the rudder forces change with vehicle speed. The correlation has been estimated by performing a set of standard manoeuvres with only slight changes in vehicle speed and has been corrected by performing complex manoeuvres over the entire speed range.

5. Control approach

The control approach is strongly associated with the hybrid nonlinear model concept continuously applicable in the complete velocity range. Therefore, a modular control concept is considered using an unified inner loop and a variable outer loop. The inner loop is designed as velocity control system, which is a substructure of the variable outer control system. These primary controllers generate the desired velocities for the velocity control loop. The inputs of the primary control system are generated by the vehicle guidance system and consist of different reference values like heading, bearing and position. Consequently, the velocity control loop is used to manipulate the actuators to obtain the desired linear and angular velocities, which are provided by the primary loop. This control structure has been employed with the SMIS-USV successfully, *Kurowski et al. (2016)*.

In general, the velocity control loop consists of feedforward and feedback control terms as well as the allocation as shown in Fig.8. At this level, effective nonlinearities of the vehicle dynamics are regarded by the feedforward terms. Consequently, simple linear feedback control structures can be used. Furthermore, this concept separates the reference tracking performance from the disturbance attenuation behaviour, which is essential for vehicles manoeuvre in limited fairways, where disturbances have a major impact. The input of the feedforward component are the command signals $\mathbf{x_c}$ to generate forces and moments, which lead to the corresponding manipulated variables $\mathbf{u}$ provided by the allocation. At this stage, the control of the variables $\mathbf{y}$ is done without considering external disturbances or errors. The feedforward parameters of the velocity control system are calculated by using inverted terms of the parameterised model (13), respectively (5) and (6), which leads to the commanded feedforward forces and torques

$$\mathbf{H_{ff}} = f\,(\mathbf{M_h}, \mathbf{D_h}, \mathbf{x_c}, \mathbf{K_{ff}}), \tag{14}$$

where $\mathbf{K_{ff}}$ are design parameters for a set of filters for the physical realisation of the excessive increase due to the differentiation of the commanded values $\mathbf{x_c}$. They can be determined by using optimisation methods considering the dynamics of each degree of freedom, and system limitations.

In contrast to the feedforward control, the feedback control term evaluates and minimises the difference between commanded and controlled variable of the model, respectively the real process. By environmental or intrinsic process disturbances, the model of the process diverges from the real behaviour. Hence, classical linear feedback controllers including integral parts are used for each degree of freedom to compensate the deviations arising from the neglected cross-couplings as well as the external disturbances. The input of the feedback term is the error signal calculated from the reference signal and the sensor signals. The outputs of the controller are the correcting forces and torques $\mathbf{H_{fb}}$. The disturbances acting on the vehicle have both stationary and stochastic nature, and their statistical characteristics are not known exactly during the design procedure. Furthermore, due to manoeuvring of the vehicle, there are substantial and rapid changes in the statistical properties of disturbances. For these reasons, various robust controller are suitable, which ensure sufficient performance in the different operation modes.

The summation of $\mathbf{H_{ff}}$ and $\mathbf{H_{fb}}$ leads to the commanded forces and torques, which manipulate the vehicle motion. In order to translate and distribute the forces and torques within each actuator in the system, an inline allocation module is inserted in the velocity control structure. The allocation algorithm has to consider different parameters like set points, operating ranges of the devices, efficiency and special properties of entire system like over- or under-actuating. In static case, the allocation is realised by using a weighting matrix to solve the over-determined numerical problem by considering the drive constraints. Further, the allocation module can be extended to consider the dynamics of drive system. Finally, the hybrid control approach implies that the dynamic model as well as the feedforward and the feedback control term are switched depending on the current motion mode. A continuously changing model for all motion states offers corresponding control solutions. During switching between different states, the system stability has to be ensured.

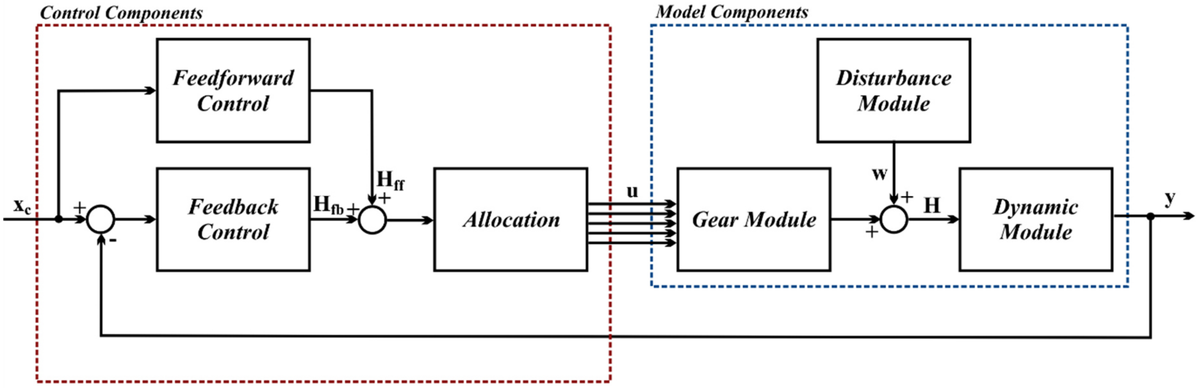

Fig.8: Generic velocity control loop structure

6. Experiments and system validation

The control approach was validated in different steps. In the first step, the combination of feedforward control and allocation was analysed in its effected correlation to the commanded variables. The feedforward as well as the allocation component are deduced from the model components. The switching within the model set has been taken into account. The more precise the motion model and the conversion to feedforward control are, the less deviations between commanded and the processed behaviour. This precision is limited by the cost-benefit ratio in development. In the second step, the use of the controller set and the switching between different controllers are evaluated under influence of disturbances.

6.1. Validation of feedforward control in ship handling simulator

Simulink Real-Time™ was applicated to validate the feedforward control in ship handling simulator. The Simulink® model consists of modules for commanded signal generation $\mathbf{x_c}$, feedforward control, allocation and the NMEA interface to the ship handling simulator. In feedforward control and allocation modules, the current motion states of the simulator vessel have to be available. In the experimental setup, the behaviours of the longitudinal velocity u_c and the rotational velocity r_c are commanded (Fig.9 plot 2 and 3 blue line). This motion behaviour is the common usage of vessels in contrast to traversing. The first plot of Fig.9 shows the manipulated signals, the outputs of allocation. In the given longitudinal velocity range between *-3* and *3m/s*, the rotation is effectively realised by thruster only. The turning manoeuvre was initialised at $t = 100s$. The activation of the thruster generates a difference in longitudinal force, which must be compensated by higher propulsion values depending on the commanded longitudinal velocity u_c. The red lines in plot 2 and 3 are the measured output signals u and r of the ship handling simulator. The yellow lines present the dynamic filter signals each generated by the feedforward module for u and r. The measured signals follow the feedforward signals for the most part of the time line. Stronger deviations occur in $r_{measured}$ especially if a zero crossing takes place in surge velocity, i.e. if the motion direction is changing. A suitable controller will reduce these deviations.

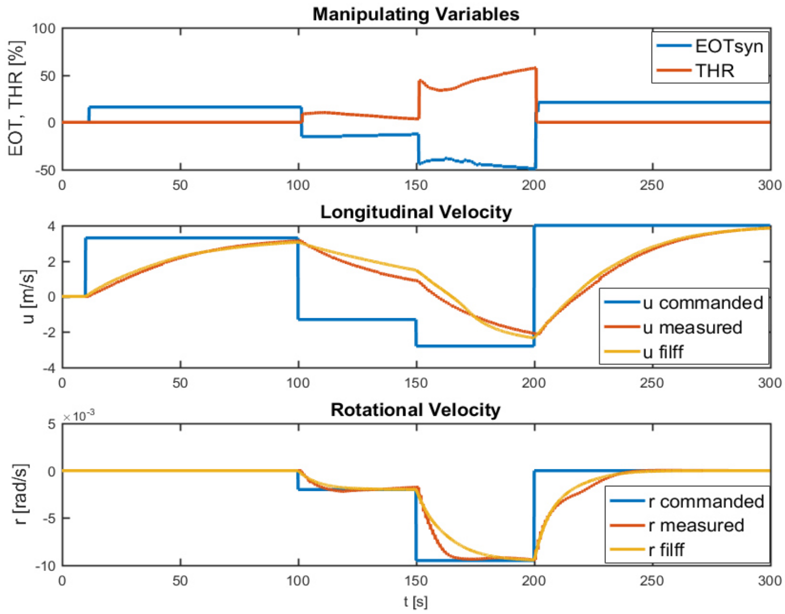

Fig.9: Results of the feedforward control validation using a ship handling simulator

6.2. Validation of USV hybrid control and guidance system

The performance of the developed hybrid control and guidance system has been evaluated during field trials with the SMIS-USV. Fig.10 shows the results of the proposed velocity control scheme. Additionally, the guidance system generates line-of-sight commands feeding a superior path controller, which operates as mission controller during the experiments. Thereby, the open water trials show measured data, which are strongly disturbed by sensor noise and environmental disturbances. The surge velocity has been measured as water reference using a Doppler-Velocity-Log (DVL) and the yaw motion data are generated by a mid-price Attitude-Heading-Reference-System (AHRS). Despite that, the actuating values of the rudder nozzle and the propulsion system are comparatively smooth due to the applied control scheme. Deviations especially in surge arise from neglected cross-couplings between surge and yaw. In detail, the figure shows the results of autonomous U-turn manoeuvres at different surge velocities commanded from the guidance system. At around $t = 7900\ s$ the surge velocity has been reduced during the lawn-mowing manoeuvre. Due to the strong nonlinearities in the motion of the small USV, the hybrid control system switches to another mode. Consequently, the control parameters of the velocity feedforward controllers have been changed, which results e.g. in adapted rudder nozzle angles to achieve the equal rate of turn and stay on the path curvature.

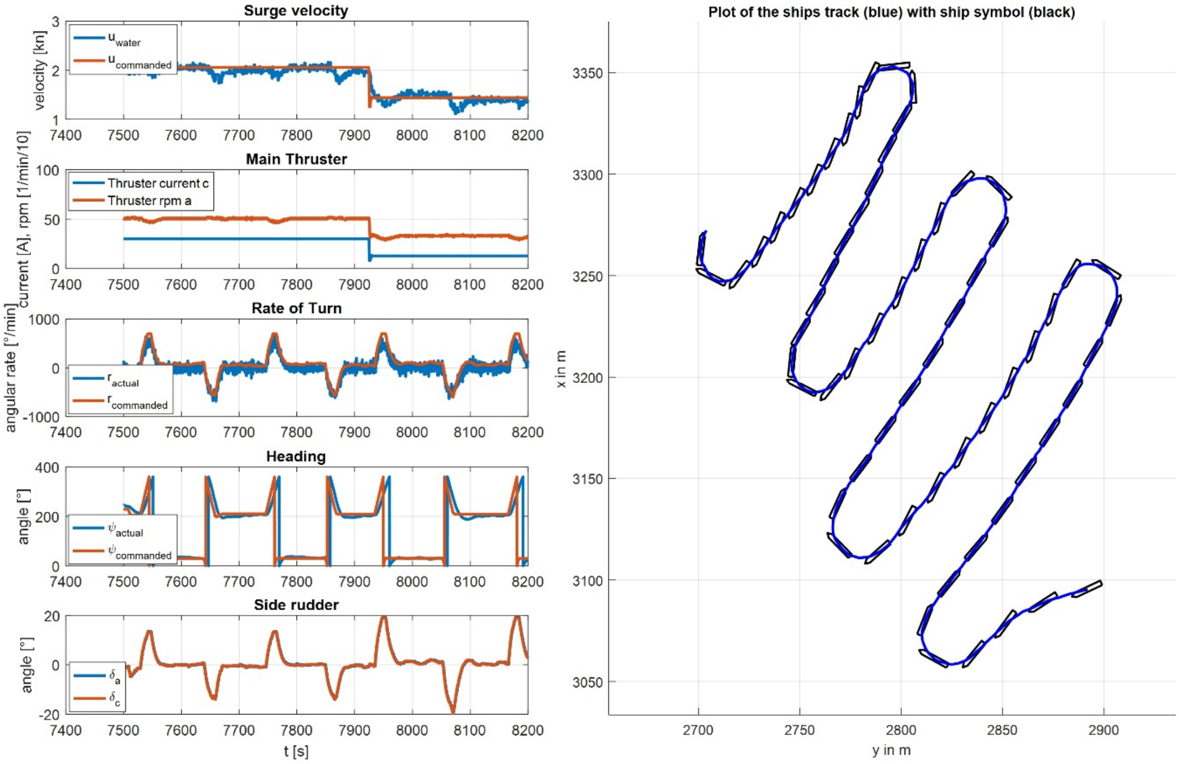

Fig.10: Results of the hybrid control and guidance validation during SMIS-USV field trials

7. Conclusion

This paper discusses the development of a generic control concept for marine vehicles based on a hybrid control scheme. A nonlinear motion model was designed based on linear first-order delay variating for each velocity and degree of freedom. The gain is determined from the forces or the torque generated by the propulsion and steering units. The simple control-oriented structure of this model facilitates the development of a feedforward and feedback control considerably. Finally, a cascaded control scheme has been introduced, where the inner loop consists of feedforward and feedback control structures as a unified velocity controller for each degree of freedom of the vehicle motion, which is applicable for manoeuvring marine vehicles. The usefulness of the proposed schemes has been demonstrated using a ship handling simulator and a ferry as well as a USV performing manoeuvring field trials.

Acknowledgements

We would like to thank the German Federal Ministry of Economics and Technology (BMWi) and the Project Management DLR for supporting the GALILEOnautic project under registration number FKZ 50NA1612.

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The Path to Real World Autonomy for Autonomous Surface Vehicles

Howard Tripp, ASV Global, Portchester/UK, howard.tripp@asvglobal.com
Richard Daltry, ASV Global, Portchester/UK, richard.daltry@asvglobal.com

Abstract

This paper presents a new autonomy architecture, developed and tested over the past two years which has taken a "dumb" remote-controlled platform and built it into a state-of-the-art Autonomous Surface Vehicle, able to navigate safely at high speeds in a COLREG aware manner, across some of the busiest waterways in the world. The architecture is made up of a hierarchy of decision making components sharing a common world model. These components consist of: a route planner, path planner and last response engine. Each element of the hierarchy is working to reduce risk within decreasing time and space horizons, ultimately providing a minimum risk navigational solution. MAST and the collision avoidance system is now at the advanced prototype stage hence. Dstl and ASV welcome interest from other organisations who would like to explore and experiment with running their systems either onboard or otherwise in command.

1. Context

ASV Global has built a reputation as the leading manufacturer of Autonomous Surface Vehicles (ASVs). In parallel to developing a wide product range of platforms, ASV Global has developed its own autonomous control system, ASView. ASView has been in development for 9 years and is actively used on over 80 platforms. It supports chart based operator situational awareness with pre-planned vehicle actions. The system currently relies on human input with limited on-board decision making.

To fuel growth of the industry, the goal moving forward is to develop a commercially useful autonomy system including and exceeding collision avoidance.

To ASV Global, real world autonomy means increasing the capability of the ASV to undertake decision making and thus enabling the remote operator to focus on safety critical issues and utilise natural human intuition. To provide the most efficient use of resources throughout the system as a whole, including the human element. In pursuit of this goal, ASV Global has developed an architecture which provides a robust foundation for the development of autonomy over the next decade. Throughout the design of the architecture a key element is the capability for expandability and future improvement, ensuring the system can meet current and future industry goals.

Initial tests and demonstrations of the system utilised data fused from radar, cameras and AIS sensors. This has been used in proof of concept demonstrations and showcased at the recent Unmanned Warrior naval exercise in the UK, deployed on multiple ASVs. Collision avoidance behaviours, taking into account important aspects of the collision regulations at sea, have been a critical part of this early development around which operational behaviours have been built.

These developments are accelerating the adoption of ASVs in the maritime industry by enabling capabilities such as over the horizon operations and the control of fleets of ASVs with minimal human input. Examples of applications spread across both military and commercial domains and include ISTAR, hydrographic survey, support of underwater systems and in the future, commercial shipping. The programme was directly funded by UK MoD through Dstl and led by ASV Global in partnership with Roke Manor Research and Cambridge Pixel.

2. Project Introduction

The developed capability centred around the guiding vision of a high speed (>30 knots) Unmanned Surface Vehicle (USV), notionally based outside Portsmouth Harbour, that could be tasked to autonomously intercept and investigate a target many nautical miles out at sea. This required development of high speed collision avoidance algorithms and on the fly route, path and trajectory re-planning all running directly on-board the USV for total self-sufficiency. The USV used was the Dstl Maritime Autonomy Surface Testbed (MAST) vehicle based on a bladerunner racing hull.

Fig.1: The MAST platform is a 34ft Bladerunner racing hull retro-fitted with ASV control system and extensive additional testbed hardware and software

The programme focused on researching what could be achieved using only current COTS sensor systems including AIS, radar, cameras and accelerometers which was successful and demonstrated that a great deal can be achieved using this approach. However, sensing remains a crucial performance driver and that there are many system/platform level trade-offs to be considered and no obvious "one-size-fits-all" sensor suite.

The concept and architecture was developed from scratch and is based on directly manipulating risk and uncertainty. This gives two key benefits: firstly a direct way for users to dynamically adjust risk appetites as mission goals change; and secondly a continuous real-time visualisation of "what I am thinking" over the next few seconds, minutes and hours for intuitive operator supervision and trust building. This contrasts with many collision avoidance systems that are purely reactive, and hence give no advanced warning about their intentions.

The system was incrementally developed with an agile customer demonstration drum beat and numerous R&D testing activities including 54 days of MAST on the water R&D and testing time. This practical real-world approach is significant as handling the real world noise was consistently more challenging than expected in all areas, and rapidly raised the TRL of the subsystems. As a result the programme has delivered hands-on capability and created the foundations of a testbed that is available for further exploitation.

A competitor analysis carried out late in the programme showed that this is potentially the fastest full autonomy USV capability in the world; that the MAST platform creates more sensor processing challenges than most competitors; that other collision avoidance systems are more reactive and tend to plan over much shorter timeframes; and has a sensor fit that is broadly similar/comparable to other approaches. In short, this programme is one of the world leaders in this field to the best of our knowledge. Equally this is evidenced by the fact ASV Global have licenced the technology developed back from Dstl via the Ploughshares organisation, for a significant upfront cost and potentially recurring license fees as it is commercialised.

A further indirect benefit is that this programme has been instrumental in developing better working relationships with local and national authorities including Southampton Vessel Traffic Service, Portsmouth Queens Harbour Master and the Maritime Coastguard Agency. These authorities approved autonomous operations for this programme in their busy controlled waters, something that would have been highly unlikely just 2 years ago.

3. Technology Overview

Much of the development work undertaken in this programme is commercially sensitive and hence much of the system detail is deliberately restricted to high level discussion.

3.1 System Overview

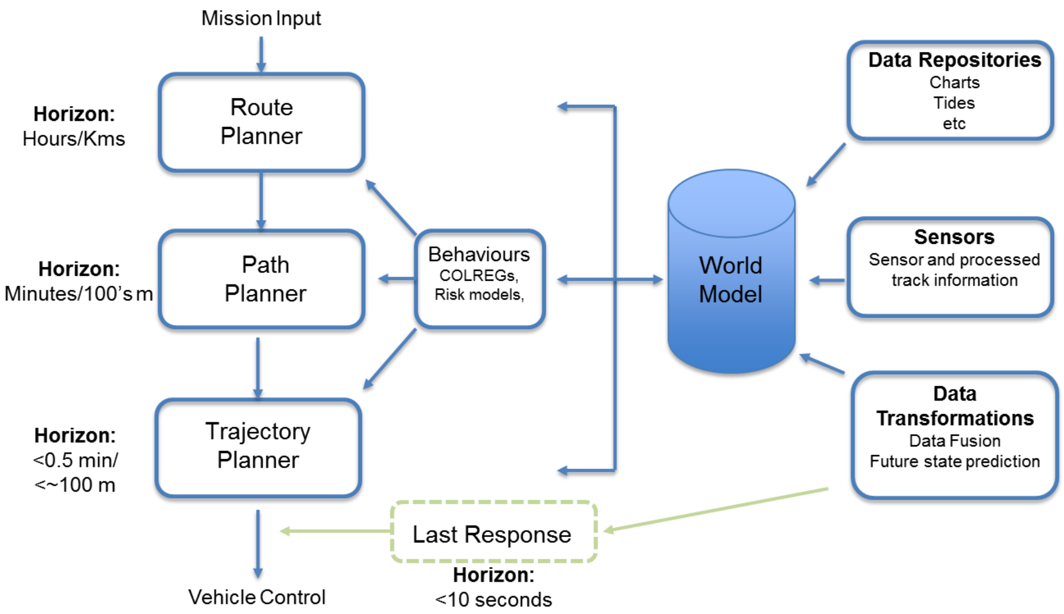

Fig.2: Schematic overview of the Advanced USV system

The Advanced USV System runs directly onboard the USV and consists of a hierarchy of decision making components sharing a common world model. Each element of the hierarchy works to reduce risk with decreasing time and space horizons, ultimately providing a minimum risk navigation solution:

- The *Route Planner* generates routes over long distances taking account of water depth (and potentially shipping lanes).
- The *Path Planner* considers the next few minutes, choosing paths that minimises collision risk in a COLREG compliant fashion with other vessels.
- The *Trajectory Planner* manages the next few seconds to smoothly control and predict USV motion based on a dynamics model.
- The *Last Response* monitors the immediate vicinity and provides a safety critical engine cut out, if an unexpected obstacle is detected.

The system includes a sensor processing pipeline, with a 360° panoramic camera, broadband radar, AIS sensor, compass, GPS and an IMU, all of which is combined into tracks and vessel position information in a world model. Further processing then calculates track statistics and generates future trajectory predictions for targets. These predictions are processed based on COLREG rules within a 3D risk landscape to calculate risks of being in the wrong place at the wrong time. Chart features such as buoyage and shore data is also added to the risk landscape for use by the path planner. The system is at the point where it would be possible to command MAST to autonomously navigate around the Isle of Wight under suitable weather conditions.

3.2 Programme Achievements

The Advanced USV programme was predicated on a series of demonstrations to showcase the development of advanced autonomous navigation.

- Demo 1 (November 2015) demonstrated a basic risk-based path planner undertaking simple collision avoidance in an open water environment at low speed (~15 knots) using only AIS sensor input from a single target. Achieved capability for one-on-one crossing situations.
- Demo 2 (March 2016) added collision avoidance with multiple vessels using a fused AIS and radar sensor input and sea state monitoring to limit speed. Achieved capability for reasoning about compound multi party crossing situations.
- Unmanned Warrior 2016 (October 2016) The MAST and collision avoidance system was used extensively in military exercises over a three-week period around the Isle of Skye. Achieved long endurance testing in more hostile environments with additional behavioural modes of operation.
- Demo 3 (November 2016**)** demonstrated multiple vessel collision avoidance at higher speed with automated last response functionality and basic route planning. Achieved the ability to operate fully unmanned at 30knots with autonomous emergency stop.
- Demo 4 (February 2017) demonstrated the addition of an initial vision processing system, a trajectory planner, AIS metadata processing to support detection/classification of objects and live extraction of chart data (both depth and objects). Achieved the integration of vision processing detections, basic vessel classification and dynamics aware planning for more advanced COLREG compliance.
- Demo 5 (March 2017) Added improved vision processing and showcased an integrated multi-phase “representative mission” on a long transit through shipping lanes and controlled waters. Achieved an end-to-end mission with “unscripted” collision avoidance. (Note: severe weather on the day unfortunately cut short the demo on safety grounds, but the system operated entirely successfully as expected).

3.3 Specific Technologies Developed

3.3.1 Core System

One of the key insights from this programme was the representation of rules within the International Collision Regulations at Sea (COLREGs) as dynamic mathematical functions to represent risk. The system uses information about the relative positions & velocities of obstacles and the USV to classify it, and then generate risk distributions based on the predicted position, appropriate avoiding action and the error/uncertainty.

With a heavy emphasis on real world trials, the programme demonstrated that there are large numbers of challenges in handling the real world noise. Systems and algorithm that seem promising and successful in simulation in the laboratory had difficulty on the water. This level or ruggedisation challenge should not be underestimated. To give one example consider a basic COLREG – “overtaking vessel must keep clear”. In human terms this is easily understandable, but for a machine we need to define when an overtake begins and ends, precise angles, relative velocities and thresholds. In theory this manageable but now what if you find yourself on the threshold one of these – how much hysteresis or fuzzy logic is needed? What if there is error and jitter in both detection and control? What if you loose and reacquire (an apparently different) vessel track midway through but need to remember that you are overtaking? What if you or it alters course and how is that differentiable from noise? What are the processing latencies in the system and how do you account for environmental effects and vessel dynamics? How do you ensure safety at all times? Some of these issues can be explored in simulation, but it is difficult to fully simulate the true level of real world uncertainty and plethora of special cases without extensive on the water experimentation.

3.3.2 Sensing Sub Systems

MAST was fitted with a SIMRAD 4G broadband radar which is the most critical sensor of the collision avoidance system. Configuring a controlling the radar, plot and track extractor on just a small mobile platform was an ongoing an persistent challenge. A significant amount of effort was spent working with the supplier of the radar track extraction system, to optimise the performance in a variety of conditions.

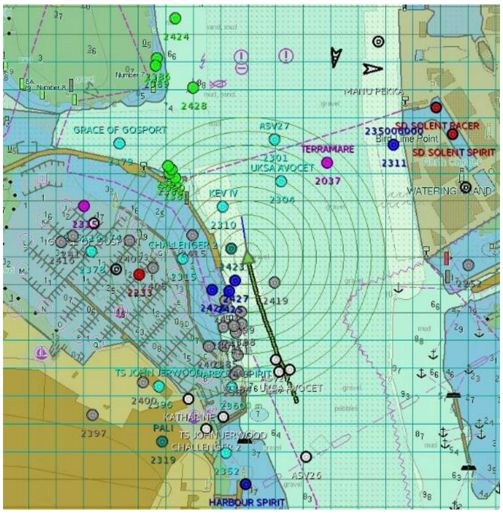

Fig.3: An example of AIS, radar & vision sensor outputs all being fused into tracks

The 360° panoramic Pt Grey LadyBug 5 camera was used for visual object detection. Work was undertaken to explore various detection algorithms including: Image masking, Horizon detection, Colour detector, Edge detector, Local Variance detector and particle probability hypothesis density (PPHD) filter.

Other sensor related work undertaken included the numerous “enabling sensors” such as compasses and GPS which again although seem conceptually simple had many challenges. Monitoring the vertical acceleration of the boat using IMUs with FFT & physics based algorithms to infer maximum safe speed was also developed.

Database algorithms were also developed to read and process electronic chart information for extraction of information relevant to collision avoidance for example water depth information, tide data and chart features such as buoys and marks.

3.3.3 Final Outcomes and Deliverables

An internal comparison with other research activities in the field was undertaken in December 2016. This re-affirmed our belief that the work undertaken in this programme is at the forefront of the ongoing research activities in the industry and highlighted:

- The capability developed under this project is potentially the fastest full autonomy capability in the world.
- The light displacement, high speed platform creates more sensor processing challenges than most competitors.
- Other collision avoidance systems are more reactive, operating over much shorter timeframes (more like trajectory planners than path planners), whereas this system provides not just short term planners but more longer range planning.
- The sensor fit on MAST is broadly similar to other products/projects.

Demo 5 (as noted in section 3.2 above) was the final deliverable of the project; a showcase of all the technological developments made to date. Each leg of the scenario demonstrated a particular element of the functionality that has been developed as part of the project.

The MAST USV was demonstrated operating autonomously (with full collision avoidance) from just outside the entrance to Portsmouth Harbour out to the outer approaches of the Solent, this included crossing the main shipping channel twice and operating at high speed. The Solent is one of the busiest shipping areas in the world and this was a significant achievement for the project.

Key functionality demonstrated during this run included various potential collision scenarios (including emergency evasive maneuvering), the last response engine, route planning, automatic sensing of the sea state and corresponding adjustment of the USVs speed. The demonstration also included a demonstration of the work done to date using machine learning techniques to automatically classify different types of vessels and buoyage.

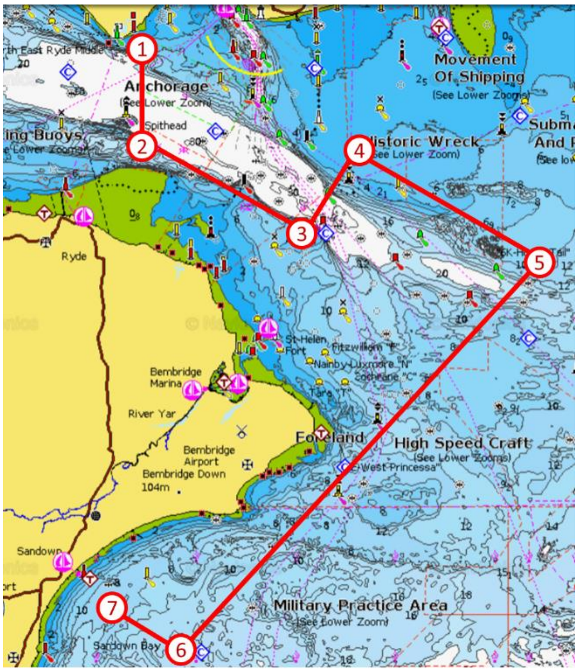

Fig.4: Overview of demo 5 operational area

Conclusion

MAST and the collision avoidance system is now at the advanced prototype stage. The system now has a level of performance and assurance that provides the opportunity for two crucial exploitation testbed activities:

1. The modular architecture approach allows additional or alternative subsystems to be easily compared against the current baseline, to evaluate performance improvement. Given that it is now established it is fundamentally possible, research can be focused towards pushing the limits (e.g. operating closer in shore or in more challenging environments).

2. Integrating into the wider context. There are numerous higher layer mission management and situational awareness systems at various TRL. MAST now provides the opportunity for those systems to experiment with real-world uncertainty by integrating with an actual representative platform.

Dstl and ASV therefore welcome interest from other organisations who would like to explore and experiment with running their systems either onboard MAST or otherwise controlling or commanding it.

Optimization of a Self-Righting Hull and a Thruster Unit for an Autonomous Surface Vehicle

Heinrich Grümmer, aXatlantic, Potsdam/Germany, gruemmer@axatlantic.com
Stefan Harries, FRIENDSHIP SYSTEMS AG, Potsdam/Germany, harries@friendship-systems.com
Andrés Cura Hochbaum, Technical University of Berlin, Berlin/Germany, cura@tu-berlin.de

Abstract

This paper presents an overview of the process of simulation-driven design both for the hull and the rim-driven thruster of an autonomous surface vehicle. Fully parametric models are the basis of geometry variation. Hydrostatic calculations are used along with a multi-objective optimization algorithm for the hull design. The thruster is designed from viscous flow simulations in open-water condition. Robustness is of prior importance and attention is paid to the special requirements of an unmanned vehicle. The design focuses on keeping the danger of entanglement low and the ships speed of advance high with respect to the technical context of the entire system.

1. Introduction

A solar powered, unmanned autonomous surface vehicle (ASV) was designed, keeping the particular demands placed upon reliability and efficiency of the system in mind. Hydrostatic characteristics were carefully engineered to allow self-righting of the vessel in rough conditions. The under-water profile of the hull was kept streamlined and narrow in section to reduce resistance and to account for the limited power available. Heavily flared sides increase deck space and facilitate the mounting of a sufficient number of solar cells. Manoeuvrability of the vessel was increased by adding a small keel.

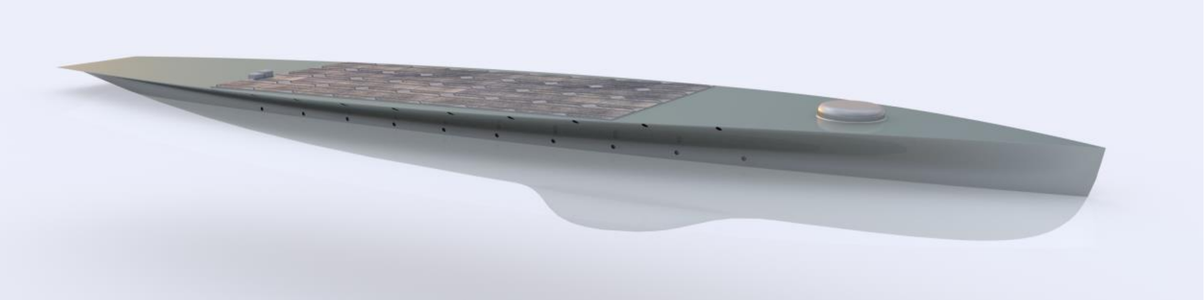

Fig.1: Concept drawing of solar powered ASV targeted to cross the Atlantic

CAESES® was used to generate a parametric model of the hull and trigger the external stability computations in MAXSURF. A set of design variables acting on the shape of the hull were introduced. The optimization targeted increased initial stability as well as increased maximum righting arm while maintaining the self-righting ability of the vessel. After an initial exploration of the design space, a MOSA algorithm was used to push the design towards a final shape. A calm-water test was conducted at TU Berlin's towing tank in order to provide resistance data over the anticipated range of speeds.

A rim-driven thruster (RDT) was designed and optimized for maximum attainable speed of the ASV. Parametric models were developed for the nozzle and the propeller blades that allow changing geometry with very few defining parameters. The fully parametric CAD model is based on class-shape transformation (CST) methodology and allows for a wide range of shape variants to be investigated with very few defining parameters. Viscous flow simulations were undertaken for the RDT in open-water condition in order to determine thrust and torque depending on the shape. Based on the amount and efficiency of the solar-cells as well as the intended time and area of operation an approximated minimum continuously available power for the propulsion was estimated. The design objective was to identify the rim drive that would yield the highest speed for a given power supply.

Flow simulations were performed with OpenFOAM while both the simulation-ready CAD and optimizations were realized within CAESES. The optimization utilized a surrogate model via Dakota, embedded within CAESES, so as to reduce computational costs. Fully automatic grid generation was achieved by integrating Pointwise into the framework.

2. Concept

The risk of getting caught in debris or obstacles for a small sized and low-powered vessel is high. Hence, the probability of entanglement of the propeller, shaft, rudder and the hull itself is minimized through careful design of each individual component. The self-righting ability of the hull, without the use of a long weighted keel protruding from the bottom, is one key part of this concept. Another substantial feature discussed within this paper is the propulsion unit which is designed as a steerable hub-less RDT.

2.1. Hull Design

To reduce the hull's resistance, the under-water part is kept streamlined and narrow with a low surface area. As the vessel depends solely on solar power, a certain amount of installation space is needed. Hence, the sides are flared above the waterline which increases the available deck space significantly to accommodate a sufficient number of solar cells. However, the buoyancy induced by the flared sides creates a negative righting arm once a certain heeling angle is exceeded (see corresponding righting arm curve given in Fig.2 for the hull without any openings).

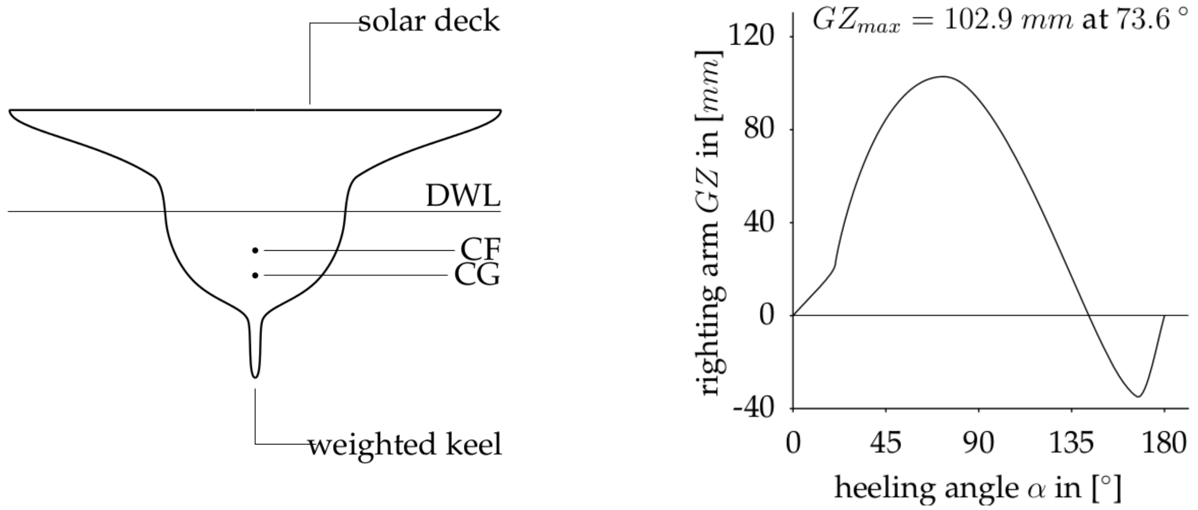

Fig.2: Baseline design hull section view (left) and corresponding RAC (right)

Instead of a fully closed hull a partially floodable design was developed in which only an inner part of the hull is closed as a watertight compartment containing the hardware necessary for autonomous operation. Fig.3 shows a section of such a hull geometry near the keel. Hydrostatic characteristics are obtained by perforating the sides to create a non-watertight volume. Small holes near the water-plane and along the edge of the deck allow the in- and outflow of water as the vessel is heeled over. A variation of the hull's center of buoyancy (COB) depending on time, grade of perforation and heeling angle α can be observed. Thus, a distinction between quasi-static stability behavior and dynamic stability characteristics can be made. In practice, a combination of both will be observed. The benefit of such a design is a hull that is well adapted to the expected operating conditions.

The dynamic stability mainly acts during normal operation, e.g. low heeling angles and common rolling frequencies. In these cases, the flared sides act similarly to an outrigger as they provide a significant amount of stability when not filled up with water completely. In more severe conditions such as high continuous external side forces and high heeling angles the quasi-static characteristics play a dominant role. Extreme events such as capsizing can be handled as the in- and outflowing water gradually shifts the COB until upright position is recovered. Figs.3 and 4 show sections along with schematic water in- and outlets for the baseline and optimized design variant.

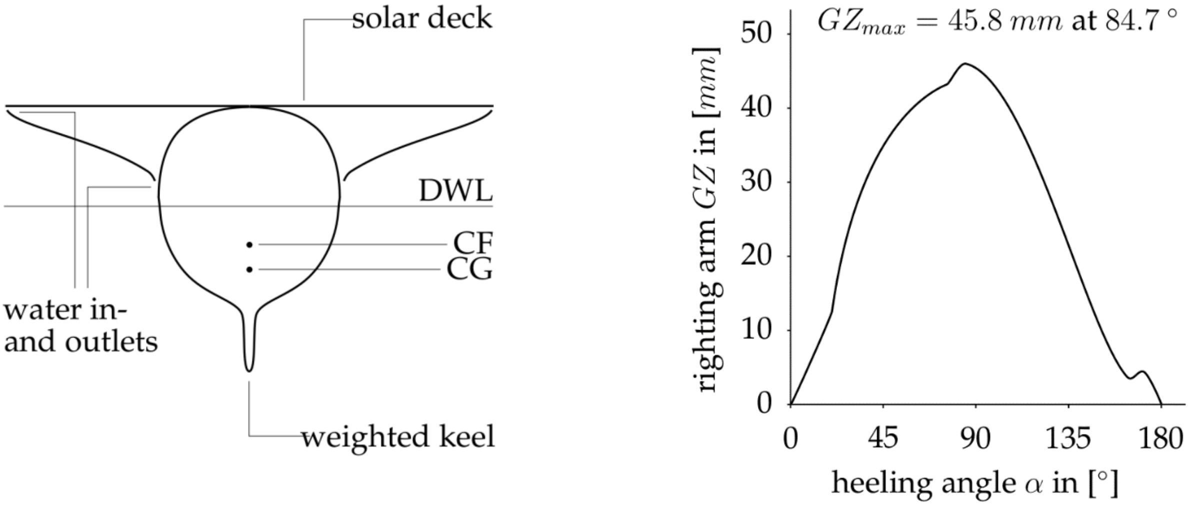

Fig.3: Hull section of the baseline including water in- and outlets (left) along with the corresponding RAC (right), showing self-righting ability

2.2. Propulsion System

Apart from the specific hull design, a propulsion system suitable for the application had to be developed as well. An RDT was chosen based on the requirements of low risk of entanglement and ease of installation. As opposed to a conventional propeller, driven via its shaft, the torque driving the blades of an RDT is delivered via a surrounding ring that is structurally connected to the blade tips. By implementing it as a steerable thruster unit, the risk of entanglement of the unmanned ASV is reduced and manoeuvrability is improved. The absence of a hub allows for objects to pass through the unit without interference. A high flow velocity area in the centre of the shaft-less thruster supports the free passage of any debris that otherwise might lead to fouling of the propeller, *Freeman and Marshall (2011)*. The absence of a hub and shaft also diminishes the frictional losses and eliminates dissipation due to formation of a hub vortex, *Cao et al. (2011)*. As the blade tips are connected directly to the rim, no tip leakage vortex exists. The compact design also helps in saving space, allows for a flexible mounting and aids in the reduction of secondary systems, *Cao et al. (2011), Hughes et al. (2000), Yakovlev et al. (2011)*. Furthermore, the nozzle creates directional stability, provides exceptional manoeuvrability due to thrust vectoring of the steerable unit, and protects the propeller blades.

3. Hull Variation

3.1. Approach

The hull was designed in CAESES based on the meta-surface functionality with the sections, including the keel, defined as NURBS curves. The weight and position of particular control points are set as design variables. As already mentioned in the introductory section, the hull design is characterized by an enclosed compartment and the additional floodable volume. In the quasi-static scenario, no additional buoyancy is provided by the floodable volume. However, the wall thickness of the perforated boundary itself needs to be considered, as the finite thickness creates a certain displacement which cannot be neglected when calculating the hydrostatic characteristics. Therefore, the wall-thickness is added to the set of design variables.

A total number of 5 variables were handed over to the optimization toolbox. To get a good overview of the design space, an exploration algorithm was applied at first. By coupling MAXSURF and CAESES, the hydrostatics of 500 variants were examined based on a Sobol sequence. Subsequently, a multi-objective simulated annealing (MOSA) algorithm was applied to the task. The center of area of the righting arm curve (RAC) was monitored to ensure good initial stability of the vessel and the maximum righting arm was maximized. A positive righting arm over the full 180° range of heeling angles was set as an inequality constraint to ensure self-righting of the hull. Another 2000 variants were examined during this second optimization phase.

3.2. Results

All calculations were carried out for the quasi-static scenario. As mentioned before, the grade of perforation, in terms of size and number of openings within the hull, affects the dynamic stability that can be observed during operation. However, this is not a critical point with regard to the actual self-righting ability and the setting can easily be manipulated during sea trials. The ideal size and number of holes can be determined empirically and no stability simulations involving the in- and outflow of water have been carried out. To get an impression of the dynamic stability behaviour, an additional RAC for the case without any perforation has been calculated. Figs.2 to 4 show the three RACs of the baseline design, both for the non-perforated and quasi-static case, as well as the quasi-static behaviour of the final optimized variant.

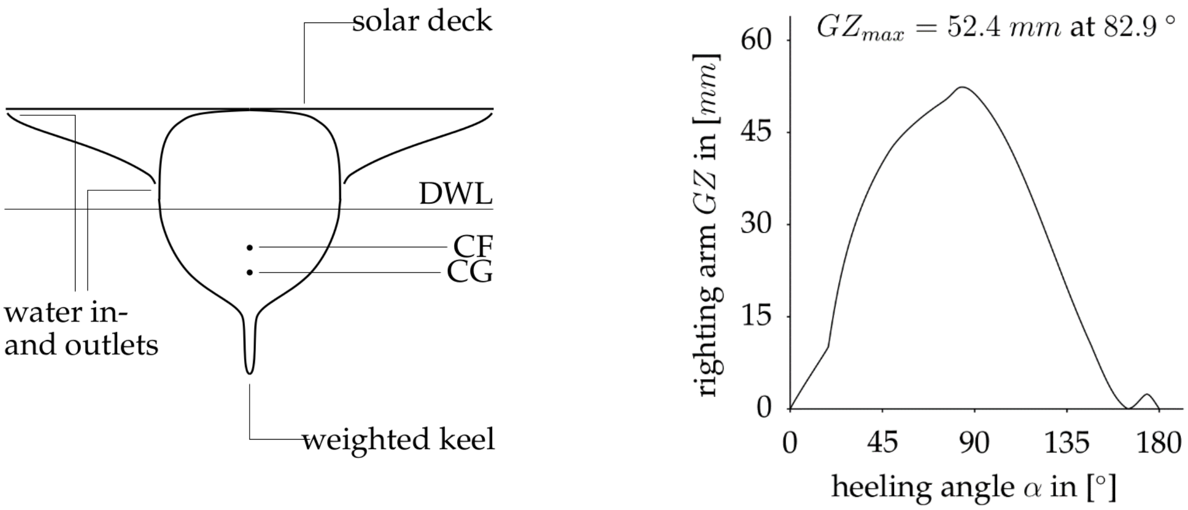

Fig.4: Hull section of the optimized design including water in- and outlets (left) along with corresponding RAC (right), showing improvement achieved from the optimization and maintained self-righting ability

The non-perforated RAC of the baseline variant shows a significantly higher maximum righting arm then in the quasi-static cases. While the buoyancy provided by the flared sides is very beneficial during regular operation of the ASV, it also prevents the vessel from self-righting once the angle of vanishing stability is exceeded. The quasi-static RACs of the baseline and optimized variant show a very similar progression over the full 180° range of heeling angles. The objective measure of the maximum righting arm has been improved by approximately 14% and a slight improvement in initial stability can be observed. Both the baseline and optimized variant show a positive righting arm over the entire interval of heeling angles. However, the optimized design shows a local minimum close to GZ = 0 mm at around α = 165°. While this still does not violate the constraint of a self-righting design, it will slow down the actual process of up-righting in practice.

4. Thruster Variation

4.1. Approach

The final hull design was taken to the towing tank at TU Berlin and resistance tests for the bare hull were carried out. To allow for an easier experimental set-up, the hull's perforations were not yet added. Several tests were performed over a range of relevant speeds. Based on these findings a method of performance prediction in terms of ship speed at a given power input has been developed, *Grümmer et al. (2017)*. In addition to the resistance data, an estimation of the expected solar energy available for propulsion, as well as the wake fraction and thrust deduction coefficient of the bare hull are needed. Furthermore, so as to identify the self-propulsion point, open-water simulations at two different advance ratios were carried out for every thruster design investigated. As a result, every thruster design could be rated in terms of attainable ship speed at a given power input.

4.2. Reference Simulation

To assure the reliability of the obtained simulation results, the OpenFOAM CFD setup was verified. Therefore, studies on the solutions independence of mesh resolution, time steps, Reynolds number, number of revolutions simulated and size of computational domain were carried out, *Grümmer et al. (2017)*. A comparison of open-water diagrams obtained from CFD simulations and those obtained from experimental investigations, *Oosterveld (1970)*, was undertaken. As the computational model does not account for the friction that occurs inside the gap between the rotating propeller's ring and the nozzle, a certain underestimation of torque was observed. These offsets are attributable to the above-mentioned neglect of friction between rim and nozzle and were therefore handled by mathematical models separately. The combination investigated by Oosterveld and reproduced as a reference case during this work was a Ka 4-70 propeller in a nozzle 19A. The open-water diagram given in Fig.5 shows a good match in propulsive characteristics after integrating the empirical correction of frictional losses.

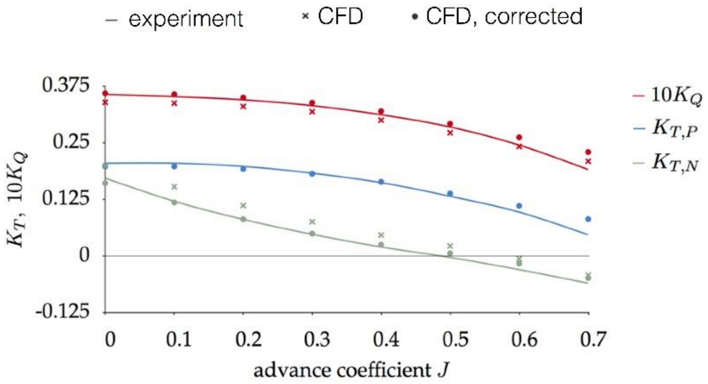

Fig.5: Open-water diagram comparing the experimental findings, *Oosterveld (1970)*, with the CFD results both with and without correction of frictional losses through the gap flow

4.3. Nozzle Design

The nozzle design is based on the class-shape transformation (CST) methodology, *Kulfan (2008), Lane and Marshall (2009)*. A NACA type airfoil was chosen as the class and three design variables where introduced into the parametric model.

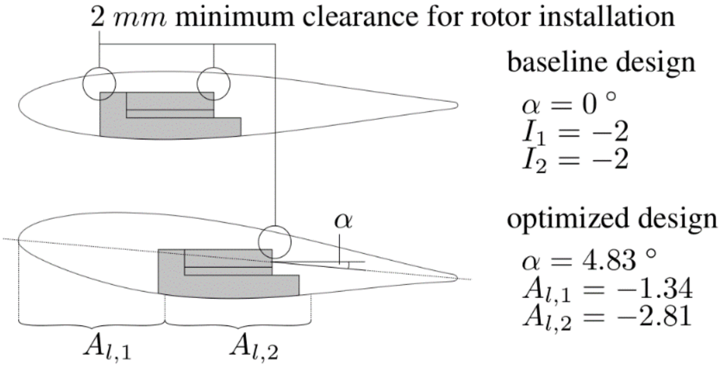

Fig.6: Nozzle sections for baseline and optimized design variants

In Fig.6 the baseline and the optimized section design of the nozzle are shown and the parameter settings, as well as their impact on the section's shape can be seen. A script optimizes the axial motor position for each parameter combination and ensures a minimum clearance between the permanent magnets and the nozzle's surface. The defining curves are based on CST methodology and the shape-defining parameters are given along with the drawings.

4.4. Propeller Design

The dimensions of the ASV and consequently the data such as required power input, speed of advance and rotational speed are very small compared to vessels that usually operate in similar environments. It was therefore assumed that criteria such as thrust loading coefficient, strength of the propeller blades or cavitation number could be neglected. Unsteady forces acting on the hull due to the discrete number of blades were not of any concern either, as they will be of low amplitude and no aspects of comfort need to be considered on an unmanned vessel. The number of propeller blades was consequently set to two as the lower surface area aids in reducing viscous forces. To start out with an already reasonably good design and so as to keep the parametric propeller model fairly simple, a baseline design has been generated, based on a set of rough data, Fig.7 (left).

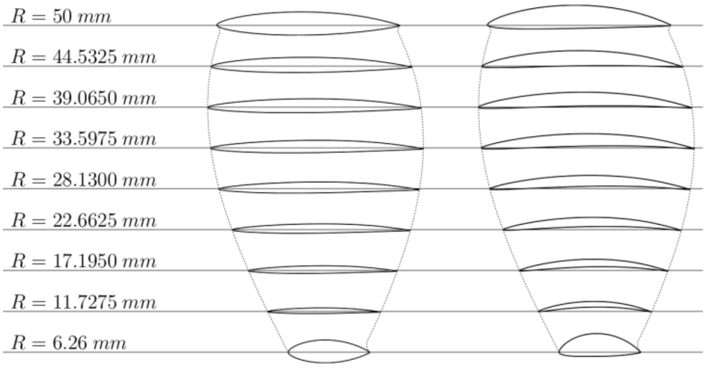

Fig.7: Expanded blade geometry of baseline (left) and optimized (right) design which features a noticeable amount of camber introduced during the optimization process

To enable geometry variation of the given blade design, a re-parametrization was performed. The radial distribution of P / D , as well as the camber as a function of radius were identified. Two design variables $\Delta\alpha$ and Δc were added which allow to change P / D as well as the amount of camber.

4.5. Automatic Grid Generation

For an automatic CFD computation of every variant of the changing geometry, an automatic grid generation tool is needed. While a manual meshing approach was sufficient for the reference simulation, the optimization task asks for an automatic grid generation. Through the use of glyph scripts, Pointwise enables the user to achieve the level of automation necessary for this task. The basis for each mesh is an IGES export with the geometry data of the design. The process of grid generation is split up into the nozzle and propeller region of the mesh.

4.6. Optimization

CAESES is used for the optimization process, controlling the interaction of the different tools applied. The generated design is exported as an IGES file and handed over to Pointwise for grid generation. After the volume and boundary conditions are applied, an OpenFOAM compatible mesh is exported. The CFD simulations are then triggered from within CAESES based on the setup obtained from the reference simulations. The correction of frictional losses due to the gap flow is applied as described in *Grümmer et al. (2017).*

The geometry variation during the first exploration phase is based on a small Sobol sequence and 25 design variants were evaluated. Based on the results of this first phase, a surrogate model was created to allow the approximation of the target measure within the entire design space. To enable the use of this kind of optimization algorithm, Dakota is embedded into CAESES as an optimization toolbox. Another 17 designs were then evaluated based on the information received from the surrogate model. While 6 of them violate given constraints and are therefore considered infeasible, the remaining 11 show a constant improvement and a good level of convergence can be observed. The final design is visualized in Fig.10 and the changes compared to the baseline can be seen in Figs.6 and 7 for the nozzle's section and the expanded blade, respectively.

4.7 Results

In Fig.8 all designs investigated are compared according to their performance in terms of attainable ship speed and the improvement gained from the optimization process can be conceived visually.

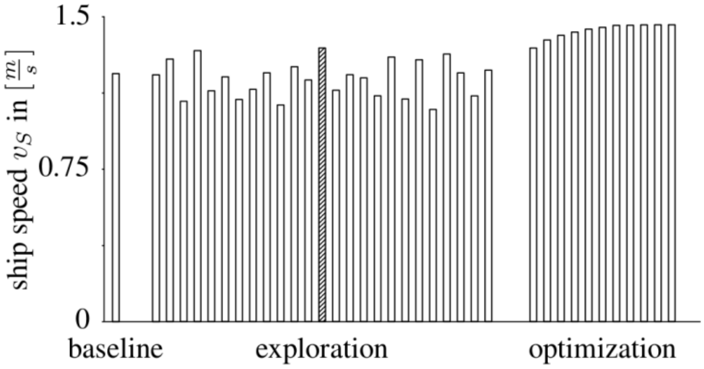

Fig.8: Objective v_S for the baseline (v_S = 1.22 m/s), the designs from the exploration phase (up to v_S = 1.34 m/s) and those from the optimization phase (optimum of v_S = 1.46 m/s)

Starting from the baseline design an increase of speed from 1.22 m/s to 1.46 m/s was achieved. This corresponds to an improvement in open-water efficiency of 168 % for the optimized variant as can be seen from the open-water diagram given in Fig.9.

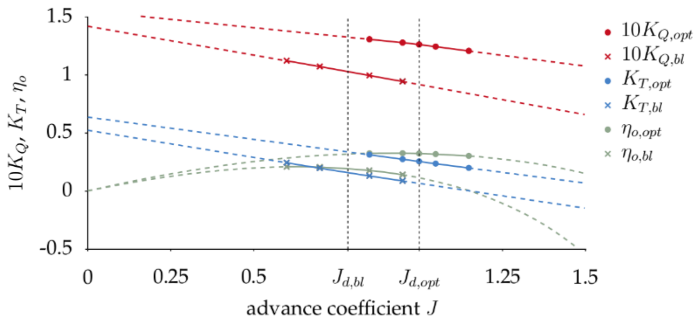

Fig.9: Open-water diagram for the baseline and optimized design variant showing an improvement in efficiency from η_O = 0.19 (baseline) to η_O = 0.32 (optimized variant)

A constant increase of advance ratio was observed along with the improvement in efficiency. The reason behind this correlation is the considerable amount of friction observed within the gap flow between rim an nozzle. This dissipation is directly related to the rotational speed of the rim. As a higher advance ratio allows a lower rotational velocity the optimization algorithm pushes the design towards a higher J while targeting for maximum attainable speed. The expanded blade geometry given in Fig.7 (right) also shows that a considerable amount of camber has been introduced during the optimization process.

5. Conclusion

A short overview on the challenging tasks of designing an unmanned ASV targeted to cross the Atlantic was given. For the design of the hull special requirements towards self-righting ability and low risk of entanglement were imposed. Hydrostatic calculations allow a well-founded interpretation of the different design variants in terms of their suitability for the given task. Many design variants were analysed and a significant improvement in the objectives was found.

After establishing the hull geometry, a RDT was designed to suit the given hull. Again, a simulation-driven design approach was taken leading towards a single-objective optimization problem. The approach has proven to be a very valuable and powerful procedure for the addressed problem. A satisfactory level of improvement was found and the performance predictions very well matched the expectations towards the concept of a solar powered ASV. Fig.10 shows the optimized thruster design as obtained from the optimization.

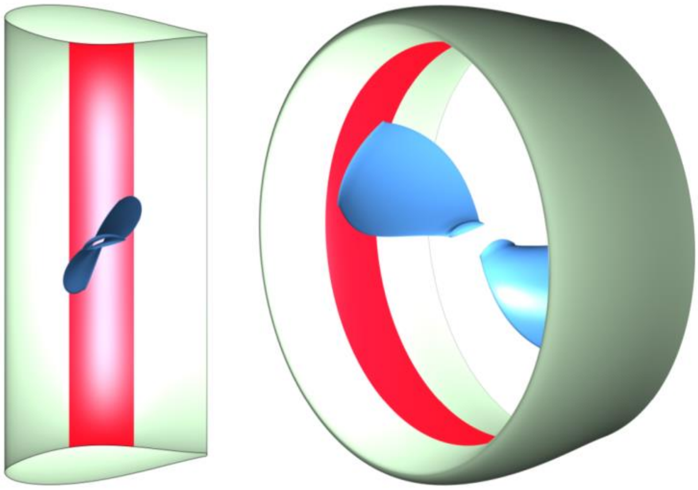

Fig.10: Optimized RDT design composed of the rotationally symmetric nozzle, propeller ring (shown schematically without the electric motor) and the two blades attached via their tips shown in section view (left) and perspective (right)

Acknowledgements

The authors wish to thank Karsten Rieck from Dynamics of Marine Systems at TU Berlin for conducting the model tests. Parts of the work presented in this paper were realized within the research and development project HYKOPS, funded by the Federal Ministry of Economics and Technology (BMWi) on the orders of the German Bundestag and PtJ as the conducting agency (FKZ 0303X432).

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JavaScript Applied to Maritime Design and Engineering

Henrique M. Gaspar, NTNU, Alesund/Norway, henrique.gaspar@ntnu.no

Abstract

This paper proposes the use of JavaScript language as a key success factor when developing open and collaborative software for maritime design and engineering. Among the many script languages available for engineers, JavaScript stands out for the size of its community, easiness of learning and wide spectrum of use, from traditional web applications to server management and mobile apps. There is a resistance, however, to use and incorporate JS in engineering, usually connected to a market trust/dominance on a traditional script-like language, such as Matlab, or lack of programming skills when using a non-engineering tool to perform complex algorithms, such as using a spreadsheet-like software for calculating CFD. The topic is introduced with a discussion on the main advantages and disadvantages of JavaScript when compared to other languages in engineering, focused on speed, compatibility, user interface and usage. A basic ship design example is presented as a bridge to introduce JavaScript variables, objects, libraries and HTML document model object. Five case studies of more complex maritime software developed in JavaScript are presented: dashboards for resistance and motion calculation, a design layout tool, data-driven documents and a 3D simulator. A call for JavaScript in engineering concludes the paper.

1. The Need for Script

The idea for the topics discussed in this paper came from the need to share design and simulation developments with other academic and non-academic colleagues, as well as re-use computer-based models without worrying about proprietary software and versioning. I cannot count the amount of time wasted in meetings and classes because the results were presented in a non-interactive and closed format. Worst, when files are copied from one computer to another, libraries are missing, software versions are outdated, compilers are updated and the simulation suddenly does not run when the audience requires it. Anyone that has tried to open a spreadsheet with a macro in another computer or shared a complex Matlab code with someone else knows the feeling. Python presented itself as a solution for this problem years ago, since it is one of the best and most versatile script (high-level) languages available (www.python.org). It is free, intuitive, easy to learn and widely used in the scientific community. But for simulation and visualization in engineering it lacks important features that JavaScript (JS) has, such as simplicity to create an interactive interface, extensive 2D and 3D graphic libraries and possibility to run and share a code with no external software installation. The internet, or more precisely the web, on the other hand, has a pretty stable history of multi OS compatibility. Sites like www.efunda.com or http://www.numericjs.com/ are providing reliable online and interactive engineering/mathematic libraries for some years already.

Therefore, a disclaimer disguised as introduction: this paper will propose JS language as key success to develop open and collaborative software in engineering. It keeps an informal writing tone with unnecessary references to the first person, since that most of the examples are based on my personal experience while developing and teaching with JS as an engineer. It expects to affect two kind of readers: the ones that know about JS but never considered it a useful tool for engineers; and the engineers that do not know JS. Computer scientists are out of the scope – this paper is too simplistic for them – as well as engineers that do not develop any model-based simulation or prototype software tools – the paper has no meaning if one just press buttons in a CAD tool and drink their coffee while a 3D fined CFD/FEM mesh is being processed. The scope is even narrower, given that most of the examples from Section 4 are for maritime design and engineering. But it can be extended with no damaged information to any kind of model-based engineering problem. In other (bolder) words, I defend that, if one is considering develop an engineering software tool for data, analysis and/or simulation that must be used, interacted, shared and developed by more than one person, using JS in a web environment is a key success factor.

The background for such statement relies on the power of scripting. Script(ing) languages are often interpreted rather than compiled and typically use some sort of abstraction to hide/self-configure the internal variable types, data storage and memory management. The most well know script-like software in engineering is probably Matlab. It may not be wrong to say that every engineer graduated from and after the 1990s have some experience with the concept of scripting via Matlab, and a simple `a = 2; b = 3; a + b => 5` can be extended to non-linear dynamic simulation without (usually) worrying about compilation and memory allocation. Such simplicity, also found in other commercial software (e.g. Mathematica) or high-level languages (e.g. Python, Ruby, R, C#) is the current norm to develop model-based simulations in engineering.

The internet, however, grew in the last years much faster than these 20+ years old style of programming. And so, it changed the routine on how to present and understand the results of analyses and simulations. Interactive dashboard and visual quantification of changes are not only a reality, but expected. The tedious process of pressing the run button hundreds of time for make changes here and see impacts there, *Nasa (2007),* can nowadays be compiled in a dashboard accessible from any pocket; pretty much every App in your smartphone has some sort of interactive page. Try, however, to create such engineering dashboards, *Few (2013),* in a software like Matlab or Excel. Besides the cumbersome programing of outdated windows and user controls, it is practically impossible to share with others as well as control versioning without tremendous risk of loss of functionalities. JS, on the other hand, incorporates useful open source features, such as available code, traceability, reproducibility and versioning control. As engineering and software design is an interactive process, to be able to track changes and fix bugs while testing and simulating are essential in modern programming.

JS is one of the core languages of the web, together with CSS and HTML, and most modern browsers support it without plugins, *Flanagan (2011).* It was released in December of 1995, made originally to control dynamically webpages, but grew in the same fast pace as the internet, being used today in pretty much every online application available, from webapps for smartphones, server management, to video game development. Besides community work, we cannot deny the role of big companies in selecting JS as main web language, such as Google's V8 JavaScript engine for compilation and execution of JS (https://developers.google.com/v8/).

2. To JavaScript or not to JavaScript

2.1. When not to JavaScript?

Before detailing the benefits of JS in engineering, let's make clear when one should NOT use JS in engineering. Such list is required to avoid frustration and angry e-mails to this author.

a) When a spreadsheet can solve your problem in less than one afternoon. We cannot deny the importance of spreadsheet-like programs such as Excel in engineering. It is probably the most used conceptual tool around the engineering community. Every designer/engineer has a spreadsheet calibrated with result from diverse simulation and experiments (e.g. sea trial). Therefore, if reliable data is available and can be gathered in less than one afternoon in just a spreadsheet, keep using it. Keep in mind that, these days there are online alternatives to this that allow for easy sharing of data, such as Google Docs (http://docs.google.com).
b) When there is no need to use macros or VBA in Excel. I assume that you use macros and VBA the same amount as I do: only when strictly necessary. Therefore, if you need a slightly more complex for/while loop in your spreadsheet, you will probably need to use VBA. And this will probably take more than one afternoon. And this will probably will not be compatible when Excel updates. Then Excel probably should not have been used for this task in the first place.
c) When there is no need to share, or re-use your results. To be fair and honest, it does not matter the time spent in coding/engineering if the results are for you only, with no need to be shared or re-used; probably you already have a code in Python or Matlab that does the job, why mess

it with JS if no one will ever see or re-use this simulation?

d) When the model does not require any graphic user interface (GUI). Anyone that tried to create a GUI in Python, Matlab or Excel knows the limitations of these tools. One of the key positive points from using JS is the possibility to combine mathematics with dynamic elements of the HTML page. It means any kind of GUI, with buttons, figures, graphs as customizable as there are different pages in the net. Creativity is the limit.

e) When one does not need to interact with the model/simulation parameters and/or data. In line with the previous topic, interacting with data is much easier with a proper GUI. Parametric models get easy with sliders and real-time visualization update. Such functionalities are one of the core reasons for JS. If your model does not require the user changing variables, plotting and replotting, creating and visualizing the data generated, JS may not be necessary.

f) When it is required to to control memory/events access and/or parallel computing. Although modern JS engines such as Google V8 are as fast as C for certain tasks, JS is not the language of choice when one wants to easily control memory access or distribute a large task among multiple cores. True that modern JS packages take care of such events efficiently, such as Node.js (https://nodejs.org), but I would only recommend this option if you are comfortable with server management and JS. But if you do, then this paper is unnecessary.

g) When it can be solved without coding/computer (e.g. sketching by hand/board). Teaching brought me many students knocking on my door with large models implemented in Matlab, Excel or even JS asking coding questions. It is very common that an answer for their problems relies not in the language of choice or ability to code, but on how the problem was modelled and the algorithm sketched. One good hour of plain paper and pencil sketches can be so efficient as hours of coding if both are done properly.

Experience shows that there is a large set of engineering cases that are not described on the excluding conditions above, and does requires mathematical models with user interactivity, efficient GUI, sharing and real time capacities. Therefore, JS benefits are described in the rest of this section.

2.2 Why JavaScript

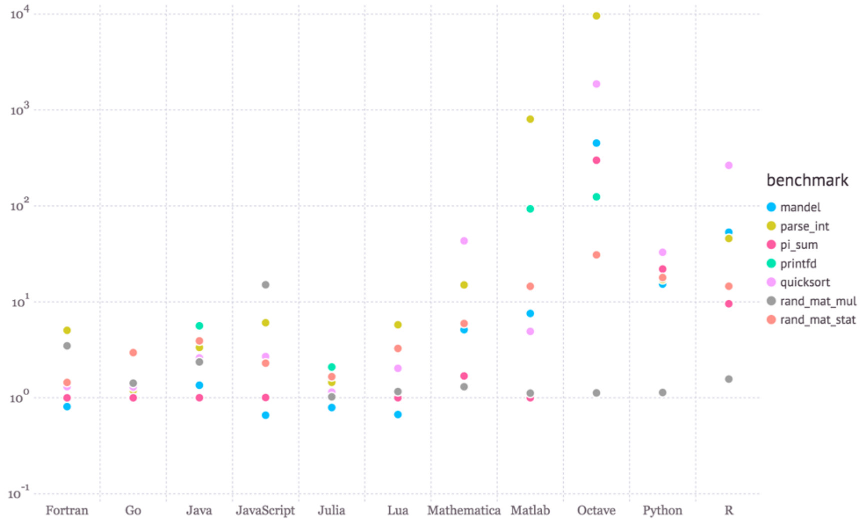
2.2.1 Speed

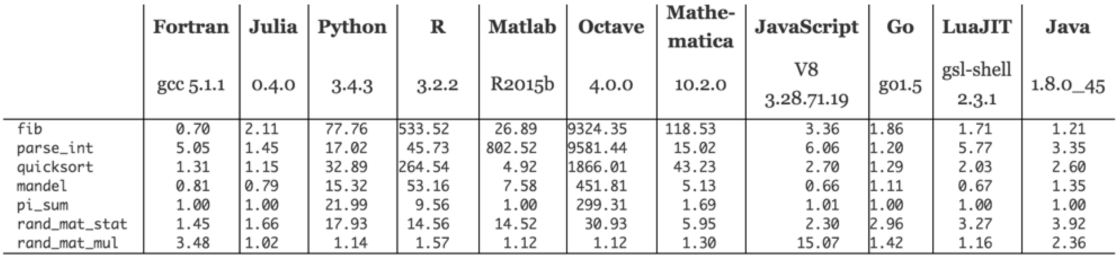
When I started to use JS for simulation I got impressed by the speed of calculation. Having looping for's and if's in vectors and matrices before in Matlab had brought me a certain time expectation between the run and the results popping out in the screen. Such expectations reached a new level when the simulation runs via a modern browser like Google Chrome in JS.

A benchmark from 2015 (https://julialang.org/benchmarks/) shows that for some basic operations, such as parse_int, which parses a string from a user input or a table of values given in text file, and transform this string in an integer number, JS can be over 130 times faster than Matlab. Even more impressive, complex numbers calculations such as Mandelbrot Set and operations like the pi sum series are faster than C, Fortran or Java, Fig.1. Given the pace of development and the fact that big companies like Goggle are behind powerful JS engines, it is not wrong to speculate that in few years the speed difference in other operations will be closer and closer to the C benchmark.

Speed to write and understand codes should also be considered. *McLoone (2012)* shows that JS requires in average 3.4 times less lines of code than C and, impressively, requires 6 percent less lines in average than an equivalent large task code in Matlab, Fig.2.

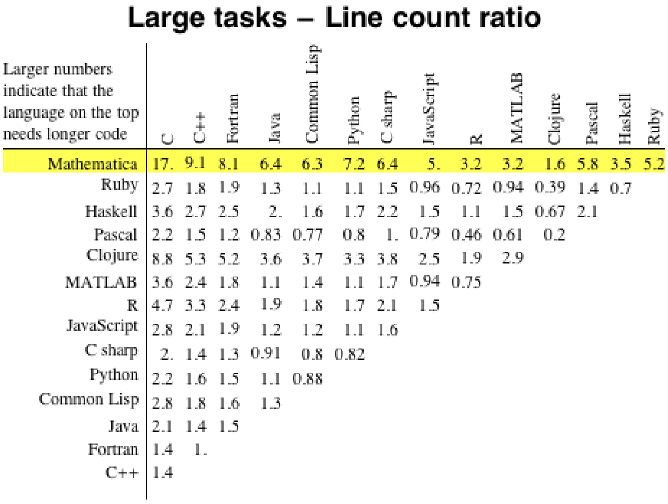
Although both benchmarks show that JS is not the fastest among all languages to process algorithms or code typing, it is so efficient as other high-level languages (either open or proprietary), with the extra functionalities from the web when combined with HTML and CSS.





	Fortran gcc 5.1.1	Julia 0.4.0	Python 3.4.3	R 3.2.2	Matlab R2015b	Octave 4.0.0	Mathematica 10.2.0	JavaScript V8 3.28.71.19	Go go1.5	LuaJIT gsl-shell 2.3.1	Java 1.8.0_45
fib	0.70	2.11	77.76	533.52	26.89	9324.35	118.53	3.36	1.86	1.71	1.21
parse_int	5.05	1.45	17.02	45.73	802.52	9581.44	15.02	6.06	1.20	5.77	3.35
quicksort	1.31	1.15	32.89	264.54	4.92	1866.01	43.23	2.70	1.29	2.03	2.60
mandel	0.81	0.79	15.32	53.16	7.58	451.81	5.13	0.66	1.11	0.67	1.35
pi_sum	1.00	1.00	21.99	9.56	1.00	299.31	1.69	1.01	1.00	1.00	1.00
rand_mat_stat	1.45	1.66	17.93	14.56	14.52	30.93	5.95	2.30	2.96	3.27	3.92
rand_mat_mul	3.48	1.02	1.14	1.57	1.12	1.12	1.30	15.07	1.42	1.16	2.36

Fig.1: Benchmark times relative to C (smaller is better, C performance = 1.0), https://julialang.org/benchmarks/



Large tasks – Line count ratio

Larger numbers indicate that the language on the top needs longer code	C	C++	Fortran	Java	Common Lisp	Python	C sharp	JavaScript	R	MATLAB	Clojure	Pascal	Haskell	Ruby
Mathematica	17.	9.1	8.1	6.4	6.3	7.2	6.4	5.	3.2	3.2	1.6	5.8	3.5	5.2
Ruby	2.7	1.8	1.9	1.3	1.1	1.1	1.5	0.96	0.72	0.94	0.39	1.4	0.7	
Haskell	3.6	2.7	2.5	2.	1.6	1.7	2.2	1.5	1.1	1.5	0.67	2.1		
Pascal	2.2	1.5	1.2	0.83	0.77	0.8	1.	0.79	0.46	0.61	0.2			
Clojure	8.8	5.3	5.2	3.6	3.7	3.3	3.8	2.5	1.9	2.9				
MATLAB	3.6	2.4	1.8	1.1	1.4	1.1	1.7	0.94	0.75					
R	4.7	3.3	2.4	1.9	1.8	1.7	2.1	1.5						
JavaScript	2.8	2.1	1.9	1.2	1.2	1.1	1.6							
C sharp	2.	1.4	1.3	0.91	0.8	0.82								
Python	2.2	1.6	1.5	1.1	0.88									
Common Lisp	2.8	1.8	1.6	1.3										
Java	2.1	1.4	1.5											
Fortran	1.4	1.												
C++	1.4													

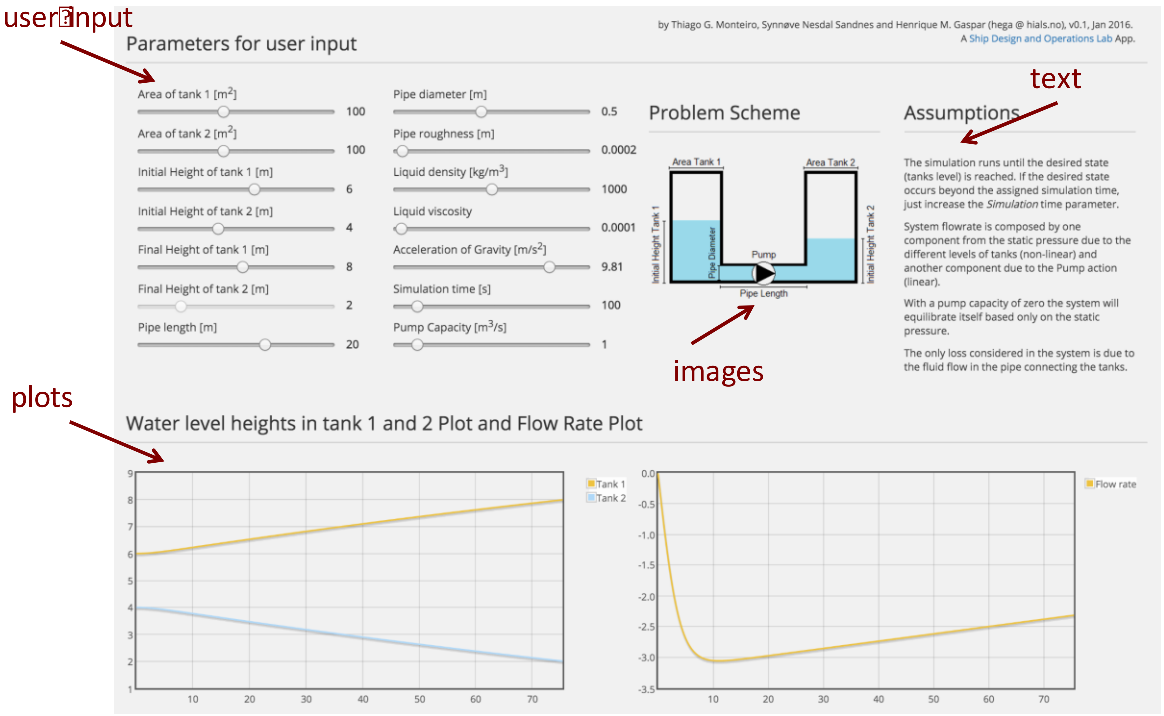
Fig.2: Average line count ratio for diverse language when programming large tasks code, *McLoose (2012)*

2.2.2 Compatibility

Close to universal compatibility is the core of online applications. The idea that anyone with any modern browser can open, explore and run an engineering model in a few clicks, with no need to install or update anything is paramount. JS web applications, therefore, passes the Shell Test. As explained informally at UCL by my colleagues John Calleya, Michael Traut and Tristan Smith, I think the Shell test is an imaginary person at Shell that wants to explore model data/input/output on their desktop without having to install anything. In other words, web applications are a key link to show and share academic results with the society and industrial partners (exemplified by Shell) without the complexity that usually follows simulation models.

For the sake of exemplification, let's investigate the simulation of a coupled tanks problem. It consists of two tanks with variable areas and volumes connected between a pipe of variable length and roughness, and a pump with variable flowrate capacity. The objective is to simulate the water level heights over time, as well as the flow rate between the tanks. This would be an initial case for ballast/antiroll tank calculation, for instance. Although a simple problem, it consists of 14 inputs, with nonlinear time dependant equations due to the roughness of the pipe and viscosity of the liquid *Ingham et al. (2007).*

A spreadsheet model is definitively possible, with the 14 variables in 14 different cells, with a long list of time steps until the convergence of the flow[1]. Another possible option is a Matlab code, with the variable as a text input, and every *run* requires a click, plus the opening of close of multiple plots windows that always mixes with other windows. Both cases would definitively work, and such coding indeed requires less than a couple of hours. But to share the results with someone that have not been exposed to the model would require *a)* to share the Excel file and *pray* that it would work in their own version; *b)* to share the multiple *.m* Matlab files and spent other couple of hours explaining how to run and re-run the code (assuming the user has already Matlab installed); or *c)* to share a static presentation with the screenshot of few simulation plots and wait for feedback, with no interactivity.



by Thiago G. Monteiro, Synnøve Nesdal Sandnes and Henrique M. Gaspar (hega @ hials.no), v0.1, Jan 2016.
A Ship Design and Operations Lab App.

Parameters for user input

Area of tank 1 [m^2] 100
Area of tank 2 [m^2] 100
Initial Height of tank 1 [m] 6
Initial Height of tank 2 [m] 4
Final Height of tank 1 [m] 8
Final Height of tank 2 [m] 2
Pipe length [m] 20
Pipe diameter [m] 0.5
Pipe roughness [m] 0.0002
Liquid density [kg/m^3] 1000
Liquid viscosity 0.0001
Acceleration of Gravity [m/s^2] 9.81
Simulation time [s] 100
Pump Capacity [m^3/s] 1

Problem Scheme

Assumptions

The simulation runs until the desired state (tanks level) is reached. If the desired state occurs beyond the assigned simulation time, just increase the *Simulation* time parameter.

System flowrate is composed by one component from the static pressure due to the different levels of tanks (non-linear) and another component due to the Pump action (linear).

With a pump capacity of zero the system will equilibrate itself based only on the static pressure.

The only loss considered in the system is due to the fluid flow in the pipe connecting the tanks.

Water level heights in tank 1 and 2 Plot and Flow Rate Plot

Fig.3: Coupled tanks dashboard simulation, http://www.shiplab.hials.org/app/twotanks/

A fourth option is to create a webpage with variables as sliders, real-time plots and include a nice figure explaining the software in only one web page, a dashboard for the simulation, as observed in the screenshot from Fig.3, http://www.shiplab.hials.org/app/twotanks/. Such interactive GUI can be opened via mobile, tablets or PCs. Sliders are very intuitive to modify variables, and the real-time update recalculates automatically every plot. It requires no compilation, no *run* button, no external installation[2], runs direct from the browser, can be shared online (in a standard configured webserver) or private (with .HTML file and additional libraries). From the user's point of view, it requires almost no explanation when the GUI is made properly – sliders change variables, which changes the simulation and updates the plots.

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[1] How many rows is required in this spreadsheet model is an unknown, given that it can converge in few seconds when the pump has a higher flowrate or very slow if only gravity applies.

[2] But a good modern browser is recommended; and by personal experience avoid using Microsoft Internet Explorer when developing models in JS.

2.2.3 User Interface

A clean user interface is not a merit of JS, but of the powerful combination of HTML and CSS. Different from commercial software that have a GUI constrained by cells (e.g. Excel) or predefined windows and buttons (e.g. Matlab), the browser always start from a blank page, where text, image, video, buttons, charts and most of the interactive digital commands that we are used to can be placed with large freedom on style and interface. Since 2003 CSS Zen Garden presents, for instance, the versatility of the HTML + CSS with examples of a same HTML code controlled by different CSS styles, http://www.csszengarden.com/.

Considering the example from Fig.3, we can observe that pretty much every element of the page can be customized, from colours to fonts, graphs to buttons, text, and images. A single page dashboard was the main objective in that app, with key information of the whole simulation condensed in one page. Deliberately *range slides* were used for user input, to facilitate parametric changes, instead of a traditional *text input* box. By the side of the slider is placed an image exemplifying the problem, followed by a text of the assumptions. Results of the real-time simulation are presented below the variables, with the two main plots that adjusts automatically to the maximum and minimum axis value until the convergence is reached. Most of the elements in the page, such as sliders and plots, are ready made via HTML5 or JS libraries, highly customizable for adapt to any application. Try to imagine creating the same dashboard, with the same efficiency, in any other software.

The fact that everyone knows how to use a browser is another benefit. A clean dashboard requires little or no training. Sliders instead of buttons instigates interactivity and the real-time calculation eliminate the need of pressing the *run* button every time that a parameter is changed. The concept of buttons, sliders, tabs, hyperlinks are already part of the everyday life of not only engineers, but all stakeholders from a simulation model. In this sense, to create a GUI that is understood and can be interacted by a wider range of people is an advancement.

2.2.4 Usage

Looking for similar examples in the internet is the first way to solve any difficulty while modelling. From ‘How to do a scatter plot in Excel’ from ‘genetic algorithms in Python’, this is how must of us and our students looks for a solution nowadays. Github (https://github.com/) is probably the largest repository for codes available online. A study from 2014 shows that JS is by far the most used language in Github (http://githut.info). It means software, tutorias and examples made available by millions of collaborators to re-use and contribute, with an extensive qualified community that shares its developments and results openly. Data Driven Documents library (D3 - https://d3js.org/), for instance, keeps an impressively neat page of examples, tutorials and documentation available in Github, with ready-made codes for most of the visualizations presented.

Such large community of developers means an extensive number of ready to use JS libraries available online. There is no best choice, since that usually the selection of a JS library is strongly connected to the needs, Does simulation X requires a real time plot of variables or a 3D object moving in the screen, or both? For the sake of exemplification, my personal suggestion, with list of JS libraries useful for engineers is presented as follows:

- Data storage: JSON (https://www.w3schools.com/js/js_json_intro.asp)[3]
- Data handling and interactivity: D3 (https://d3js.org/)
- 2D Plots: Flot (http://www.flotcharts.org/) and Chart.js (http://www.chartjs.org/)
- 3D Plots: Plotly (https://plot.ly/javascript/)

---

[3] JSON is not a library, but a syntax for storing and exchanging data, written in JS object notation. Although data can be easily converted from XML, CSV and even Excel XLXS to JSON, understanding JSON notation saves precious time when testing and using JS libraries.

- Numerical computations: Numeric JavaScript (http://www.numericjs.com/)
- 2D Drawings (with SVG): Snap.svg (http://snapsvg.io/)
- 3D Drawings (with WebGL): Three.js (https://nodejs.org/en/)
- GPU Numerical Calculation: WebCLGL (https://github.com/stormcolor/webclgl)
- JS in the server side: Node.js (https://nodejs.org/en/)

The Computer Science 101 course in Stanford uses a version of JS to introduce topics of computer science to its students, such as the nature of computers and code, jargon (bits, bytes), loops, structured data and digital media. As mentioned in the prerequisites of the course Zero computer experience is assumed beyond a basic ability to use a web browser. Even better, the course is available online (https://cs101.class.stanford.edu/).

2.2.5 It just works

I am aware that this paper could have not been written 5-10 years ago. Most of the libraries commented in 2.2.4 were not available by then, and we did not have the powerful JS engines encoded in the browser as we have now. However, today, it just works. The fact that JS is a web language means that developers should take in consideration different devices, operating systems, browsers, versions and languages, and create standards and libraries that are functional for all of them. It is not wrong to speculate that the in the future we will not have to use a software that runs only in Windows XP with Service Pack 2. The reality is that we are already able to login via web in a powerful server in the cloud, allowing CFD calculations being made from a tablet and e-mailed back to you when finished, *Gentzsch et al. (2016).*

I am not affirming that every software or simulation model should be developed only in JS. But the fact that a modern browser is the new standard for user interface means that developing in JS will most likely avoid future compatibility problems between versions and operating systems. As the scope of this paper is aimed to people like me, professional engineers while amateur developers, it is a relief to realize that a code just works, does not matter if open in the Windows 10 PC with Internet Explorer from my boss, or in the Macbook with Safari from my students.

Looking at the functional side for developing model-based engineering tools JS, as a high-level language, presents many ways to solve the same problem. Data can be considered text, integers, floats, vectors (lists), matrices and objects with no need of variable declaration. Objects and prototypes are an efficient way to describe a hierarchical system, such as a ship, which proved to be very efficient when exploring a design space, *Monteiro and Gaspar (2016).* Although possible to copy the similar structure of declare variables, create function, calculate case 1 to case n, plot, found in a spreadsheet or Matlab-like programs, one is not constrained by it, neither requires a function with different variable names in a separated .m file or a VBA macro to develop a model.

3. To JavaScript – The Basics

Many JS tutorials are available online, with Codecademy being my favourite as a self-study tool for introducing JS to students (https://www.codecademy.com/learn/javascript). The examples in these tutorials, however, are not focused in basic engineering. This section presents a simpler barge example that I have been using in the last years to introduce basic calculation in JS for my marine engineering students and colleagues. To understand the following tutorial the reader requires only knowledge in basic programming elements, such as variables, lists, functions, objects and loops. It starts with a basic JS console calculation (i) until a basic Web App with extra features (xii).

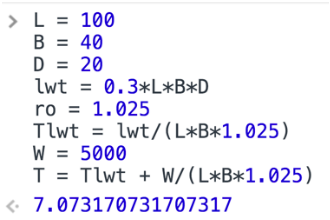
i) Console: Your browser is already apt to run JS code, via console, in a very similar way as the console of other high-level languages such as Python or Matlab. (In strict terms, Matlab is not really considered a high-level language.) The way to access this console changes from browser to browser, but usually it is considered a developer tool. When opened, it is possible to try the simple `a = 2; b = 3; a`

+ b => 5 as observed in Fig.4.

```
> a = 2
< 2
> b = 3
< 3
> a + b
< 5
>
```

Fig.4: Google Chrome JS console with the *a*+*b* example

ii) Barge Problem: Imagining the simplest maritime engineering problem to start with, the draft calculation of a rectangular barge. Main variables are length (L), breadth (B), depth (D), draft (T), main deck cargo load (W), freeboard (FB) and water density (ro). Let's assume the lightweight (lwt) as a function of the cubic number, and the barge floating in sea water. Just typing the sequential variables and formulas in the console would solve automatically our problem, as observed in Fig.5.

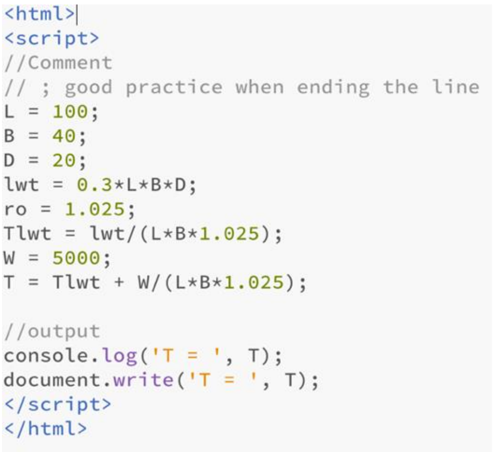


```
> L = 100
  B = 40
  D = 20
  lwt = 0.3*L*B*D
  ro = 1.025
  Tlwt = lwt/(L*B*1.025)
  W = 5000
  T = Tlwt + W/(L*B*1.025)
< 7.073170731707317
```

Fig.5: Screenshot of the barge problem solved in the browser JS console

iii) Editor: Console is a useful tool to debug your code, but a good editor is fundamental. Many free choices are available. Brackets (http://brackets.io/) is my actual choice, with many useful features as autocompletion, Github connection and a pleasant colouring scheme.

iv) Editing: pure JS code is not computed in the browser, it needs to be written in the HTML file (browser readable) among the tags <script></script> or included in it as external library. Therefore, bringing the barge problem to a standalone file, made in the editor, would add few lines, as well as better understanding of our problem. The same code from Fig.5 is presented in Fig.6, typed in the editor and saved as .html file. Running this code means opening the .html file that it was saved as, giving that this code would work in any modern browser, with no need of installing any additional software. The console.log() function is used to print the result (variables and objects) in the console.



```
<html>
<script>
//Comment
// ; good practice when ending the line
L = 100;
B = 40;
D = 20;
lwt = 0.3*L*B*D;
ro = 1.025;
Tlwt = lwt/(L*B*1.025);
W = 5000;
T = Tlwt + W/(L*B*1.025);

//output
console.log('T = ', T);
document.write('T = ', T);
</script>
</html>
```

Fig.6: Screenshot of the barge problem in the editor, using the colour scheme of an .html file[4].

---

[4] Good practice recommends changing *<html></html>* for *<!doctype html>*.

v) HTML: Besides printing outputs in the console, we can get any variable printed in the main page, via the document.write() function. The Document interface is an object model (DOM), and represents any web page loaded in the browser, serving as an entry point into the web page's content (https://developer.mozilla.org/en-US/docs/Web/API/Document). Most of the element and attributes contained in a Document can be tagged, identified and modified, Fig.7, from text to figures and interactive graphs. It means that we can put tags and ids in the elements of the page, and modify these elements via JS, updating a result after a calculation or when e.g. a parameter is changed. (To know more about the potential of handling the HTML document object model (DOM), elements, attributes and events, start with the good and reliable W3S tutorials, https://www.w3schools.com/js/js_htmldom.asp.)

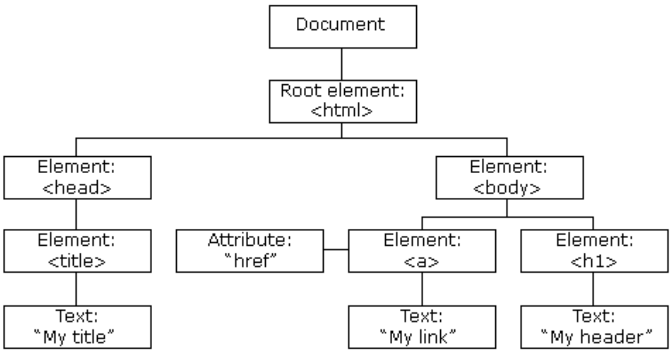
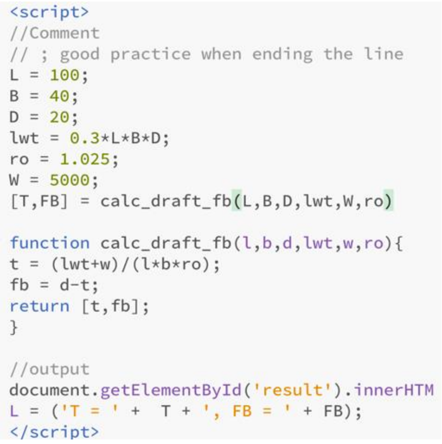


Fig.7: HTML Document Object Model (DOM) three of objects, https://www.w3schools.com/js/js_htmldom.asp

vi) Functions: Creating a function in JS follows similar syntax as other high-level languages: it requires a declaration, input of variables or objects, calculation and output of results. Fig.8 presents the code from Fig.6 with a *calc_draft()* function, which receives *L*, *B*, *D*, *lwt*, *W* and *ro* and outputs *T* and *FB*.

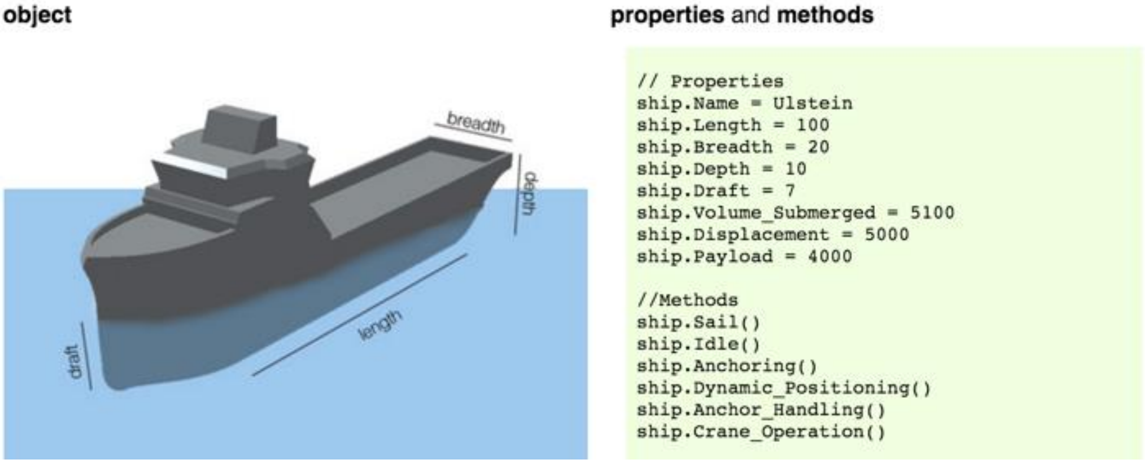


```
<script>
//Comment
// ; good practice when ending the line
L = 100;
B = 40;
D = 20;
lwt = 0.3*L*B*D;
ro = 1.025;
W = 5000;
[T,FB] = calc_draft_fb(L,B,D,lwt,W,ro)

function calc_draft_fb(l,b,d,lwt,w,ro){
t = (lwt+w)/(l*b*ro);
fb = d-t;
return [t,fb];
}

//output
document.getElementById('result').innerHTM
L = ('T = ' +  T + ', FB = ' + FB);
</script>
```

Fig.8: *Calc_draft* function to calculate draft *T* and freeboard *FB* for the barge problem

vii) Objects: The barge can be defined as an object, with properties and methods. Such taxonomy is one of the key elements of JS to handle complex hierarchical structures as ships and its simulation. A well-defined object can be used in different calculations, for simulation and visualization of complex engineering models. Fig.9 presents the idea of a ship as an object, with properties like *Name* and *Length*, and methods such as *Sail()* and *Anchoring().*

Similarly, the barge from our problem can be defined as an object in the code described in Fig.10. It consists of the user input properties *L*, *B*, *D*, while *T* and *FB* are calculated via the function *calc_draft()*. Note that the function receives now an object *ship* as input, rather than the variables separated, and uses the properties of this generic *ship* for its calculation.



```
// Properties
ship.Name = Ulstein
ship.Length = 100
ship.Breadth = 20
ship.Depth = 10
ship.Draft = 7
ship.Volume_Submerged = 5100
ship.Displacement = 5000
ship.Payload = 4000

//Methods
ship.Sail()
ship.Idle()
ship.Anchoring()
ship.Dynamic_Positioning()
ship.Anchor_Handling()
ship.Crane_Operation()
```

Fig.9: A ship as a JS object, with properties and methods

```
<script>
//Ship as object
Barge = {};

Barge.L = 100;
Barge.B = 40;
Barge.D = 20;
Barge.lwt = 0.3*Barge.L*Barge.B*Barge.D;
ro = 1.025;
W = 5000;
[Barge.T,Barge.FB] =
calc_draft_fb(Barge,W,ro)

function calc_draft_fb(ship,w,ro){
t = (ship.lwt+w)/(ship.L*ship.B*ro);
fb = ship.D-t;
return [t,fb];
}

//output
document.getElementById('result').innerHTM
L = ('T = ' +  Barge.T + ', FB = ' +
Barge.FB);
</script>
```

Fig.10: The barge presented as an object *Barge*

viii) Prototype: Every JS object has a prototype, which is also an object. One way is to understand prototype is as a function that constructs a new object, which inherits the properties of the prototype constructor. Let's imagine *Ship()* as a prototype, able to create any object with properties *L*, *B*, *D* and *lwt*, such as *Ship X* and *Ship Y* instances. Both instances would inherent the properties and methods of *Ship()*, but can also be modified and include new properties and methods if necessary. Fig.11 shows a simple code for a *Ship()* prototype with two instances, *Barge_1* and *Barge_2*, with the last having its property length *L* modified from 100 to 120. A list called *myShips[]* is created, containing both instances.

ix) Design Space: With a constructor in place, we can start to create a preliminary design space, using a series of *for* loops to vary *L*, *B* and *D*. Fig.12 exemplifies this process for creating a design space with 769526 unique instances, varying in a single unit step the properties length (*L*, from 10-200), breadth (*B*, from 10-100) and depth (*D*, from 5-50). The whole design space is saved in the list *myShips[]*.

```
<script>
//Ship as object
function Ship (name){
this.name = name;
this.L = 100;
this.B = 40;
this.D = 20;
this.lwt = 0.3*this.L*this.B*this.D
}

Barge_1 = new Ship('Barge 1');
Barge_2 = new Ship('Barge 2');
Barge_2.L = 120;

//A list of objects
myShips = [Barge_1, Barge_2];


//output
console.log(myShips);
</script>
```

Fig.11: *Ship()* as prototype to construct instances

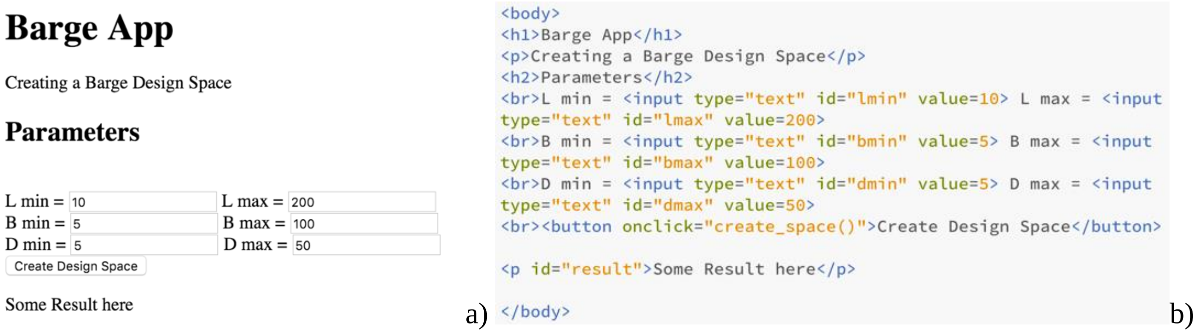
```
function Ship (name){
this.name = name;
this.L = 100;
this.B = 40;
this.D = 20;
this.calc_lwt = function (){return 0.3*this.L*this.B*this.D}
}
barge_id = 1;
myShips = [];
//For all L's from 10 to 200, every 1 step
for (l = 10; l < 201 ; l++){
//For all B's from 5 to 100, every 1 step
    for (b = 10; b < 101 ; b++){
    //For all D's from 5 to 50, every 1 step
        for (d = 5; d < 51 ; d++){
            barge = new Ship(barge_id);
            barge.L = l;
            barge.B = b;
            barge.D = d;
            barge.lwt = barge.calc_lwt();
            myShips.push(barge);
            barge_id++;
        }
    }
}
//output
console.log(myShips);
```

Fig.12: A series of *for* loops to create a design space with 799526 unique instances based on the *Ship()* constructor

x) User Interface: So far, we have been calculating our barge in the console, as we would do in Matlab. To bring the potential of the web we need to use the browser as GUI, creating a *web app*. It requires the understanding that two different languages are interacting between each other to control the main document (DOM): HTML and JS.

The HTML part of the code between the tags *<body></body>* controls what we see and interact in the main body of the DOM. A text between the tags *<h1></h1>* will be interpreted as a title, while *<input type=´´text´´>* shows in the screen a box where the user can input any text or number. A button for calling a calculation function is possible and presented, but practically unnecessary, given that each of elements can trigger actions on certain events, such as *onchange*, *onclick* or *onmouseover*. Keep in mind that each element requires a unique *id*, since the JS part of the code will interact with it, reading input and writing outputs. A very simple GUI with a title and the parameters presented in *ix* is observed in Fig.13a while Fig.13b shows the equivalent HTML code.

xi) Web App: To create an interactive web app the JS code must interact with the HTML elements. For this simple *Barge App* case it means reading the user input, calculate all the possible designs and print info about them back in the document under the div identified as *result*. The code presented in Fig.14b parses the string of each of the input boxes from the HTML, creates the design space, and print the whole list of unique designs on the document, via the *getElementbyid()* method. The final web app with the design space calculated after user input is presented in Fig.14a.



Barge App

Creating a Barge Design Space

Parameters

L min = 10 L max = 200
B min = 5 B max = 100
D min = 5 D max = 50

Some Result here

a)

```
<body>
<h1>Barge App</h1>
<p>Creating a Barge Design Space</p>
<h2>Parameters</h2>
<br>L min = <input type="text" id="lmin" value=10> L max = <input
type="text" id="lmax" value=200>
<br>B min = <input type="text" id="bmin" value=5> B max = <input
type="text" id="bmax" value=100>
<br>D min = <input type="text" id="dmin" value=5> D max = <input
type="text" id="dmax" value=50>
<br><button onclick="create_space()">Create Design Space</button>

<p id="result">Some Result here</p>

</body>
```

b)

Fig.13: Basic GUI for a *Barge App* (a) and its equivalent HTML code (b)

Barge App

Creating a Barge Design Space

Parameters

L min = 10 L max = 200
B min = 10 B max = 100
D min = 5 D max = 50

Total designs: 799526

```
{"name":0,"L":10,"B":10,"D":5,"lwt":150}{"name":1,"L":10,"B":
{"name":4,"L":10,"B":10,"D":9,"lwt":270}{"name":5,"L":10,"B":
{"name":8,"L":10,"B":10,"D":13,"lwt":390}{"name":9,"L":10,"B"
{"name":12,"L":10,"B":10,"D":17,"lwt":510}{"name":13,"L":10,"
{"name":16,"L":10,"B":10,"D":21,"lwt":630}{"name":17,"L":10,"
{"name":20,"L":10,"B":10,"D":25,"lwt":750}{"name":21,"L":10,"
{"name":24,"L":10,"B":10,"D":29,"lwt":870}{"name":25,"L":10,"
{"name":28,"L":10,"B":10,"D":33,"lwt":990}{"name":29,"L":10,"
{"name":32,"L":10,"B":10,"D":37,"lwt":1110}{"name":33,"L":10,
{"name":36,"L":10,"B":10,"D":41,"lwt":1230}{"name":37,"L":10
```

a)

```
function create_space (){
    lmin = parseInt(document.getElementById("lmin").value);
    lmax = parseInt(document.getElementById("lmax").value) + 1;
    bmin = parseInt(document.getElementById("bmin").value);
    bmax = parseInt(document.getElementById("bmax").value) + 1;
    dmin = parseInt(document.getElementById("dmin").value);
    dmax = parseInt(document.getElementById("dmax").value) + 1;

    barge_id = 0;
    myShips = [];
    for (l = lmin; l < lmax ; l++){
        for (b = bmin; b < bmax ; b++){
            for (d = dmin; d < dmax ; d++){
                barge = new Ship(barge_id);
                barge.L = l;
                barge.B = b;
                barge.D = d;
                barge.lwt = barge.calc_lwt();
                myShips.push(barge);
                barge_id++;
            }
        }
    }
    //output
    designs = '';
    document.getElementById("result").innerHTML = "Total designs: " + myShips.length;
    for (i = 0; i < 1000; i++){designs = designs + JSON.stringify(myShips[i])};
    document.getElementById("designs").innerHTML = designs;
}
</script>
```

b)

Fig.14: Barge App GUI with 799526 designs (a) and JS code interacting with the HTML elements via *getElementbyid()* method (b)

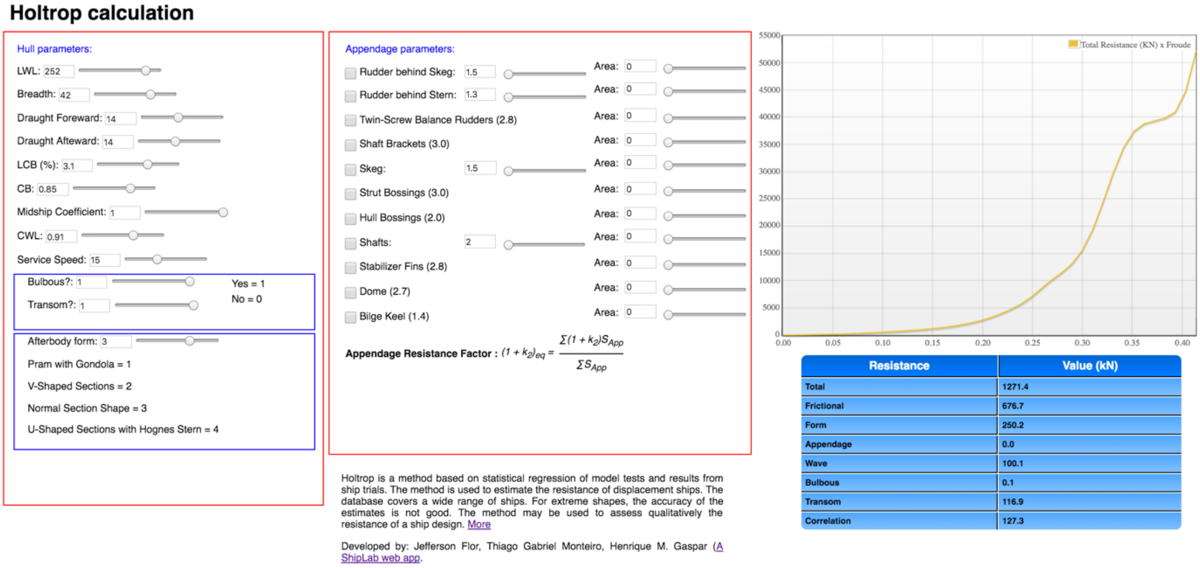
xii) Extra Features: Adding extra features is a natural step further. JS offers so many options that, rather than technology availability, user requirements and creativity are the main constraints. Improvements in the GUI are done by properly use of CSS and ready-made template libraries, such as the *Bootstrap* framework, http://getbootstrap.com/). Graphs and plots can be inserted, as well as any other digital features observed in web pages, such as range sliders, buttons, video, sound, 2D and 3D drawings. This interactivity is the main bonus of JS, since no other language provides so much freedom and examples when manipulating the DOM document to create useful GUIs.

4. Maritime Design and Engineering

This section presents short a list of examples of web apps and simulations developed in the last years by the author at the Ship Design and Operations Lab at NTNU in Ålesund (www.shiplab.hials.org). Most of the examples are available online, with code and algorithms free to update and reuse.

i) Ship Resistance: Fig.15 presents a dashboard to calculate in real-time the total resistance of a ship via the *Holtrop and Mennen (1982), Holtrop (1984)* method. It was mainly developed by a master student in a couple of weeks, *Flor* (2016), http://shiplab.hials.org/app/holtrop/).

ii) Ship Motion: Estimation of ship motions via closed-form expressions is a powerful method to derive frequency responses for the wave-induced motions for monohull ships, *Jensen et. al. (2004).* Fig.16 shows a dashboard to calculate motion and acceleration using closed-form expressions, developed by a master student, *Andrade (2015)*, www.shiplab.hials.org/app/shipmotion/.



Holtrop calculation

Hull parameters:

LWL: 252
Breadth: 42
Draught Foreward: 14
Draught Afteward: 14
LCB (%): 3.1
CB: 0.85
Midship Coefficient: 1
CWL: 0.91
Service Speed: 15
Bulbous?: 1
Transom?: 1
Yes = 1
No = 0
Afterbody form: 3
Pram with Gondola = 1
V-Shaped Sections = 2
Normal Section Shape = 3
U-Shaped Sections with Hognes Stern = 4

Appendage parameters:

☐ Rudder behind Skeg: 1.5 Area: 0
☐ Rudder behind Stern: 1.3 Area: 0
☐ Twin-Screw Balance Rudders (2.8) Area: 0
☐ Shaft Brackets (3.0) Area: 0
☐ Skeg: 1.5 Area: 0
☐ Strut Bossings (3.0) Area: 0
☐ Hull Bossings (2.0) Area: 0
☐ Shafts: 2 Area: 0
☐ Stabilizer Fins (2.8) Area: 0
☐ Dome (2.7) Area: 0
☐ Bilge Keel (1.4) Area: 0

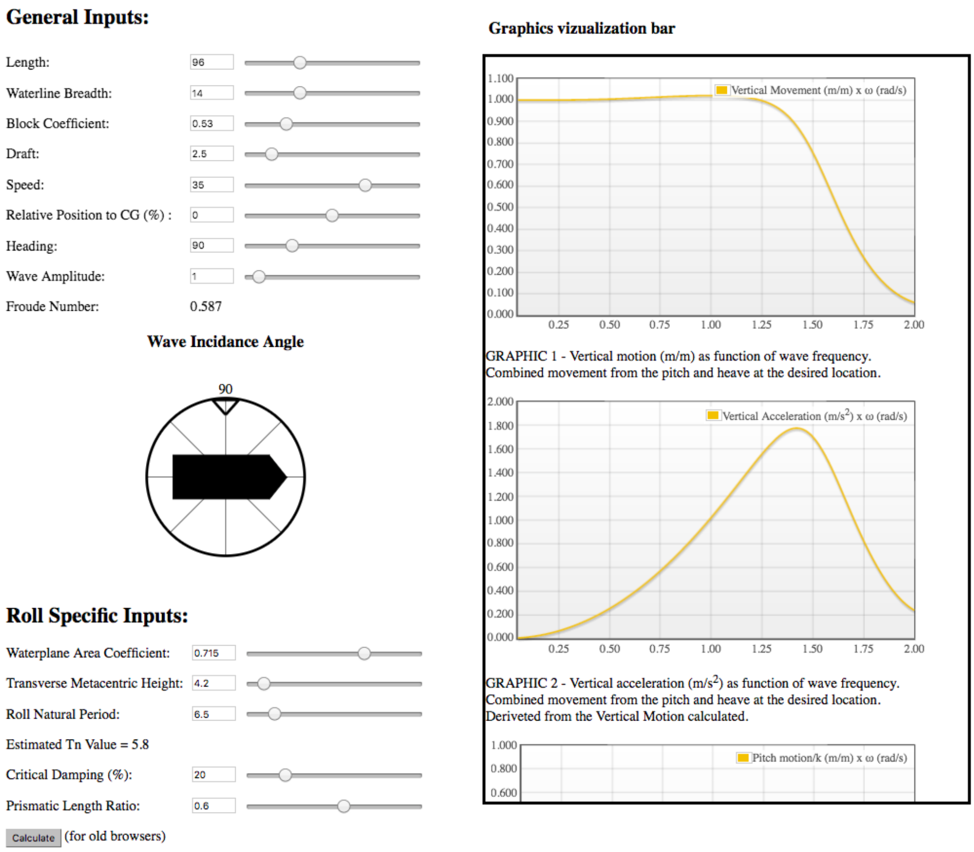
Appendage Resistance Factor : $(1+k_2)_{eq} = \frac{\Sigma(1+k_2)S_{App}}{\Sigma S_{App}}$

Holtrop is a method based on statistical regression of model tests and results from ship trials. The method is used to estimate the resistance of displacement ships. The database covers a wide range of ships. For extreme shapes, the accuracy of the estimates is not good. The method may be used to assess qualitatively the resistance of a ship design. More

Developed by: Jefferson Flor, Thiago Gabriel Monteiro, Henrique M. Gaspar (A ShipLab web app.

Resistance	Value (kN)
Total	1271.4
Frictional	676.7
Form	250.2
Appendage	0.0
Wave	100.1
Bulbous	0.1
Transom	116.9
Correlation	127.3

Fig.15: Dashboard for total resistance calculation via Holtrop & Mennen method



General Inputs:

Length: 96
Waterline Breadth: 14
Block Coefficient: 0.53
Draft: 2.5
Speed: 35
Relative Position to CG (%) : 0
Heading: 90
Wave Amplitude: 1
Froude Number: 0.587

Wave Incidance Angle

Roll Specific Inputs:

Waterplane Area Coefficient: 0.715
Transverse Metacentric Height: 4.2
Roll Natural Period: 6.5
Estimated Tn Value = 5.8
Critical Damping (%): 20
Prismatic Length Ratio: 0.6
Calculate (for old browsers)

Graphics vizualization bar

GRAPHIC 1 - Vertical motion (m/m) as function of wave frequency. Combined movement from the pitch and heave at the desired location.

GRAPHIC 2 - Vertical acceleration (m/s²) as function of wave frequency. Combined movement from the pitch and heave at the desired location. Deriveted from the Vertical Motion calculated.

Fig.16: Ship motion calculation via closed-form expressions

iii) Layout Tool: A proof of concept tool to demonstrate that it is possible to quickly develop a web-based app for handling ship design layout during conceptual phase is presented in Fig.17. The app reads from a database (.csv file) the general arrangement information as *blocks*, plot them into a grid, Fig.17a, and evaluate their positioning, attributes, neighbours and connections. A connection wheel plots the relationship between blocks, Fig.17b, to quantify physical interfaces. The total work for develop this tool was approximatively 14 h, including concept development, coding, debugging, examples, layout detailing and text writing.

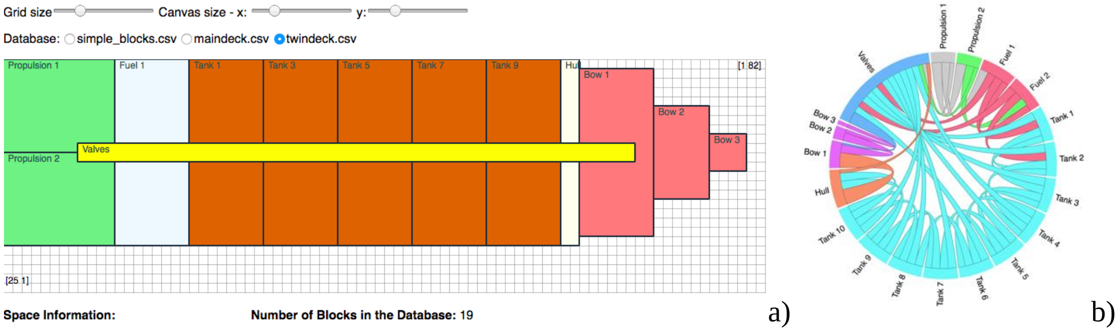


Fig.17: Ship design layout tool (http://uscience.org/files/grid/, *Gaspar (2015)*

iv) Data-driven documents (D3): Fig.18 presents five D3 examples applied to the conceptual ship design process, based on *Gaspar et al. (2014) and Calleya et al. (2016).* All examples are done in JS, and visualized in a standard .html file via browser.

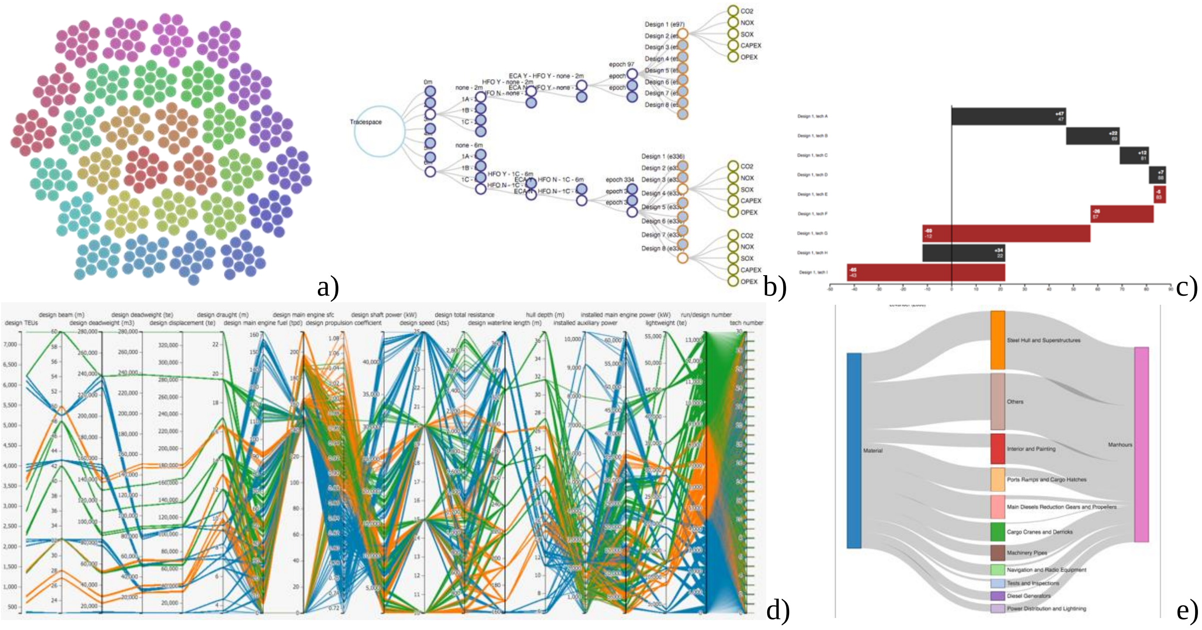


Fig.18: D3 examples applied to ship design: a) clustering of 360 designs; b) tree layout with 336 scenarios and 13440 simulation results; c) waterfall chart to quantify effect of design options; d) parallel coordinates chart applied to 13392 design; e) Sankey diagram relating material and hours cost, based on *Gaspar et al.* (2014) and *Calleya et al. (2016)*

v) 3D Simulation: Fig.19 gives screenshots from the 3D ship motion simulator based on modular design theory, closed form-expressions and WebGL libraries http://uscience.org/compit2016/, *Chaves and Gaspar (2016).*

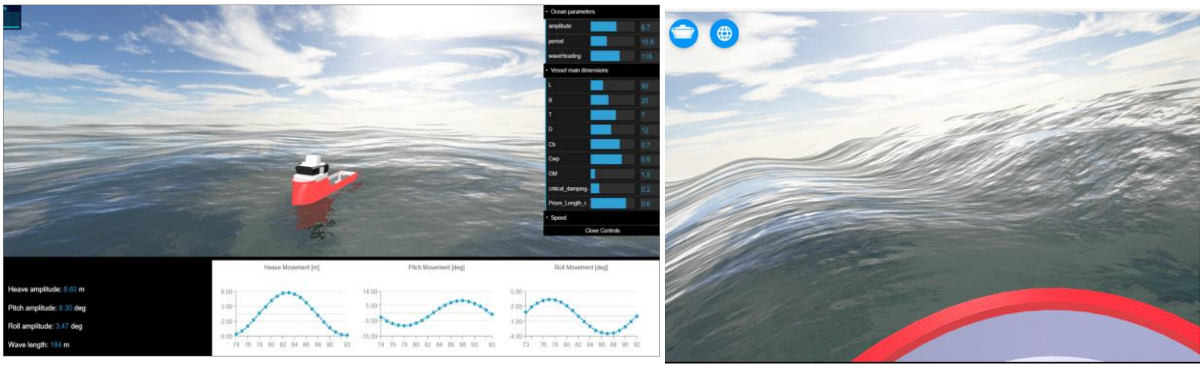


Fig.19: Screenshots from the 3D Ship Motion Simulator, *Chaves and Gaspar (2016)*

5. Call for JavaScript

I close this paper with a call for my colleagues and students to consider developing future engineering analysis and simulation in JS. I believe that, combined with web elements, no other framework will allow so much continuing collaboration and re-use of codes and libraries as JS. Even for more advanced applications JS is becoming a reliable option, with online compilers such as WebAssembly coming as standard feature soon in modern browsers, which will allow C and C++ compilation direct from the client, http://webassembly.org/.

Regarding JS and the ship design community, other examples rather than the ones presented by this author are yet very seldom. To instigate more users, a repository with ship related JS codes, developed by me and my students, is being organized, www.vesseljs.org. Monteiro is a pioneer of this process with a *Vessel.js* library already in place, *Monteiro (2016), Monteiro and Gaspar (2016).* Resistance and motions methods as the ones discussed in Section 4 are already available as JS functions, as well the ship as object via system based design.

Research is also being developed on testing the limits of the tool. The simulator from Fig.19, for instance, is being tested with multibody analysis, and nowadays 10^3 different floating bodies is an acceptable order of magnitude when using parametric equations or pre-calculated CFD analyses. GPU calculation for particles via WebCLGL is also another instigating topic, with potential to future real-time fluid dynamics simulation.

Acknowledgements

The author holds currently an associated professor position at the Department of Ocean Operations and Civil Engineering at NTNU (Ålesund, Norway), and has no commercial or professional connection with the software and companies cited. Statements on usability and performance reflects solely my opinion, based on personal experience, with no intention to harm or diminish the importance of current commercial state-of-the-art engineering tools.

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Remote Hull Surveys with Virtual Reality

Christian Cabos, DNV GL, Hamburg/Germany, christian.cabos@dnvgl.com
Viktor Wolf, DNV GL, Hamburg/Germany, viktor.wolf@dnvgl.com
Przemyslaw Feiner, DNV GL, Gdynia/Poland, przemyslaw.feiner@dnvgl.com

Abstract

Today, assessment of the structural condition of a vessel mostly takes place during survey, i.e. during physical tank entry. The presence of the surveyor reduces the need for the recording of condition – assessment can be performed on site. Upcoming inspection techniques such as drones and self-localizing cameras potentially enable cost efficient full visual mapping of tank condition on a 3D ship model. The paper explores in how far such techniques could allow structural condition assessment to be performed remotely, thereby prospectively avoiding human tank entry.

1. Hull surveys of ships in service – common practice

Structural integrity of a ship is today ensured through hull maintenance performed on behalf of the ship owner. In this process, which is characterized through periodic inspections and repairs, the actual condition of the structure may not fall below a certain level. This level is specified in rules and regulations, see e.g. *IMO (1993), IACS (2003)*. Through periodic surveys, classification societies verify that appropriate structural condition is maintained.

The maritime industry is under continuous cost pressure. This leads also to a search for more efficient means for performing surveys. Today, survey of the hull structure requires the physical presence of a surveyor.

A key aspect of hull surveys for ships in service today lies in the extensive on-board activities of class surveyors. A main portion of hull surveyor's activities on board is related to physically accessing the structure for assessing hull condition. This typically comprises the overall and close-up visual inspection of hull structures as well as monitoring and evaluating of thickness measurements. The need for surveyor's presence on board also implies cost and time loss due to travel. Time efficiency of the hull survey itself is normally low because of difficult access conditions: narrow manholes in double bottom ballast tanks, or 20 m high elevations in cargo holds, Fig.1. Reporting of findings furthermore requires good orientation skills when e.g. examining a double bottom tank.

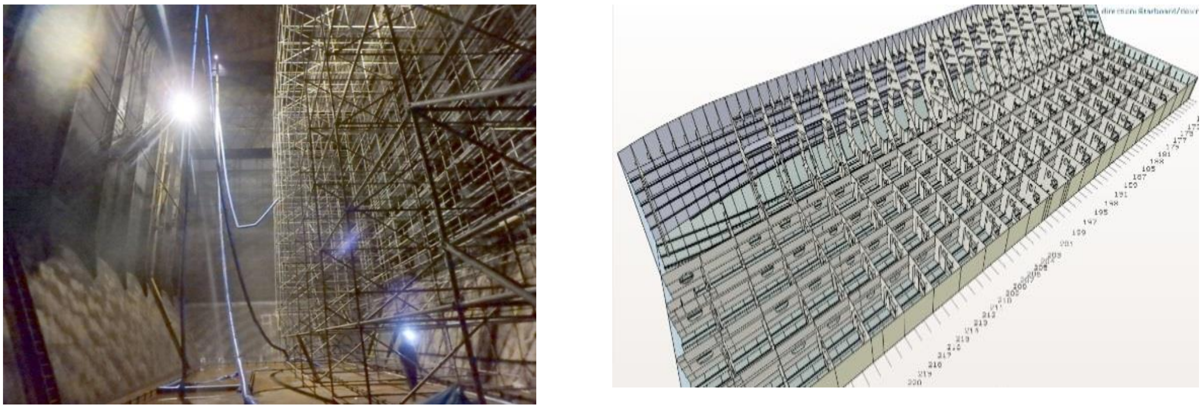

Fig.1: Staging erected for accessing and surveying bulkhead of cargo hold (left); ballast tank with high number of bays to be examined during survey (right)

Moreover, the survey preparation on board is in many cases even more time-consuming than the examination of the hull condition itself. In particular, the internal examination of spaces, such as ballast and cargo tanks, requires the tanks to be extensively prepared for physical entry. This comprises emptying the tanks, cleaning the structure from e.g. oil and sediments, gas freeing and maintaining continuous ventilation, and installing sufficient access means such as scaffolds. Thus, class hull surveys typically cannot be initiated and carried out on a short-term basis to make use of e.g. vessel's unplanned waiting time for new cargo. Although this preparation effort does not affect surveyor's time, it is an effort and operational interruption for the ship operator.

Finally, physical tank entry in many cases is hazardous: typical dangers are falling from height, lack of oxygen and presence of toxic gases. This clearly points towards the question: can the need for tank entry be reduced or be avoided altogether?

2. Remote hull surveys

Based on the above description of the current situation regarding hull surveys it is attractive to consider replacing human tank entry through alternative techniques. This also reflects existing ambitions in land based industries which target at avoiding human entry of enclosed spaces (e.g. pressure vessels) altogether in the future. In this paper, we are drafting a scenario for remote hull surveys based on several technological elements. Before describing the changed survey process in more detail, we list what could or should be available when we want to consider such procedure:

- Access to structure would be provided by an autonomous vehicle. This can be a drone or a diving or crawling robot. We will refer to a drone in the following to simplify the text but alternatives are possible.
- The orientation of the drone is enabled through automatic indoor positioning technology
- Image capturing methods allow taking photos or hyperspectral images
- Optionally, flight path is guided through a pre-existing map which can be a 3D model, possibly in a simplified format. This model would also serve as a map for marking potentially critical areas before tank inspection
- Optionally, historical findings, experience databases, or Risk Based Inspection (RBI) survey plans aid in programming specific flight paths
- Through an image mapping algorithm, captured photos can be displayed on the model, thereby comprising an updated "digital twin"
- Image recognition methods identify photos for marking necessary follow-up and/or prioritize them for additional human assessment
- Remote connectivity allows a user to interact with and guide the drone for additional close-up capturing where found necessary
- Virtual Reality (VR) techniques facilitate access to the pre-scanned tank information
- Optionally, measurement gear is carried by the drone for measurements of thickness and deformations and/or detection of cracks
- Optionally, captured images are used to automatically reconstruct a 3D model which refines the existing coarse structural model

Note that no storage of captured video material (other than for backup purposes) is proposed as it appears to be more appropriate to navigate freely in the mapped 3D output via VR rather than needing to linearly scan video material.

3. VR aided remote hull survey

The VR aided hull survey process is illustrated in Fig.2 on a high level. The main process phases – survey planning, pre-scan on board and remote hull condition assessment – are described below.

3.1. Survey planning

In general, the survey planning and preparation aims at selection of spaces for overall external and internal examination and of locations for close-up visual inspection and thickness measurements (what, where, how to inspect). For this purpose, the surveyor would explore the vessel's digital twin enriched with historic data, including results of previous class surveys and owners' inspections, as well as related data for sister vessels.

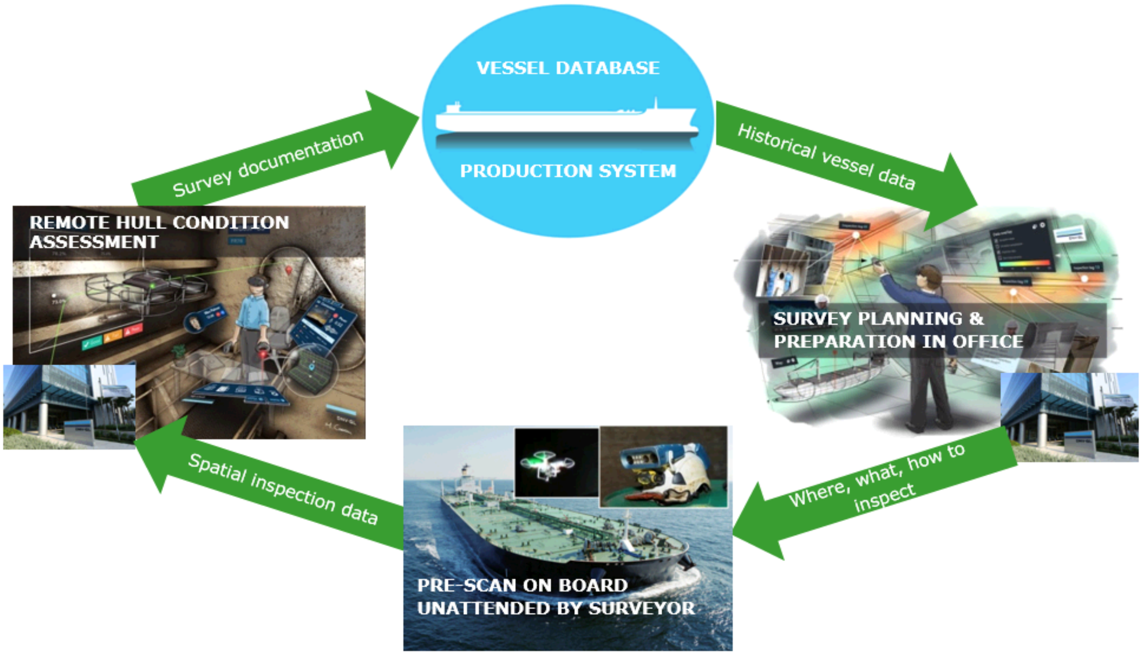

Fig.2: Remote hull surveys with VR technology

In a virtual environment, the class surveyor can be provided with advanced abilities of viewing, interacting and navigating through the vessel's virtual twin in real scale and model scale, Fig.3. Different types of structural representation, e.g. transparency mode showing structural arrangement e.g. behind the tank boundaries (Fig.4, left), support a quick and comprehensive insight into vessel's tank arrangement, structural arrangement, hull equipment, etc. Orientating and navigating in the virtual vessel may be further supported by displaying frame numbers, structural member labels, position above the base, etc.

Fig.3: Examining hull structure in VR

VR supports different strategies for long, medium and short range locomotion. For long range, the user may “jump” to a hull compartment of interest by selecting it from the small-scale model, Fig.4 (right). For the medium range navigation, fly mode and teleport mode may be available. Short range navigation is supported in VR by tracking the physical motions of the surveyor in real scale.

Fig.4: Setting control and X-ray mode for fast overview (left). Changing location by selecting target in mini-map(right).

In the different representation scales, different detail levels of information are provided. For instance, in the model scale representing the general hull form and compartmentation, the surveyor would be provided with the high-level information such as main ship data, list of relevant codes, tank arrangement, etc. In real scale representation of a specific location like a tank, the surveyor would be provided with detailed information associated with this location, e.g. the most critical weld connections in the tank, details on previous repair measures in the tank, etc. In VR, the surveyor can be provided with information in form of virtual documents/lists which can be arranged in the virtual space as appropriate for the surveyor. In addition, spatial data like locations of substantial corrosion, cracks, deformations, etc. can be displayed on the corresponding locations in virtual tank. By selecting such items on electronic lists in VR, the surveyor can be guided to the corresponding location in the virtual hull structure. Photos of the structure captured by a camera with tracking system, e.g. during previous class surveys, can be mapped on the associated virtual structure resulting in a realistic representation of the structural condition at a given date.

Provided with the above means in VR, users can efficiently extract insights relevant for specifying the survey scope like selection of spaces for overall internal examination, and of locations for close-up visual inspection and thickness measurements. The surveyor can instantly document the survey plan and other relevant documentation for the owner’s survey preparation note. In particular, the surveyor would determine and record in VR the sequence for entering the spaces for overall internal examination and the optimum path for the drone (or as an intermediate development step for the technician with e.g. helmet camera) through those spaces during inspecting. Moreover, the surveyor would make marks on the virtual structure and prepare check lists and action lists for each location to be inspected as appropriate. This would be available in VR in execution phase for efficient surveyor guidance and progress documentation.

3.2 Hull inspection as pre-scan

Hull inspections would be performed with the help of remotely operated or even autonomous inspection means, like camera equipped drones, crawlers, etc., combined with an indoor positioning system. For higher time efficiency, hull inspections would be preferably done in a pre-scan unattended by the class surveyor, following the inspection plan prepared in planning phase. As the drone or crawler would carry an automatic indoor positioning system, inspection photos could automatically be mapped onto a 3D model. An example for this procedure based on image capturing with the IRIS system, *Wilken et al. (2015)*, can be seen in Fig.5.

Camera equipped drones can already today remove the necessity for installing scaffoldings. This is the case when visual confirmation of good condition is sufficient. Crawling robots or lightweight contactless thickness measurement could prospectively abandon the need for physical tank entries.

The effort for survey preparation on board will thereby be dramatically reduced allowing voyages or even short unplanned downtimes of the ship to be effectively used for the pre-scanning of the hull structure.

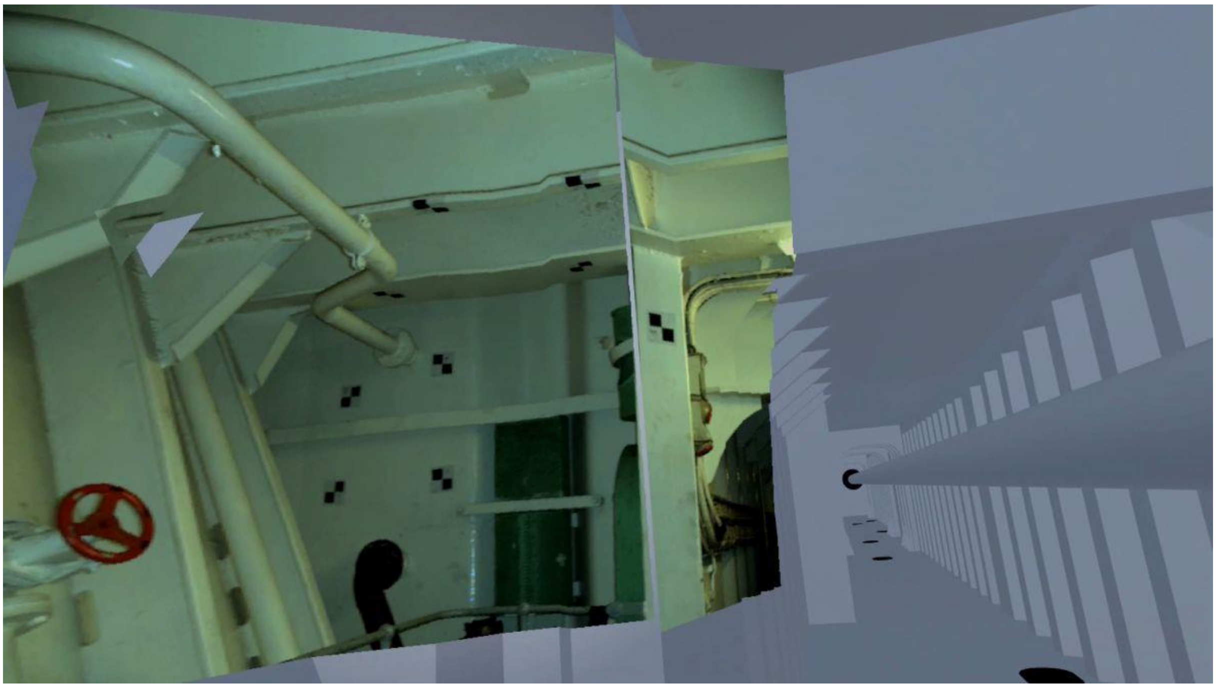

Fig.5: Inspection photo taken with IRIS inspection camera positioning the photo automatically. The photo is projected in VR onto the existing coarse 3D model.

As long as autonomous drone flight is not possible, pre-scanning can be performed through a remotely guided drone carrying the indoor positioning system. Here, human tank entry is still avoided, but the remote pilot can watch the drone's position in the virtual model. If the positioning system is still too heavy for carrying by the drone, pre-scan can be performed by a service technician carrying a camera system. Through equipping the carried camera system with indoor positioning technology, image capturing towards a 3D model still is very efficient.

Already today, drones far outperform humans when it comes to quickly accessing structures. For this reason, it becomes viable to scan a larger area of the tank surface at low cost. Depending on degree of automation, it could therefore become possible to reach 100% surface coverage from a distance, possibly even full close-up imagery.

3.3 Hull condition assessment and reporting

After the pre-scan, inspection data captured on board (overall and close-up footage and measurement readings) is spatially allocated to the ship's 3D model. In a more prospective view, a complete 3D scan of the tank may be generated during the tank inspection and, thus, remove the need for building a separate 3D model in advance.

The ship's 3D model – populated with the new inspection data (image footage and measurement results) – can be explored by the class surveyor in virtual space using the VR capabilities for navigating, orientating and interacting with data in the virtual tank as described in 3.1, Fig.6. That is, the surveyor can assess the actual hull condition based on an accurate virtual twin of the real ship reflecting the actual hull condition. Thus, the surveyor can attend the survey remotely from any office worldwide using VR. Consequently, remote hull survey techniques would reduce travel and would allow a higher degree of surveyors' specialisation – on specific ship types or even individual ship series.

Although a fully automatic pre-scan might become possible in the future we assume that in the medium-term scenario, a surveyor would still need the ability to interact with the drone in the tank. The reason is the need for additional close-up photos in case of uncertain assessment. In this scenario, suspect areas detected in VR in the pre-scan imagery is followed up through remotely advising the drone to re-visit specific locations and obtain more detailed imagery. See Fig.7 how this process can be visualized in VR.

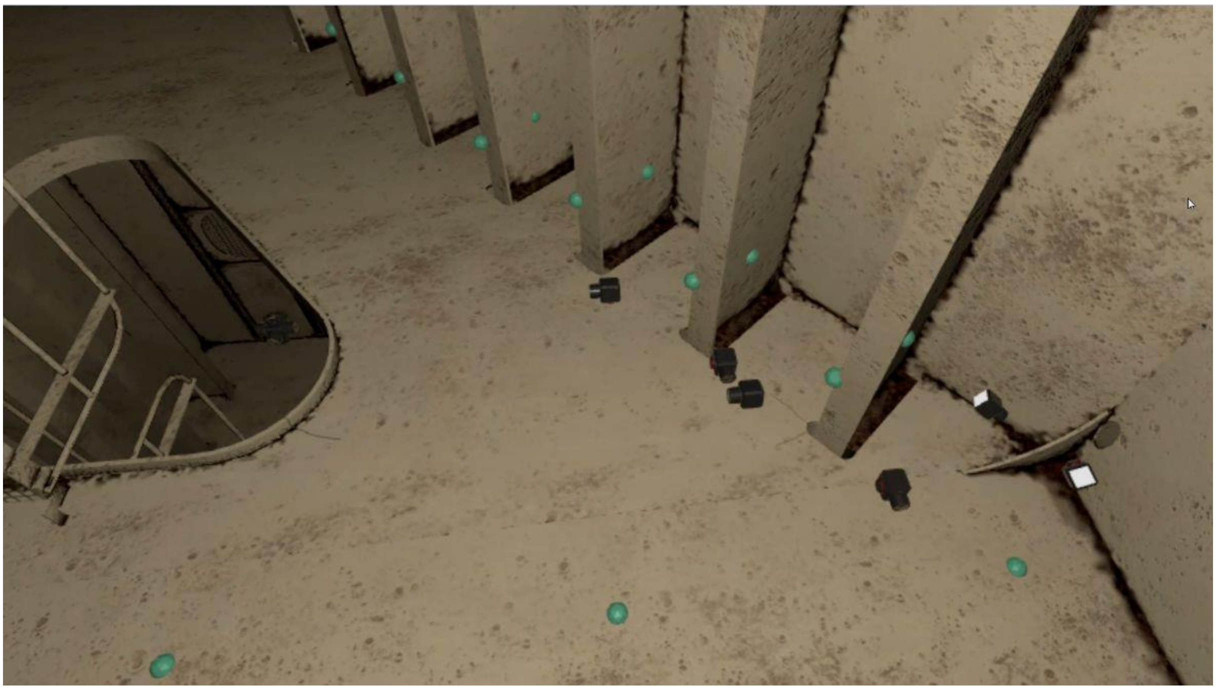

Fig.6: Indication of thickness measurement points and camera positions for close-up imagery viewed in VR

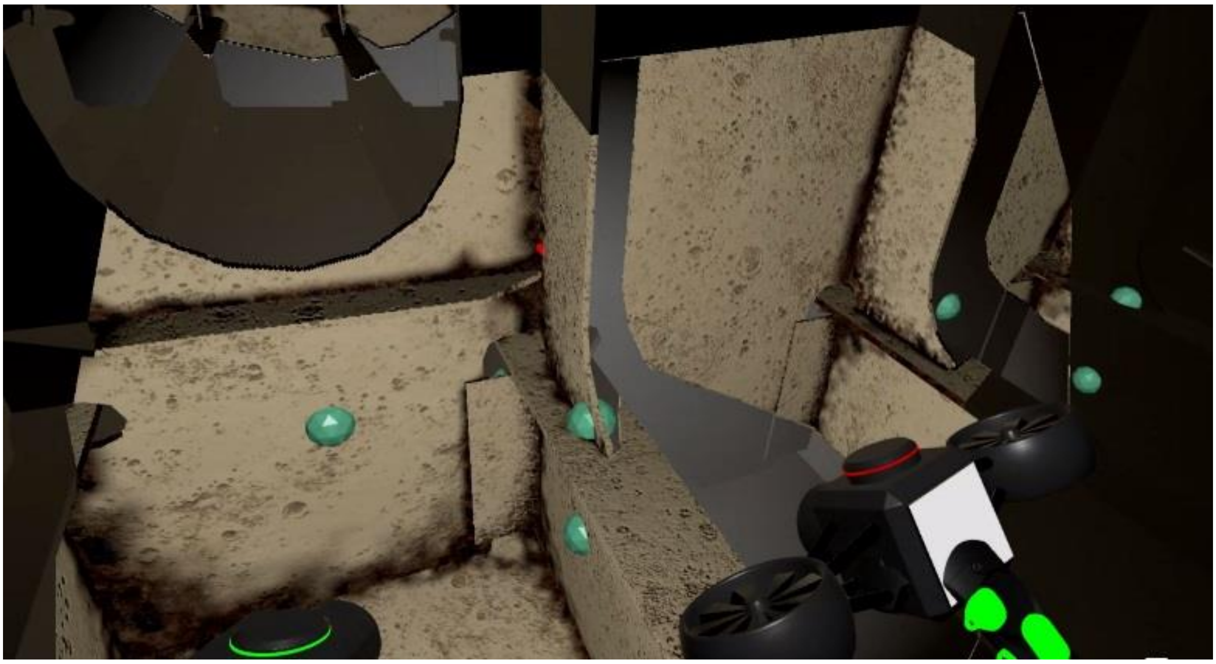

Fig.7: Scenario in VR showing real-time interaction with drone for additional close-up photo

In the virtual environment, on-board the virtual ship, hull condition can be assessed and documented very quickly. Moving around (e.g. examining bulkhead plates from both sides by simply walking through the virtual bulkhead and turning around), accessing thickness measurement results, comparing to previous records, etc. becomes fast and easy. Automated algorithms for image recognition can direct the surveyor to locations with suspected cracks, deformations, heavy corrosion wastage, coating break-down, etc. and would therefore accelerate the process of hull condition assessment.

Inside the virtual tank, the surveyor is efficiently guided in terms of all relevant data from vessel database like design analysis data, risk-critical areas, ship operation history (trading pattern, encountered wave climate, loading pattern), survey and inspection history (condition of hull at last survey), condition of sister ships, etc. In complicated cases, an expert from helpdesk can be brought into the same virtual space for decision support.

Findings, repair measures, memo to surveyor, etc. can directly be recorded on the structure and linked to the production system. Voice notes and text dictation further facilitate instant reporting. No additional work is necessary for the surveyor after leaving the virtual ship – documentation is done when survey is done.

Results can be presented and necessity of possible maintenance and repair measures can be explained to the superintendent/ship owner representative in a virtual meeting on-board the virtual ship in an efficient and most intuitive way.

4. Remote hull surveys – technological status

Today, hull inspection techniques using remote means like camera-equipped drones are starting to be accepted on a case-by-case basis. They might e.g. be used for the overall and close-up visual inspections of large hull compartments. Drone inspections currently require two persons to be present during the survey: the drone pilot with clear line of sight to the drone and the surveyor interpreting the screen image. The surveyor also needs the line of sight to the drone to understand its current position. Drone inspection techniques for narrow spaces – where no line of sight to the drone is possible – are a matter of research.

From the perspective of a class surveyor, thickness measurements in the context of class hull surveys are performed today de facto remotely as well: third party technicians carry out the thickness measurement at designated locations inside the hull compartments, while the class surveyor monitors the thickness measurement process and later evaluates the measurement results. Prospectively, remotely operated or even autonomously operating robots may play a key role for remote thickness measurement techniques and for avoiding human tank entry. Currently, crawling/rolling robots (using magnets), diving robots, and floating robots (internal examination through gradually filling tanks) are tested and partially used in the industry for thickness measurements. Thickness measurements via drones are in an early development stage.

While remote inspection devices like drones and robots equipped with cameras and sensors are fundamental prerequisites for remote hull inspections, the automated spatial allocation of imagery and measurement data captured e.g. inside a ballast tank is essential for efficient documentation and (visual) representation of the hull condition. Accordingly, several systems for automated indoor positioning of cameras and sensors are currently under development. For instance, the IRIS system enables photos captured in closed spaces to be properly associated to 3D models, *Wilken (2015)*. The same technique would allow the drone to orient itself in space. Further development of indoor positioning technologies for cameras and sensors (e.g. UTM sensors) is needed regarding their precision and portability by drones and robots. As an intermediate development step, IRIS or other existing systems can be used by inspectors/surveyors for capturing (visual) inspection data inside hull compartments.

Remote connectivity can further leverage performing remote hull surveys. As stated above, techniques for remote inspections of closed spaces available today and those under development are expected to reduce the need for physical tank entries by humans in the near future. The remote connectivity between back office and ship capable of two-way audio and video transmission would even enable the hull survey (as a follow-up to pre-scan) to be performed in real time remotely from the back office. Although technology for two-way communication between surveyor in the office and persons in closed spaces on board has already been tested, the capability of remote connectivity technology of data transfer at rates appropriate for large amount of inspection data is uncertain today. In particular, live connectivity to a ship on voyage would require further technological progress.

In the medium term, follow-up to hull pre-scan would be performed by the surveyor being on-board. Without the need to enter the tank, the on-board surveyor could connect to the drone flying in the tank and guide it to suspect areas for further close-up.

5. The role of VR

The technologies described above are in different development stages – between prototype and testing – their further development in the near future is expected. The detailed scenario how remote surveys could be realized will very much depend on actual availability and maturity of each technology over time. Eventually, remote hull condition assessment would be enabled based on visualisation of spatial inspection data, captured by (autonomous) drones and robots inside the hull compartments, by mapping them on a ship's 3D model. Thus, the need for physical tank entries and even for surveyor's presence on board would be avoided in many cases. This would not merely increase the time efficiency of hull surveys but also reduce the health risks surveyors and inspectors are facing today when working inside the tanks.

On the other hand, being outside the tank and, thus, being not able to use all human senses, see section 6, involves potential difficulties for the surveyors to comprehend the inspection data and draw insights regarding the actual hull condition. The unique capabilities of VR technology for visualisation and interaction with spatial data can be used to partially compensate for this deficiency.

The realistic immersive simulating of an interactive environment with VR enables an accurate replication of e.g. ballast and cargo tanks in a virtual space. It allows the surveyors to be immersed in a virtual tank populated by imagery and measurement data captured inside the real tank, and to explore it in the most natural and safe way. In other words, VR brings the remotely captured (spatial) inspection data closer again to surveyors' human senses. Moreover, VR combines the natural human perception with augmented spatial data sets and improves surveyors' ability to draw insights from multiple data sources. For instance, in VR, the current hull inspection data can be aggregated and compared e.g. with the data from previous inspections, including sister vessels, or with strength calculation data from the design phase.

The potential of VR technology is not limited to enhancing the remote hull condition assessment only. Benefit with respect to time efficiency and quality is also seen in the use of VR for survey planning enabling quick insights e.g. into required survey scope and critical locations inside the tanks under consideration. In addition, surveyors can be provided with all necessary (virtual) tools for instant, largely automated recording and reporting of findings during the hull condition assessment in the virtual tank. Thus, follow-up activities for survey documentation after the survey, which make up a significant portion the total survey process today, could be substantially reduced. Finally, VR offers new opportunities for collaborative working. Surveyors can invite other users like Helpdesk experts or ship owner representatives, who are physically somewhere else, into the same virtual space for e.g. decision support and sharing insights.

6. Can a drone replace physical tank entry?

A class surveyor, being physically present on board during survey, uses more than his/her visual sense:

- Touching/feeling objects and substances to examine their condition and nature (Is the surface smooth? Is it wet? Is this water or oil?)

- Use of hammer or other impacting force, e.g. to remove scaling or to test the mechanical and acoustical response of structure for indication of deficiencies
- Testing the smell, e.g. as indication of smoke or cargo vapours in a space, etc.

As autonomous vehicles today typically cannot perform these actions, we need to understand whether other capabilities could compensate this so that this lack of information from autonomous pre-scans does not lead to less safe structures. Today, the survey regime requires partial examination of tanks at given time intervals. E.g. after five years (first class renewal) selected transverse shell frames in one forward and one aft cargo hold of a general dry cargo hold must be examined through close-up visual inspection. This inspection scope increases with ship age. If – through automatic scanning – visual scan of the structure becomes easy, a more frequent and more extensive examination of the structure becomes feasible. More frequent and more extensive inspections will increase the structural safety of the hull. Therefore, infrequent partial check with all human senses would be replaced by frequent complete visual check with e.g. a drone – combined with image recognition techniques to increase probability of detection of structural deficiencies.

Another option is to fit additional imaging techniques on the drone such as hyperspectral imaging – being able to analyse the full spectrum of the light reflected by the structural surface. Thereby corrosion or coating breakdown could be detected with higher likelihood than with the naked eye.

7. From idea to prototype

DNV GL have developed a working prototype demonstrating how hull condition can be assessed and documented in a virtual space. The prototype allows VR users to experience a water ballast tank of a large crude oil tanker. They can enter the tank virtually and explore the structural arrangement in real scale. Navigation and orientating are supported by various navigation and visualisation modes like teleportation and transparent view. Users can spatially display and examine emulated thickness measurement data and drone footage (360° view, close-up photos and a complete 3D scan). They can search for locations with corrosion, cracks or buckling and document possible findings. Emulated data from previous inspections of the ship and her sisters can be displayed and compared with the actual tank condition. See Fig. 8 for visualization of the environment.

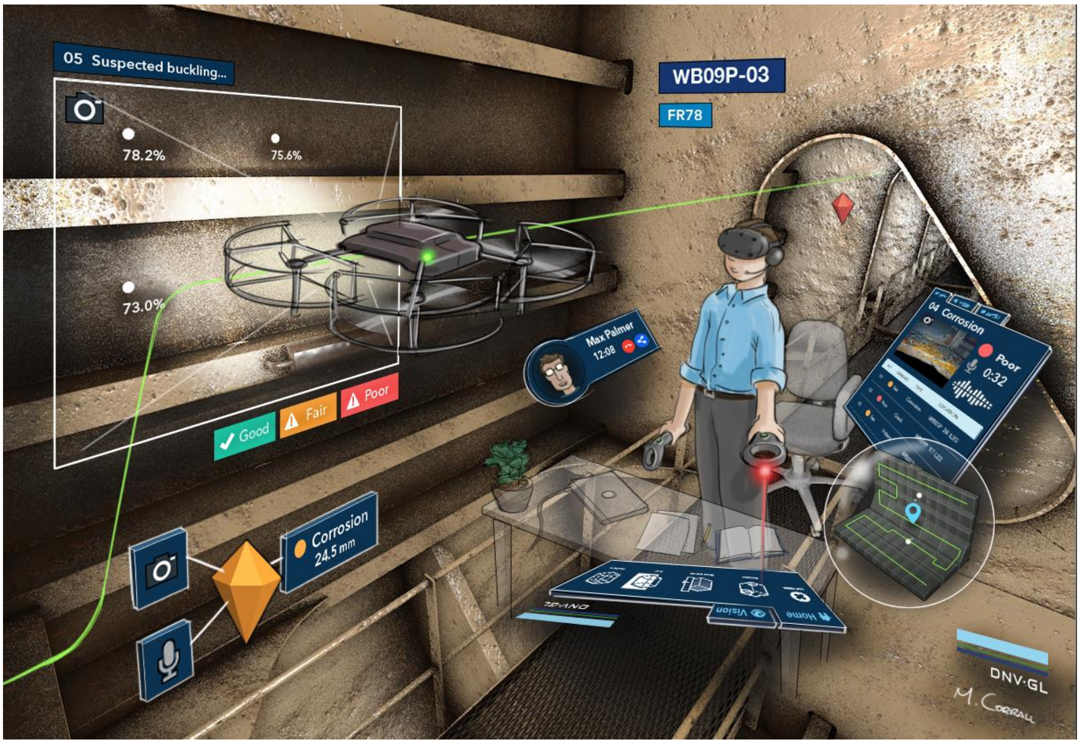

Fig. 8: Concept image of realized VR environment for remote hull surveys. (Image by Matt Corrall)

For actual inspections performed by a person using the IRIS self-localizing camera system, photos can be uploaded to the ShipManager Hull model of the vessel. The photo results can be examined in VR using the developed prototype. Therefore, without drones the system can be used in pilot studies on-board real ships.

8. Summary and conclusions

Avoiding human entry into enclosed spaces is a valuable ambition. Technological developments in many areas deliver the elements which will make this possible while at the same time reducing cost level and service interruptions of the ship. By automating hull pre-scans with the help of drones, the surface coverage and frequency of inspections could be increased. This, and the use of new imaging and image recognition technology then has the potential to compensate for the missing human perception of the tank environment. Thereby, the proposed procedure could result in the same or a higher safety level than reached today through assessing the less frequent inspections carried out by crew, superintendents, UTM operators and class surveyors.

It is not yet clear when a full autonomous scan of a ship compartment might become reality. But the maritime industry is clearly working towards this. Further conceptual work should be performed to investigate safety equivalence. VR will bring the captured images as close to physical presence as possible. Thereby, VR might turn out to be an important element in making remote hull surveys possible.

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MAXCMAS Project - Autonomous COLREGs Compliant Ship Navigation

Jesus Mediavilla Varas, Spyros Hirdaris, Renny Smith, Paolo Scialla, Walter Caharija,
Lloyd's Register, Southampton/UK, jesus.mediavillavaras@lr.org
Zakirul Bhuiyan, Terry Mills, Southampton Solent University's Warsash Maritime Academy, Warsash/UK, zakirul.bhuiyan@solent.ac.uk
Wasif Naeem, Liang Hu, Queen's University Belfast, Belfast/UK, w.naeem@qub.ac.uk
Ian Renton, David Motson, Atlas Elektronik UK, Winfrith Newburgh/UK, ian.renton@uk.atlas-elektronik.com
Eshan Rajabally, Rolls Royce, Derby/UK, eshan.rajabally@rolls-royce.com

Abstract

This paper discusses the concept and results of the MAXCMAS project, an approach to COLREGs compliance for autonomous ship navigation. In addition to desktop testing, the system is being implemented and tested thoroughly on networked bridge simulators as well as on an unmanned surface vessel. Both bridge simulation-based and desktop-based results exhibit suitable collision avoidance actions in a one-on-one and multivessel ship encounters respectively. The eventual aim of the project is to demonstrate an advanced autonomous ship navigation concept and bring it to a higher technology readiness level, closer to market.

1. Introduction

The MAXCMAS ("MAchine eXecutable Collision regulations for Marine Autonomous Systems") project aims at developing a COLREGs compliant path planner for autonomous vessel guidance and control. COLREGs are the "rules of the road" which were defined by the IMO (International Maritime Organization), to prevent collisions between two or more vessels. A significant challenge, which is tackled in the project, is to translate the COLREGs, which were written for human consumption, into state of the art collision avoidance algorithms. MAXCMAS is a £1.27 million collaborative research project, with funding from InnovateUK. The project brings together key expertise of industrial partners: Rolls Royce (RR) as lead, Atlas Elektronik UK (AEUK) and Lloyd's Register (LR); and academic partners: Queen's University Belfast (QUB) and Southampton Solent University's Warsash Maritime Academy (WMA).

This paper follows on from *Mediavilla et al. (2016)*, which described the approach and objectives of the MAXCMAS project. MAXCMAS started in mid-2015 and will be completed at the end of 2017. In the interim, much progress has been made, as summarized below, which is discussed in this paper.

- System requirements were derived earlier on to comply with COLREGs and good seamanship practices. Additional safety requirements were derived to mitigate possible hazards, such as sensor failure or malfunction.
- A system architecture was designed, Fig.1. The sensors information is fused, providing a world picture; the autonomy executive and collision avoidance algorithms generate navigation demands (heading, speed) to a controller interface. Those were then translated to control demands (throttle and rudder) for the autonomous vessel. For this project, experimental testing of the algorithms is carried out on two platforms: an autonomous bridge simulator and the ARCIMS unmanned surface vessel (USV) from AEUK. This platform is an in-service military autonomous system primarily used for mine countermeasures.
- Key COLREGs rules and seamanship behaviours have been formalised and implemented in the QUB's collision avoidance module (CAM) (Section 2).
- The system has been integrated and made operational in the WMA networked bridge simulator environment (Section 3). Validation is done by simulating multiple potential collision scenarios, to date: one-to-one and multi-vessel encounters, non-compliant behaviour of the target vessel and vessels with different degrees of manoeuvrability.

- Further demonstration and validation is being done via desktop simulations (Section 4): either Monte Carlo simulations, and by reproducing actual collisions incidents.
- System implementation and sea trials in the ARCIMS vessel is under way, with suitable sensors being identified and tested (Section 5).
- Assurance of the non-deterministic nature of the CAM is also discussed (Section 6).

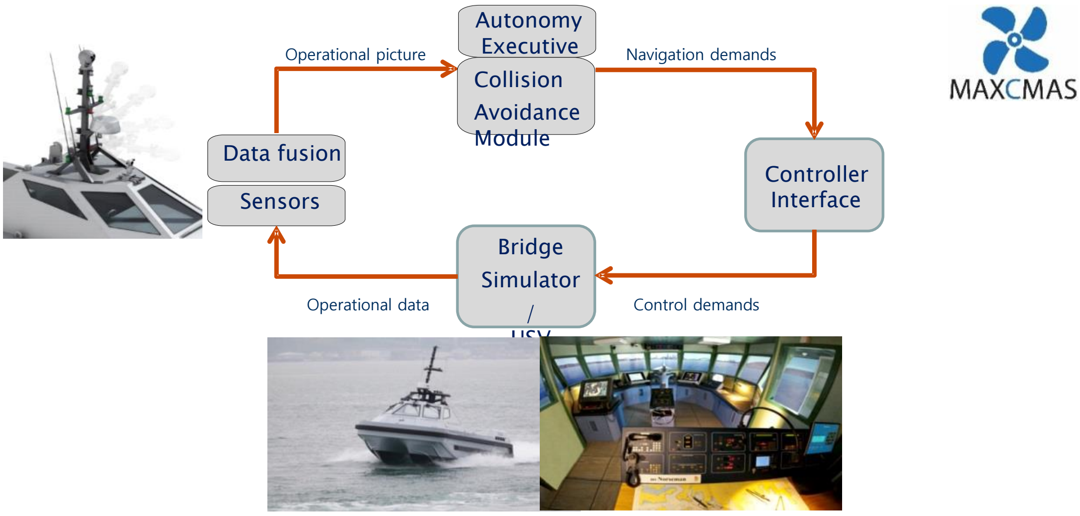

Fig.1: MAXCMAS system architecture

2. Path planning and collision avoidance

The collision avoidance module (CAM) software regularly evaluates collision risks with the surrounding ships and/or landmass and, if necessary, provides collision avoidance decisions and actions that can be executed by the autonomous vessel. In this paper, it is assumed that the USV equipped with CAM is the own ship (OS) whilst all other vessels around the OS are referred to as target ships (TGTs). As presented in Fig.2, the CAM consists of an interface and four sub-modules: risk assessment, situational assessment, decision making and path re-planning. The 'map information' input defines any prohibited areas (restricted water space) which is then taken into consideration by the collision avoidance algorithm so that no path could be generated in those waters. The interface links CAM with the Autonomy Engine which consists of a mission planner and a track pilot among other functions. The Autonomy Engine provides CAM with all necessary data such as OS's and TGTs' parameters, mission waypoints and environmental data.

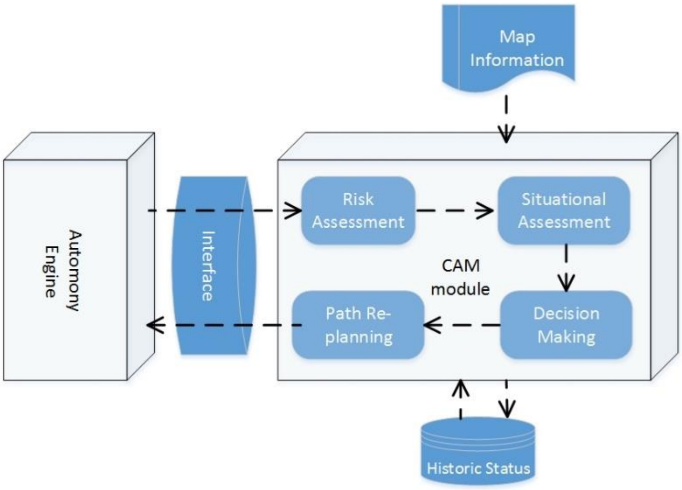

Fig.2: The system structure of the CAM

Based on data provided to the CAM by the Autonomy Engine, if a target ship is present, the risk assessment submodule is activated which determines if there is a risk of collision with the target. To assess a risk of collision, the widely-used closest point of approach (CPA) method has been adopted, *Campbell et al. (2014)*. However, the existing CPA method is not sufficient to determine whether a target vessel indeed complies with COLREGs or not. Indeed, without a proper assessment of the situation, the USV may continue to follow irrelevant COLREGs rules thus failing to make the required evasive manoeuvre in time. Hence, an extended risk assessment criterion has been developed to detect urgent risks of collisions caused by target vessels whose behaviours are not COLREGs-compliant.

The situational and risk assessments sub-modules work alongside each other to distinguish between COLREGs compliant and non-compliant targets. A criterion based on the historic status of a target ship is used. Once a collision risk is deemed to exist and the TGT is assessed as COLREGs-compliant, the next stage is to determine which COLREGs encounter, i.e., “head-on”, “crossing” or “overtaking”, should be applied. An alternate evasive path is then generated, if required. On the other hand, if a collision risk is caused by a non-compliant TGT, no specific encounter-related COLREG applies and the unbounded evasive behaviour of USV is directly activated. Note that *in extremis* caused by non-compliant behaviours of target vessels, the USV should avoid collision at all costs which may be required by the ordinary practice of seamanship, or by the special circumstances of the case admitted under COLREGs rule 2 on responsibility[1].

A variety of path planning techniques with consideration of COLREGs have been developed in recent years, such as artificial potential fields, *Naeem et al. (2016)*, velocity obstacle method, *Kuwata et al. (2014)*, evolutionary algorithms, *Smierzchalski and Michalewicz (2000)*, fuzzy logic, *Kao et al. (2007)*, and heuristic A* method, *Hu et al. (2017)*, to name a few. However, most, if not all, of the existing techniques do not scale well to multiple target ships and multiple COLREGs rules, and usually one objective is considered only when using these techniques. To fill such a gap, a multi-objective optimisation framework, based on particular swarm optimisation is developed for path re-planning, which is flexible and scalable to accommodate multiple target ships and objective functions, *Hu et al. (2017)*. Specifically, the risk of collision, smoothness and length of the path are considered as three typical objectives in this research. In addition, a novel and unified representation in the form of mathematical inequalities is proposed for COLREGs rules selection and other USV constraints, which is rather simple to incorporate in the multi-objective framework for path re-planning.

One of the simulation results of the collision avoidance system is presented in Fig.3. The scenario is depicted in Fig.3(left), where the OS encounters four TGTs in the surrounding. The imminent risk is due to TGT1 which is head-on to OS. However, any incorrect manoeuvre could potentially create another risk of collision with one of the other TGT vessels in the area. As depicted in the simulation result of Fig.3(right), having detected and confirmed a head-on collision risk with TGT1 (marked by red star), a manoeuver to starboard is planned in real time by the CAM. Since the CAM is designed to take multiple vessels into consideration when replanning a path, a desired CPA is maintained with all vessels in the vicinity. The overall path of the OS is thus collision free and in accordance with COLREGs.

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[1] COLREGs rule 2: Responsibility.
(a) Nothing in these Rules shall exonerate any vessel, or the owner, master or crew thereof, from the consequences of any neglect to comply with these Rules or of the neglect of any precaution which may be required by the ordinary practice of seamen, or by the special circumstances of the case.
(b) In construing and complying with these Rules due regard shall be had to all dangers of navigation and collision and to any special circumstances, including the limitations of the vessels involved, which may make a departure from these Rules necessary to avoid immediate danger.

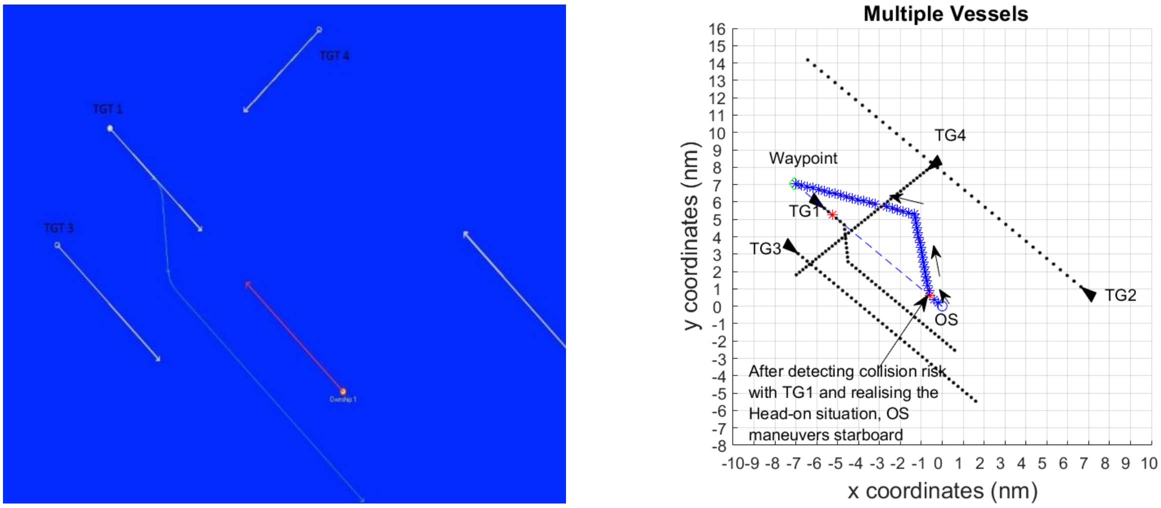


Fig.3: Four-vessel encounter scenario (left); overall path (right)

In summary, the proposed CAM is able to determine the type of encounter in addition to determining whether a target ship complies with the COLREGs. The effectiveness of the proposed algorithm has been validated extensively through desktop simulations as well as on bridge simulators showing a range of difficulties encountered at sea.

3. Bridge simulator trials

The prime objective of bridge trials is to validate and refine the robust machine executable algorithms for ship navigation in accordance with the collision regulations (COLREGs) at sea. WMA's networked bridge simulators have been considered as a safe and effective test environment for this purpose.

Since COLREGs were written for human consumption, their machine interpretation is non-trivial. Within the MAXCMAS project scope, more than 100 system requirements have been developed using an 'equivalence' approach (an "alternative approach" that delivers the objective of a prescribed rule or regulation) of existing COLREGs in view of the primary focus on the safety of navigation. A number of challenges were identified while carrying out the validation of these requirements and some of the examples include:

- A variety and subjectivity of collision regulations and their wide range of applications during the different collision avoidance scenarios.
- To consider the man-in the-loop while running the scenarios in the bridge simulators where the interaction between manned ships and autonomous ships are needed.
- The operational difficulties such as encountering multiple ships, sea state and environmental conditions, situation assessment with degraded sensors (e.g. intermittent and/or problems with sensor uncertainty).

To address the above challenges, a variety of simulator-based scenarios with mariners' expertise were designed ranging from basic level single vessel encounters to more complex level multi-ship situations. These scenarios have been categorized into 5 levels, which are basic, intermediate, advanced, good seamanship and breakdown with sensor degradation.

The MAXCMAS system has been installed in one of the six WMA's conventional bridges and it includes the AEUK's ARCIMS autonomy executive, the QUB's CA algorithms and a RR's interface. This autonomous vessel (bridge simulator) is able to interact with one or more manned bridge simulators and other simulated target ships following predefined routes. During the scenario trials, the autonomous vessel uses the common sensors (e.g. Gyro, AIS, and GPS) and these driving sensors have initially tested the algorithms using ground truth positional information and later with artificially degraded positional information.

Bridge simulation trials at WMA is currently ongoing, therefore the authors have only highlighted their experiences during the first set of trials, where the different scenarios were designed for encounters between own-ship (the autonomously guided vessel) and one target ship (instructor controlled from simulator control room). These were all basic scenarios encountering head-on, crossing and overtaking with different permutations (total 36 trials). Some of the examples of scenarios were:

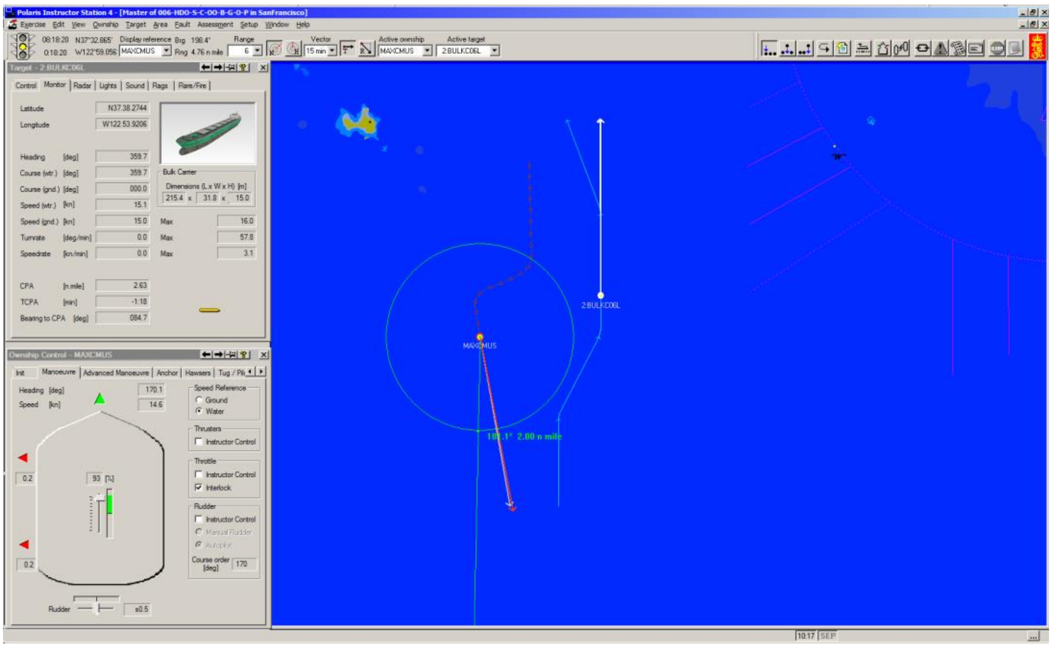
- Head on
- Crossing with own-ship stand-on
- Crossing with own-ship give-way
- Target overtaking own-ship
- Own-ship overtaking target
- Target ship diverts to starboard
- Target ship diverts to port
- Target ship maintains course
- Target vessel adopts non-compliant heading
- Target vessel adopts non-compliant speed
- Good sensor picture
- Poor sensor picture

Subjective and objective assessment criteria have been developed for each scenario. The subjective criteria are based on performance, while the objective criteria are based on weighted scoring of CPA/TCPA, variables and track parameters. The objective of such combined assessment methodology is to allow the structured evaluation of simulator recorded scenario performances against the benchmark criteria and scores. Examples of subjective assessment are given below:

- Acquire targets/objects within detectable range
- Ascertain risk of collision
- Select appropriate ‘Rules of the Road’
- Action to ‘comply with COLREGS’
- Substantial action (if in doubt the assessor will note the amount of alterations of course and/or speed)
- Early action (if in doubt the assessor will note the time)
- Does not result in close quarters with another vessel
- Maintain safe CPA/TCPA
- Return to planned track

Non-compliance with any one of the above assessment criteria does not indicate failure of the MAXCMAS ship autonomous system. However, failure to rectify any non-compliant grading on subsequent experiments is benchmarked as failure of the MAXCMAS system.

During the first trials, amendments and improvements were made to the CAM algorithms. It was clear that the CAM software responded correctly to standard situations where the target vessel stood on or gave way correctly. An example scenario is given in Fig.4, showing a ‘head-on’ situation to demonstrate safe navigation and collision avoidance maneuvering; where both target and own vessels are expected to deviate appropriately as the give way vessels and later the own-vessel will return to the planned track in an expeditious manner. In this particular scenario, the Closest Point of Approach (CPA) was set to 2 nautical miles and Time of Closest Point of Approach (TCPA) to 12 mins. It is shown that the MAXCMAS ship did correctly assess the ‘head-on’ situation with the target and generated a sub-waypoint to starboard.



08:18:20 N37°32.865' Display reference MAXCMUS Brg 198.4° Range 6 Vector 15 min Active ownship MAXCMUS Active target 2:BULKC06L
0:18:20 W122°59.056' Rng 4.76 n mile

Latitude N37.38.2744
Longitude W122.53.9206
Heading [deg] 359.7
Course (wtr.) [deg] 359.7
Course (gnd.) [deg] 000.0
Speed (wtr.) [kn] 15.1
Speed (gnd.) [kn] 15.0 Max 16.0
Turnrate [deg/min] 0.0 Max 57.8
Speedrate [kn/min] 0.0 Max 3.1
Dimensions (L x W x H) [m] 215.4 x 31.8 x 15.0
CPA [n.mile] 2.63
TCPA [min] -1:18
Bearing to CPA [deg] 084.7

Heading [deg] 170.1
Speed [kn] 14.6
0.2
93 [%]
0.2
Rudder s0.5
Speed Reference ○ Ground ● Water
Thrusters ☐ Instructor Control
Throttle ☐ Instructor Control ☑ Interlock
Rudder ☐ Instructor Control ○ Manual Rudder ● Autopilot
Course order [deg] 170

Fig.4: Example scenario showing ‘head-on’ situation of MAXCMAS autonomous vessel (OS) with a target vessel (TGT), with red and white arrows, respectively

After the first series of trials, further development took place in the CAM, such as distinguishing COLREG compliant and non-compliant targets and a subsequent mitigating alteration of course to counter such non-compliant targets. Once these changes were introduced, the own-ship has successfully met the assessment criteria when encountering non-compliant vessels in the one-on-one trials listed above.

Several scenarios were planned for bridge simulation such as handling COLREG conflicts in multi-vessel encounters, differing environmental conditions and congested waters including traffic separation schemes. Resource allowing, scenarios with interaction between manned and bridge simulators and MAXCMAS will also be investigated.

4. Desktop simulations: stress testing and historical cases

In addition to the desktop simulations performed in Section 2, aimed at developing and testing the CAM, additional desktop simulations are being conducted: i) Monte Carlo simulations are done to stress test the CAM, and hence detect any weaknesses; ii) simulations of historical collision incidents are done to demonstrate the performance of the CAM in more realistic scenarios and gain further confidence.

4.1. Monte Carlo simulations

The aim of ODIN[2] Monte Carlo simulation testing is to evaluate one-on-one encounters between a simulated USV, directed by the autonomy and Collision Avoidance Module (CAM), and a simulated target vessel that behaves as a manned vessel. Through variation of scenario parameters and target platform behaviour the testing will try and expose weaknesses that would otherwise be difficult to detect in real-time simulations. The Monte Carlo approach allows the testing of a large number of permutations of each scenario, potentially allowing it to find “edge cases” in the algorithm (cases where one or more parameters are at one of their limits, and the algorithm does not respond as expected) that would be missed during other testing.

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[2] ODIN is a complete underwater warfare software simulation tool, property of Atlas Elektronik UK. https://www.atlas-elektronik.com/what-we-do/submarine-systems/odin/

The six vignettes that are to be exercised in the sea trials (Section 5), i.e. passing a fixed object, overtaking a moving vessel, being overtaken by a moving vessel, vessel crossing from port, vessel crossing from starboard, vessel approaching head on; are modelled in the ODIN entity-based modelling tool. Two examples of the vignettes tested are shown in Fig.5. The simulations executed allow selected parameters to be varied to quantitatively evaluate the performance of the CAM. For each variation of a given vignette, one variable is changed at a time. The variables that are changed include detection range, speed of target vessel, angle of approach of target vessel, and target vessel behaviour. The target vessel behaviour can be changed to assess the outcome when it behaves in a manner compliant with COLREGs as well as when it acts in a non-compliant manner. Where weaknesses are identified changes to the CAM can be implemented.

An interface has been created that allows evaluation of autonomous behaviour and collision avoidance within the ODIN software, either as a real-time simulation or as a statistical model using the Monte Carlo method. More complex scenarios could be developed to increase the stress with which the autonomy behaviours are evaluated. Re-testing of unsuccessful scenarios may also be carried out to re-evaluate updates that have been implemented.

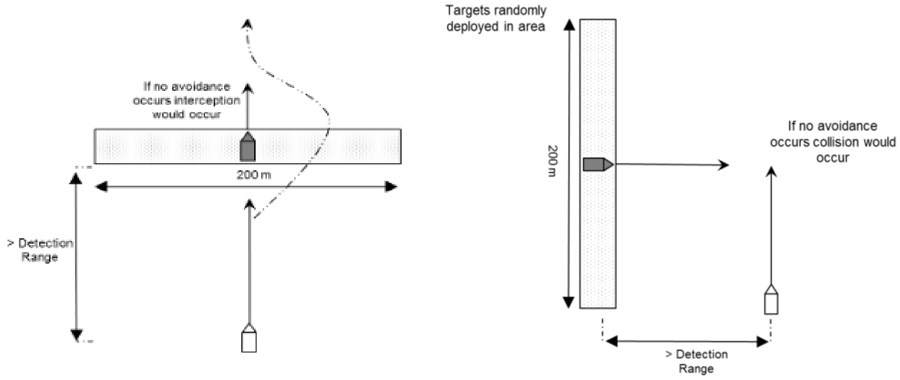

Fig.5: Vignettes illustrating an overtaking (left); crossing scenario (right)

4.2. Simulations of historical collision incidents

Historical multi-vessel collision accidents have been selected and are being simulated using the CAM software on a desktop environment. The simulations aim at illustrating how MAXCMAS enabled autonomous ships would behave in realistic situations, albeit with the limitations of a desktop. Hence environmental conditions, communications among vessels, and other real factors that played a role in the accident are omitted. For simplicity, it is assumed that all the vessels are autonomous, MAXCMAS enabled. This is a major simplification, which may never happen in the foreseeable future; it’s expected than autonomous and conventional ships will coexist. Interaction between manned and autonomous vessels is not possible and it’s also not the objective of these simulations, which will be tackled with the networked bridge simulations and the sea trials. Despite of these limitations, desktop simulations of historical cases add great value, complementing the other desktop and bridge simulations (Sections 2 and 3), and the sea-trials (Section 4); giving confidence of the validity of our approach to autonomous navigation.

The historical collision incidents that are being considered were caused by human error (like in most cases, *IMO (2004)*), namely lack of situational awareness and failure to comply with the COLREGs; often with dire consequences, in terms of loss of life, damage and/or environmental impact. In the simulations, vessel characteristics and initial conditions (position, speed, and bearing) are replicated from the actual encounters, to make them as realistic as possible. Fig.6 illustrates one of the collision scenarios considered, where two vessels A and B collided in a highly congested coastal area. At the time of the collision, Vessel B was run over by Vessel A, causing the hull of Vessel B to break and thereby sinking the vessel within a matter of minutes. All of the crew in Vessel B went missing, and there was a large oil spillage. Vessel A sustained damage in the bow section including ruptures leading to flooding, but no casualties to her crew. Visibility was good weather conditions were not an issue. Post-mortem analysis revealed that Vessel A did not keep proper lookout, infringing rule 5 [3], and neither of the two vessels significantly alteration course and or speed to avoid collision, infringing rule 8 [4].

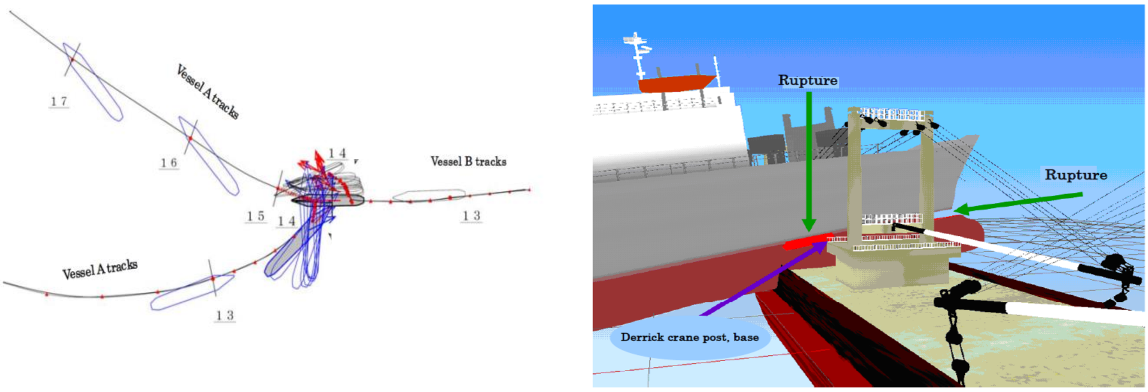

Fig.6: Trajectories of vessels A and B before and after collision (left); vessel A breaking the hull of vessel B (right).

At the moment of the writing, simulation work is underway which will illustrate how MAXCMAS autonomous vessels would have behave in nearly the same situation, demonstrating COLREGs compliance and seamanship, and thus avoiding collision, albeit with the simplifications earlier mentioned. The simulations adopt the same planned route and the same initial speed and bearing as in the actual collision, until a risk threshold is reached; at which point the CAM triggers a collision avoiding action, to finally returning to the original route.

5. USV sea trials

The aim of the sea trials is to exercise the Collision Avoidance Module (CAM) in a real environment under true platform motion, sensor performance and environmental conditions. One goal from this type of testing is to validate the results observed in simulated testing and gain an understanding of the differences between real and synthetic trials. A further goal is to assert the performance of the CAM or expose any additional weaknesses that have not been observed in other testing that will be fed in to algorithm refinement.

Since one of the primary goals of the sea trials is to validate testing already conducted in simulation, the test scenarios that will be exercised will replicate scenarios tested during the bridge simulation trials (Section 3) as well as the Monte Carlo stress testing (Section 4). This involves execution of six vignettes involving one-on-one encounters between the autonomous USV and a target vessel or obstacle. The six vignettes to be executed are as follows: passing a fixed object, overtaking a moving vessel, being overtaken by a moving vessel, vessel crossing from port, vessel crossing from starboard, vessel approaching head on.

Initially the target vessel will be virtual and is presented as having been detected with perfect sensor data. This approach allows the motion and manoeuvring of the USV to be the first factor to be considered when compared against entirely synthetics trials results. Following testing against a synthetic target a real target will be introduced. The real target will be a channel marker, for avoidance of a fixed obstacle, and then a RIB (rigid inflatable boat) fitted with a radar reflector for a moving target.

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[3] COLREGs rule 5: Lookout.
Every vessel shall at all times maintain a proper look-out by sight and hearing as well as by all available means appropriate in the prevailing circumstances and conditions so as to make a full appraisal of the situation and of the risk of collision.

[4] COLREGS rule 8: Action to avoid collision.

Preparatory work has been undertaken to evaluate a range of object detection sensors (radar, electro-optical camera, PTZ camera, AIS, etc.) system that will be fitted to the ARCIMS USV and used to provide target data to the CAM. The sea trials using the CAM will be conducted later in year. Fig.7 shows the ARCIMS vessel, the sea-trial controlled environment, and an example of one of the EO sensors that the vessels will be equipped with.

Fig.7: ARCIMS USV (top-left); sea-trial controlled environment (Bincleaves/UK) (top-right); Electro Optical camera (bottom-left); EO image (bottom-right).

6. Assurance and non-deterministic behaviour

A functional failure analysis (FFA) was carried out to identify possible hazards, risks and mitigations measures. Examples of hazards are: failure or malfunction (e.g. intermittence) of sensors, incorrect data fusion, communication problems between the CAM and the autonomy engine, high data latency, etc. Based on the outcome of the FFA, safety requirements were derived and imposed to the system. For example, the system shall provide notification of sensor failure, or hardware failure to a human operator. Suitable verification methods have been proposed, to demonstrate that safety requirements are met, either during simulations or the sea trials.

In addition to the safety requirements, another important aspect is the assurance of the CAM software. This is not straightforward, since the CAM, which is based on a swarm optimisation algorithm (Section 2), is non-deterministic. That means the solutions it generates (the subway points) are not the same, for a given input. It's worth noting that the assessment of risk, choice of COLREGs rule and down-selection of safe navigable space are all deterministic; although the specific path is not. Software assurance is traditionally done based on standards that have been developed for deterministic behaviour; and assurance of non-deterministic software (including machine learning) is a new area of research. As part of the MAXCMAS assurance work, the project is investigating the relevant standards across different industries (e.g. aviation, railway, etc.), as well the work being done in academia. Some standards that have been identified are: IEC 61508 "Functional safety of electrical/electronic/programmable electronic safety-related systems"; ISO 26262:2011 "Road vehicles - Functional safety"; RTCA DO-178C "Software Considerations in Airborne Systems and Equipment Certification", MIL-STD-882E "U.S. Department of Defence Standard Practice-System Safety". Regarding the state of the art, a promising novel method to assure non-deterministic software consists in creating a policing function, *Wilkinson et al. (2015)*, which sets the boundaries of operation of the non-deterministic behaviour. The advantage of such an approach is that the policing function can be assured using existing standards. Work is in progress, to identify the degree of non-deterministic behaviour of the CAM software, the applicability of these standards and the policing function, the knowledge gaps and what further work would be required.

7. Conclusions and future work

Since the last paper presented at COMPIT2016, much progress has been made in the MAXCMAS project. A considerable amount of effort has been dedicated to deriving appropriate functional and safety requirements to ensure COLREGs compliant behaviour, which has been implemented in the CAM. The system architecture, with the CAM, has been seamlessly integrated in a bridge simulator environment. The system is being thoroughly tested under a multitude of scenarios using desktop and bridge simulators, to demonstrate its robustness, and prove that the different requirements are met. The WMA bridge simulators have provided a unique platform to help develop and test the MAXCMAS autonomous vessel, in a near real environment, with one-to-one and multi-vessel encounters and different types of vessels. Desktop simulations have proven to be quite useful, to complement the bridge simulations in an inexpensive and fast manner.

Future work will deal with: conflicting rules, interaction of autonomous and manned vessels, poor or degraded sensor picture, manoeuvring in restricted waters. Preparations are underway to test the system at sea using the ARCIMS USV in a controlled environment, with virtual and real targets, using a range of advanced sensors. The MAXCMAS project is in fact bringing up an advanced autonomous ship navigation concept closer to commercialization.

Acknowledgments

We would like to thank all the MAXCMAS partners: Atlas Elektronik UK, Queen’s University Belfast, Rolls Royce, Southampton Solent University’s Warsash Maritime Academy and Lloyd’s Register, for their input, and great contributions to the project. This project would have not been possible without the support of InnovateUK, under grant number 50121-378137, which is greatly acknowledged.

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The Ungoverned Space of Marine Fire Safety

Carl S.P. Hunter, Coltraco Ultrasonics, London/UK, csphunter@coltraco.co.uk

Abstract

This paper explores the trending topic of harnessing data from improved and continuous monitoring on smart ships in order to, primarily, increase safety and secondly, to make economical savings, with regard to the "Ungoverned Space" of fire safety. Going above and beyond regulation compliance to secure additional benefits are vital to increasingly high value and safety critical vessels in terms of fire safety. The Shipping, Naval and Oil and Gas Industries among others, are all safety critical sectors which can have catastrophic and expensive results in the event of fire. The size of vessels and the on-board technology have been subject to a constant process of optimization. But safety measures, particularly with respect of fire protection, have been left lagging behind in the face of ever bigger, ever better ships.

1. Introduction

Over the last few decades cargo has generally been increasingly transported in containers rather than as open bulk cargo, thus mistakenly leading shipping companies to disregard the importance of fire protection systems, instead focusing on transporting greater quantities facilitated by the container system. However, this outlook is dangerous and misplaced. The risk of fire is significant with growing incidences of fire events exposed in the trade press, posing a risk both to expensive cargo and to human life on-board the ships. With a movement towards autonomous shipping systems and smart-ships, the importance of remotely monitored fire-fighting systems could grow exponentially, providing the opportunity to monitor vessels from an external location. Technological developments and companies such as Coltraco Ultrasonics, are working towards this end goal. The current on-board fire-fighting facilities remain inadequate in the face of the capacity of such large vessels. Fire therefore remains an ever-present risk on the high seas.

2. Economic risks

Traditionally, the maritime industry treats fire protection systems as a necessary expenditure, rather than a means to safeguard valuable crew and cargo and maintain business continuity of the vessel. Owners focus on systems delivered at the most competitive rates rather than seeing fire protection as an investment. The definition of a free market is an idealised form of a market economy in which buyers and sellers are allowed to transact freely based on a mutual agreement on price without state intervention in the form of taxes, subsidies or regulation. The competitiveness of the free market places great pressure on cost cutting: to deliver systems which often only minimally comply with regulations, and deliver asset protection at the most economical budget. With the value of assets, vessels and importance of business continuity growing, insurers are asked to underwrite almost incalculably high risk.

Unquestionably, the first priority of fire safety systems is to protect human life. Having said that, the economic benefits of a truly integrated, continuous, ultrasonic monitoring system in the future would be significant. Cargo damage remains an important negative result of on-ship fires, with 2 of the top 5 most expensive cargo claims on container ships in the last 10 years being fire-related according to www.swedishclub.com/media_upload/files/Publications/P%26I%20Claims%20Analysis%20web.pdf. Fire protection measures should hence be understood as a worthwhile business investment. Yet we accept minimally compliant fire systems. Given both the crew lives and cargo are at stake, it seems unfathomable that regulations do not mandate fire systems should be permanently monitored rather than certified typically just once a year, if that, particularly since it is a regulatory obligation and or recommendation to ensure that crew can check these themselves.

3. What is the “ungoverned space”?

Who would build a ship or offshore platform and install a power generating or auxiliary machinery without installing emergency power systems or monitoring their condition states? Who today would consider installing an alarm system without monitoring its overall status, not only its actuation, and integrating the whole system into the ship safety management system, with central monitoring being an essential part of it? These are basic engineering principles: building in redundancy and constantly monitoring critical systems.

Traditionally, the industry cares little about this ungoverned space, with too few qualified engineers considered subject matter experts. Yet when it comes to marine fire maintenance, never mind continuous monitoring, of gaseous fire extinguishing systems, there is a lack of knowledge amongst the -majority of the industry, regarding the potential risks. Awareness should exist about the huge expenses incurred by fire, both in terms of costs upfront from the damage and long-term due to reputation and unknown losses or damage to seafarers, vessel integrity, and cost of downtime and recovery. Above all is the risk to human life presented by fire. Poor maintenance of suppression systems risk accidental fatalities due to lack of training about the lethal properties of CO_2 (the predominant suppressant agent used on vessels, because it is the cheapest whilst being highly effective): when released it reduces oxygen levels to extinguish fire. Limited appreciation of the need for room integrity testing of protected spaces leads to minimal regulation compliance which could mean a failure of the fire system suppressing a fire because the room is unable to hold the discharged gas due to leaks of the space into which it actuates.

4. Fire Extinguishing Systems

Gaseous extinguishing/suppression systems are installed to protect against special hazards in critical infrastructure at sea. They deliver the infrastructure resilience our advanced maritime society requires. If the hazard is special and the vessel is critical, then this is the case for the constant monitoring of the fire systems that aim to deliver their protection. There is a lack of knowledge of the characteristics of the various extinguishants and the types of fire for which they are suitable. For too many years the industry has been left to too few brilliant experts to determine safe outcome.

Two broad categories of ship and offshore extinguishing systems exist: sprinkler systems and pressurised gaseous systems. While the former can suffer leakage, the latter can cause catastrophic effect due to their pressures. These large gas cylinders are pressurised liquefied gases or non-liquefied gases that are pressurised on actuation. CO_2 is permanently under 720 psi or 49 bar of pressure, i.e. nearly 50 times atmospheric pressure (by comparison a cup of water at sea level exists at 1 bar or 14.5 psi). Its’ state changes under increased temperatures to one that is neither a liquid nor a gas. Gases under pressure are often effectively considered by the industry as single and passive cylinder columns of solid material from the perspective of their monitoring following installation. Whereas being under pressure and constantly changing under temperature they should be considered as active and dynamic systems requiring constant monitoring. These are not passive systems therefore; they are dynamic ones, and all dynamic systems under pressure need constant monitoring to ensure their effectiveness and longevity. An engineered marine fire system typically lasts 20 years, longer than some vessels!

4.1. Traditional Cylinder Testing Methods

Typical methods for on-ship regular cylinder inspection primarily consists of trained professionals weighing the chosen cylinder, to assess if there has been weight loss due to gas leakage. However, although this method is widely used, it ultimately holds risk as an unsafe practice in reality, requiring constant handling of tanks in a delicate, high-pressure state. Whilst weighing is the most commonly cited method, it may be practical in the light of new and improved technology to add ultrasound as a recommended method.

4.1.1. Poor Maintenance Practice

Marine servicing companies bid to service a ships CO_2 system; this can comprise 200-600 x 45 kg CO_2 cylinders per ship. They can discharge accidentally. One of the highest probabilities of discharge occurs during their maintenance. Some service companies estimate that at one time 20% of a ships CO_2 cylinders have discharged or partially leaked their contents and there are over 55000 commercial vessels at sea at any time. On average, each cylinder will take 40 minutes to dismantle, weigh, record and re-install. Too many times therefore, even good servicing companies may not have the physical time to perform the inspection required, because the vessel may only provide them a few hours. But alongside them there are other companies who are said to randomly check some cylinders and then place "tested stickers" on the rest. Because the normal design concentration of CO_2 of 34-72 v/v % is above the nearly immediate acute lethality level an extremely narrow safety margin exists for these systems. Its mechanism of fire suppression is through oxygen dilution to 8-15%, rather than the chemical disruption of the catalytic combustion chain as with other clean agents.

4.1.2. Anecdotal experiences

- Safety pins being retained in position in the cylinder valves after installation.
- Marine CO_2 systems with 20% of the CO_2 cylinders installed on commercial shipping being empty or partially filled.
- Over-filled and under-filled cylinders.
- Pipework and cylinders freshly painted but with severe internal corrosion.
- Room integrity testing with questionable results and with the room integrity remaining un-monitored after testing.
- Liquefied extinguishants being confused by installers with Inert gas systems.
- There exists a lack of understanding of the organic compounds of some liquid extinguishants and their corrosive effect on the cylinder in the event of condensate ingress.
- Shipping companies not implementing the FSS code of the IMO SOLAS regulations.
- We have been regularly asked how to operate portable Portalevel™ liquid level indicators on dry powder extinguishers.
- WIKA Instrument discovered 25% of pressure gauges failed in an audit of 250 plants.

The problems cannot be denied. The International Maritime Risk Rating Agency (2016) has declared fire safety to be the most common deficiency on tankers in October 2016, with 126 incidents.

5. Regulations

5.1. Fire Extinguishing Systems

- International Maritime Organisation (IMO) Safety of Life at Sea (SOLAS) International Fire Safety Systems (FSS) Code Chapter 5, 2.1.1.3 specifies that "means shall be provided for the crew to safely check the quantity of the fire extinguishing medium in the containers."
- MSC.1-Circ.1432 REVISED GUIDELINES FOR THE MAINTENANCE AND INSPECTION OF FIRE PROTECTION SYSTEMS AND APPLIANCES, also discusses the need to inspect the contents of fire-protection systems' cylinders.
- CO_2 UK Marine Equipment Directive (MED) UK/EU legislation with US Coast Guard Mutual Recognition 7.3.2.6: "Means should be provided to verify the liquid level in all the cylinders, either by weighing the cylinders or by using a suitable liquid level detector."
- United States Coast Guard Marine Safety Alert – May 27, 2015 "Receive adequate training to perform routine inspections of their vessel's fixed CO_2 systems and fully understand their operation, particularly those protecting large spaces or multiple areas."
- NFPA 12 code 4.8.3.4.2 specifies that if, at any time, a container shows a loss in net content of more than 10 percent, it shall be refilled or replaced.

It can be argued that the existence of regulation (including but not limited to the examples above) guides – and occasionally curbs – the direction taken by the free market. This then means that the current state of the market, where 'price is king' is either due to unwillingness on the part of the regulators to create an environment where safe engineering is rewarded or because the industry itself is unaware of new technology that will help them meet both the spirit and letter of the regulation.

5.2 Protected Space Integrity

Compartment room integrity testing is essential under ISO 14520 where gaseous extinguishing systems have to be designed in relation to the discharging agent hold-time (if the room cannot hold the agent because of leaks the agent will disperse and not extinguish the fire) and discharging agent peak pressure (if the pressure is too high for partition walls or suspended ceilings they will be blown apart or damaged and possibly destroying the room integrity). If the room contains leakages, slowing down the process to achieve the required flooding concentration, the CO_2 extinguishing system would be unable to achieve the desired concentration in the time limit proposed. IMO SOLAS Chapter II-2 Regulation 10, G23.3 states, "The Regulations require that 85% of the required concentrations for machinery spaces and cargo pump rooms is achieved in such spaces within two minutes." ISO 1452 requires testing of a compartments integrity every 12 months to ensure the fire extinguishing system will still be effective, however in reality checks are necessary far more regularly.

6. Safeship® Technology

In shipping, unless a fatality occurs, it is left un-reported. This does not seem accurate or correct considering the aforementioned assumption that systems leak and protected space integrity changes. New smart ship technology counters the environment in which a "safety first" culture remains un-pursued and unrewarded. With multiple ships sailing with partially-filled, over-filled or empty cylinders, and unpublished instances of accidental discharges or slow seepages, there is a real cause for concern – now there is an impetus to change.

6.1. Case Study 1

On 07 September 2015, a fire was detected inside one of the cargo holds of Barzan, a Maltese registered container ship. At the time, the vessel was about 60 nm off Cabo Finisterre. The crew responded and commenced fire-fighting with boundary cooling and the use of the water drenching system on board. Subsequently, the fixed CO_2 system was used but due to several leaks in the CO_2 line, the required amount of gas did not reach the cargo hold to be effective to smother the fire. The starboard fire main line then developed a large leak at a joint in the under deck passage way and had to be isolated. This restricted the fire-fighting efforts to only the port side, and rendered the starboard side water drenching system unusable. What if more care and attention had been placed on the CO_2 fire-fighting system?

6.2. Case Study 2

With delicate electrical systems, semi-open decks that may restrict fire suppression effectiveness and a culture of undeclared cargo, Ro-Ro vessels have been identified as one of the highest fire risk marine vessels. On 28 April 2015, Sorrento caught fire whilst on a voyage from Palma de Mallorca to Valencia. The ship was 15 nm off Mallorca when a fire was discovered on one of the car decks. An emergency was declared and several vessels went to the assistance of Sorrento, including the ferries Publia and Visemar One. Publia rescued most of the 156 passengers and crew, who had left the ship by lifeboat. Four crew were injured, and there was a fear that the entire ship would sink. According to lawyers in Greece and Italy the fire was caused by a number of 'oversights and mistakes' on the part of crew. Once the fire had broken out, it has been said that poor training and a lack of understanding of the fire extinguishing systems by the crew members restricted their ability to adequately extinguish the fire. There were also 'violations of protocol' when it came to managing the fire extinguishing systems, managing the incident itself and evacuating the ship. Raising awareness, education and training are key, hence the development of easy to use, advanced technology like Portalevel®.

7. Innovative Measuring Solutions

However, with the impact of fire being more widely recognised, new research and development explores ultrasonic technology to monitor the extinguishing systems through inspection and integrated, continuous monitoring with alarm relay and remote diagnostics. The latter gives eyes to shore-based operators at a time of fewer, poorly trained crew and a trend towards autonomous shipping.

One of the key advantages of ultrasonic measuring solutions is they allow a comprehensive maintenance program to be implemented as part of a strategic approach to business continuity and reducing the risk of accidental discharges and leaks not being picked up. Further reducing areas of ungoverned or regulated space within the industry, ensuring a safer working environment for all.

7.1 Constant monitoring of fire extinguishing systems

Permalevel® Multiplex is the first system worldwide that is capable of monitoring the liquid level of critical fire suppression cylinder systems on a constant basis. It gives a vessel total visibility on the real-time status of all their critical fire systems. The Permalevel® Multiplex is designed to ensure that fire suppression systems are always fully operational and that no accidental discharge has occurred, which could affect the effectiveness of the overall fire protection system in the event that it is required for use.

The most critical point of a pressurised cylinder is the meeting of the cylinder neck with its valve. For over 100 years the industry has monitored and permanently weighs (even suspends) cylinder pressure and weight of contents at that critical point. The assumption is that the cylinder pressure gauge is of high, almost MIL-SPEC quality, but they are often not and commercial pressures under a bidding process can incline some to select low-end budget, minimally compliant gauge mechanisms. Technologies will soon exist to monitor both liquefied gaseous content and non-liquefied gaseous pressure safely - from the external sides of the cylinder rather than within it – in both fixed and portable forms.

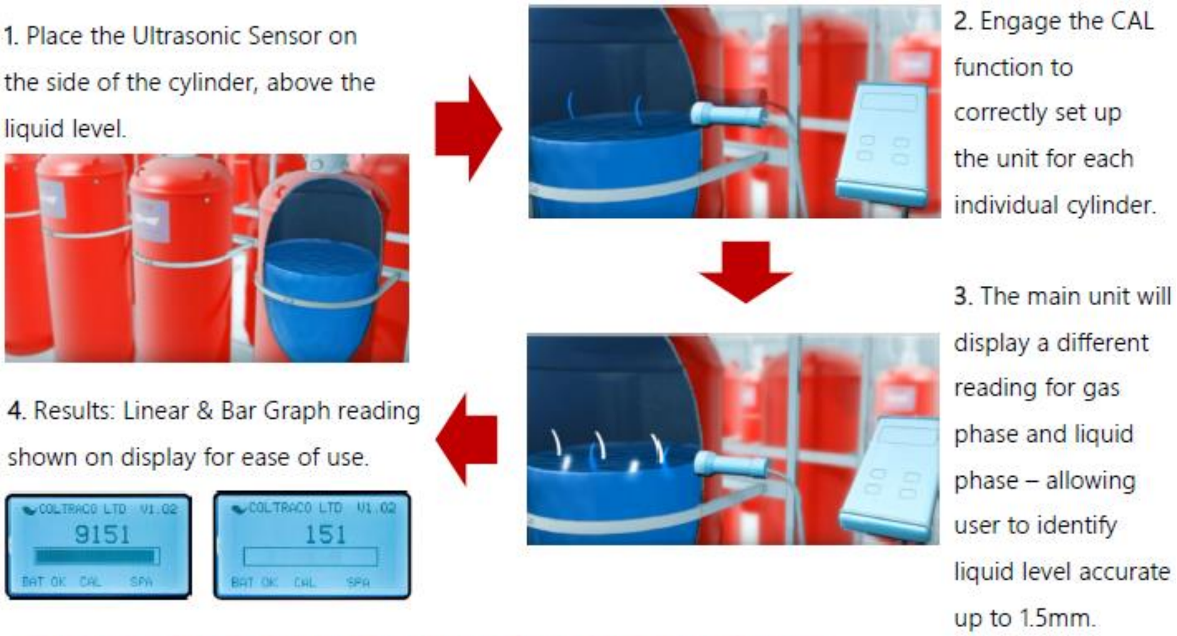
7.2 Ultrasound: An Under-Appreciated Technology

One of the sciences being harnessed by innovators in the fire safety sector is that of ultrasound: i.e. acoustic (sound) energy in the form of waves of high frequency that are above the human audible range. Although the shipping world largely sees it as a tool to gauge thickness, it has seen far more varied use across military, medical and industrial fields and is now being put to more advanced, innovative uses in shipping for fire safety solutions too.

Many will know this as SONAR in the UK from the military where it was first developed by the British by ASDIC in WWI. Ultrasound is sound beyond our audible range. Sound is, in itself, vibrations that propagate as a mechanical wave or pressure and transmit through solid, liquid or gaseous mediums. We are familiar with it through our hospitals during pregnancy scanning or the BBC when we "hear" dolphins and bats using it to communicate and navigate on wildlife programmes. We only hear that on our televisions as the ultrasound is hetrodyned to convert the ultrasound into something we can hear. But just as sound travels more quickly through water than air we understand how it travels through both. And its speed of travel can be measured. And because a gaseous system contains liquid or gas and it discharges into a protected space, so too can ultrasound be used to monitor all 3 of these. Coltraco is one of a number of companies using these fundamental physical principles to design and manufacture products and systems that can be used by fire engineers and their customer installations.

7.3 How Ultrasonic Technology works

This technology uses the attenuation of the ultrasound as it travels through different materials. It is the extent of this attenuation and its energy dissipation that differentiates between different materials. Instrumentation such as Coltraco Ultrasound's Portalevel® MAX handheld liquid level indicator and its Permalevel® Multiplex constant monitoring system convert electrical energy into ultrasonic waves through the reverse piezoelectric effect. The liquid level of a cylinder can be found because the ultrasonic signal received from the vapour section of the cylinder is different to the liquid section. The large difference in density suggests that the liquid and gas sections disperse ultrasound very differently. The ultrasound generator emits a modulated signal of a specific frequency of ultrasound. By using a lower frequency of ultrasound, attenuation in air is reduced to allow effective wave propagation through any leaks in seals. The receiver then picks up the signal leaking through the seal and converts it into a result indicating room integrity.



Images describing the Portalevel® model manufactured by Coltraco Ultrasonics

Fig.1: A description of Portalevel® handheld ultrasonic liquid level indicator identifying the difference between gas and liquid phase in a typical fire extinguishing system cylinder. (Coltraco Ultrasonics)

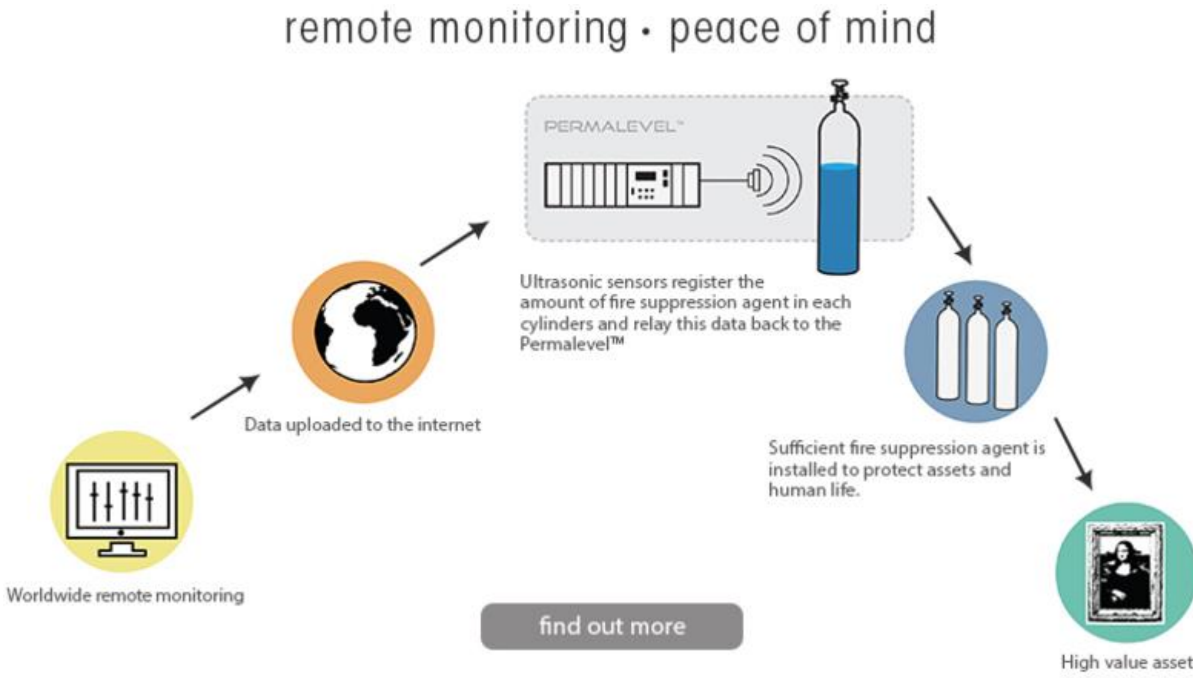


Fig 2: Infographic outlining how the Permalevel® Multiplex network links together (Coltraco Ultrasonics)

8. Compartment Room Integrity Testing

Moreover, as discussed above, marine gaseous fire systems deliver the self-contained resilience a ship needs at sea and resilience means the permanence of capability and functionality that can only be delivered by constantly monitoring the systems which enable it. If this is neglected, it is at the peril of lives and financial risk to the vessel or offshore platform. Within the ungoverned space of fire-fighting, just as importantly as checking the agent in cylinders has not leaked is the need to check the "protected space" into which the agent will discharge on actuation. If that space cannot hold the agent on discharge or sustain the pressures of the gaseous agent on discharge, the agent will disperse and the fire will grow unimpeded.

8.1 Ships are not monolithic structures, but bend and turn

As aforementioned, clean agents are designed to operate in limited spaces where there is a need for speed of suppression given the asset risk and where the space is occupied by people. They must extinguish a fire without damaging the asset they protect and enable operational continuity of the vessel whilst power is maintained. They must be easily maintained in-situ by qualified teams. They must comply with NFPA 2001 standards demanding fast discharge in 10 s and fire extinguishing within 30 s. In order to achieve this speed of extinguishing the protected space must also be inspected because the space will change: along its voyage a ship "turns and bends" as it travels through the sea, and the extent of that is determined by its load-state, sea state and wind state. It ages and as its structure changes leak sites develop. The dynamic movement of a vessel is illustrated through analysis of stills from a video in 2016 showing the stress and effect on a vessel during passage from Suez Canal to Singapore in severe weather conditions) as shown by the analysis in the inset figure below taken from a Coltraco Ultrasonics report, hence the alternate numbering.

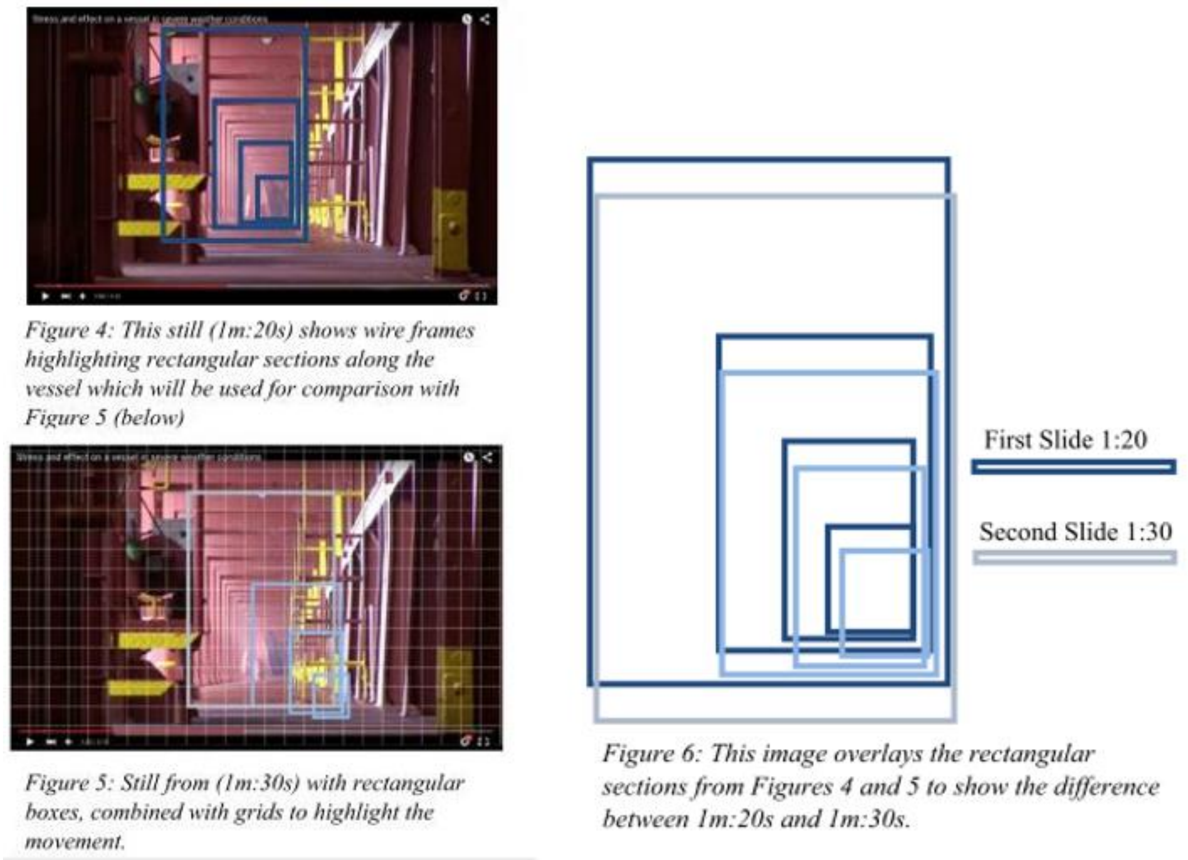


Figure 4: This still (1m:20s) shows wire frames highlighting rectangular sections along the vessel which will be used for comparison with Figure 5 (below)

Figure 5: Still from (1m:30s) with rectangular boxes, combined with grids to highlight the movement.

Figure 6: This image overlays the rectangular sections from Figures 4 and 5 to show the difference between 1m:20s and 1m:30s.

Fig.3: Images demonstrating the extent that a ship bends and turns at sea (Coltraco Ultrasonics)

8.2 Maintenance & Testing

Testing is essential under ISO 14520 where gaseous extinguishing systems have to be designed in relation to -the discharging agent hold-time (if the room cannot hold the agent because of leaks the agent will disperse and not extinguish the fire) and discharging agent peak pressure (if the pressure is too high for partition walls or suspended ceilings they will be blown apart or damaged and possibly destroying the room integrity). At the design stage of a fire extinguishing system protected spaces are tested for room integrity by positively pressurising a room and detecting escaping pressure, to verify that the room itself into which the gaseous extinguishant discharges on actuation, can both hold the agent after its discharge and hold its pressure on actuation. The fire system is then installed and commissioned.

Regulations may require the protected space to be tested every year, and it should be tested after every major change to the room. Any changes to the compartments state could result in leak sites developing which would stop the effectiveness of clean agent fire suppression systems should a fire occur. In order to ensure these fire extinguishing systems maintain their effectiveness over long periods of time, regular inspection is required. Inspection and constant monitoring of the compartment room integrity is now possible with products such as Coltraco Ultrasonics' Portascanner® 520.

As part of the testing procedure and to ensure unknown leak-sites do not develop, ultrasonic technology can help assess the relevant compartment and detect and precisely locate any leak sites. Products such as the Portascanner™ WATERTIGHT integrity test indicator is able not only to pinpoint precise leak locations, but to determine their leak apertures as small as 0.06 mm with a tolerance of ±0.02 mm, making it the most accurate device for this function. The Portascanner™ also provides an interpretation of the seal for desired locations, the results signifying them either watertight, weather tight or full leak site as appropriate. The advantages of being able to accurately detect the exact leak locations and size are self-evident when considered alongside the importance of reaching Peak Pressure for clean agent fire suppression to be effective.

9. Conclusion

The science of a marine gaseous extinguishing system is a complex one. The mathematics that underpin its science are demanding ones. But in simple terms gaseous systems are pressurised and in that they are dynamic not passive ones. They are there to protect critical marine structures in a safe and expeditious manner in the only way that a gaseous system can, complemented by the integrity of the protected space.

Ultrasonic Technology provides an opportunity to use technological advances to monitor these gaseous fire extinguishing systems and ensure the safety of crew and vessel, in both onshore and offshore situations. To leave a gaseous cylinder unchecked creates enormous risk which is easily preventable using ultrasonic technology. Ultrasonic liquid level indicators are portable, require little training and provide accurate results. Partnering with other readily available products provides recordable data, providing quantifiable measurements which can be used to accurately assess the quality of fire systems and its relevant protected spaces to ensure they will be effective. Through inspection and integrated, continuous monitoring with alarm relay and remote diagnostics facilitated by ultrasonic technology, smart ships can have an efficient and safe fire extinguishing system with longevity. The use of remote diagnostics in particular gives eyes to shore-based operators at a time of fewer crew and hopes for autonomous shipping.

As the world changes, so must our industry integrate technological solutions to provide a bulwark against wider industry misinterpretation and minimal, even occasional and flagrant, disregard in the application of standards and good global engineering practice, creating standards which all can understand and apply. This "Ungoverned Space of Marine Fire Engineering" can be addressed today, with minimal education and cost, to create a "safety first" culture where owners and operates are rewarded for pursuing above and beyond regulation compliance.

Acknowledgements

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Elucidating Families of Ship Designs using Clustering Algorithms

Ted Jaspers, TU Delft, Delft/Netherlands, T.J.M.Jaspers@student.tudelft.nl
Austin A. Kana, TU Delft, Delft/Netherlands, A.A.Kana@tudelft.nl

Abstract

This paper proposes a method to elucidate families of ship designs generated by the TU Delft packing approach using data clustering algorithms. The authors explore whether commonly used data science techniques can extract new information from the existing data. To test this hypothesis this paper applies data clustering algorithms to a test case of layouts of a Mine Counter Measures Vessel (MCMV) generated by the packing approach. Results look to improve the understanding of the multidimensional structure of the data, as well as to improve the comprehension and visualization of the complex interactions between the design and performance space.

1. Background

Early stage design is the initial phase in ship design where the balance between the different desired performances of the ship is explored. In ship design this process is often initiated by performing concept exploration, where various design solutions are explored in order to acquire knowledge about the interactions between design and performance space. Especially during concept exploration of complex ships, new requirements and/or new relationships between requirements can be elucidated. This results in an iterative process called requirement elucidation *Andrews (2013)*. On top of that, the traditional method of manually iterating through the design spiral is very time consuming. These aspects cause that in general only a small part of the design space is explored, which leads to an increased probability of converging to a suboptimal design, *Vasudevan (2008), Duchateau (2016)*. In order to explore the design space more extensively, the ‘packing approach’ was developed at the Delft University of Technology, which automatically generates tens of thousands of coarse feasible ship designs. By dividing this design space into ship design families, which share common design features and performance characteristics, the designer may then be able to better understand interactions between design and performance space. Think for instance of a ship where you can choose for either a long and narrow design corresponding to low resistance and low initial stability or short and beamy corresponding to high resistance and high initial stability. This paper explores the use of clustering algorithms to study the presence of ship design families stemming from the packing approach.

1.1 The packing approach

The packing approach is a tool that assists in enhancing the concept exploration process. The idea is to automatically generate a vast number of low level of detail feasible ship designs that cover a significant part of the design space. This is obtained by using a genetic algorithm on a parametric model of the desired ship, where all compartments in the ship are represented by building blocks. The designs are thus coarse, but detailed enough to calculate some performance measures (such as cost, speed, displacement, etc). Details on this approach can be found in *van Oers (2011), van Oers (2012)*. The resulting data set may consist of tens of thousands of designs, where each design has hundreds of design and performance attributes. This data is then structured and visualized so that information about the relation between design and performance space can be extracted *Rowley (2007)*. One visualization method applied to the packing approach is described in *Duchateau (2016)*. He proposed a method of displaying the data in matrix scatter plots, where numerical and architectural constraints could interactively be added. In Fig.1, L, B, GM and packing density are plotted, and the constraint added is that designs have deck 4 as damage control deck (dcd) instead of deck 5. Several results can be deducted from this figure. It shows for instance that the length and packing density are negatively correlated. The reason is that since a longer design has more space available, it has therefore more empty space to fit the same number of objects. Furthermore a higher dcd results in a lower GM, since objects (such as the main gun) should be above dcd, which raises the center of gravity.

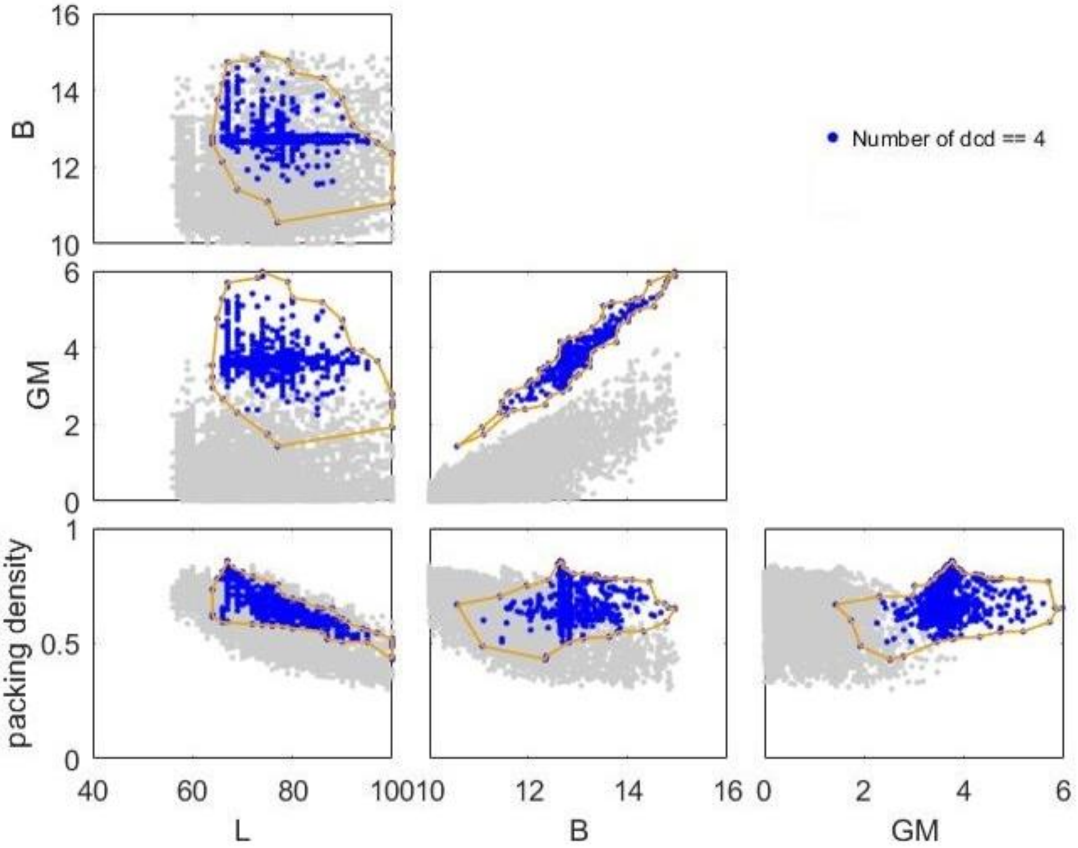

Fig.1: Visualization method of packing data as described by *Duchateau (2016)*. Various features are selected for plotting in matrix plots and constraints can interactively be applied.

Although the plots in Fig.1 contain a lot of information, they also raise new questions. Looking for instance at the clusters present in the middle plot, they are not separated in the plot in the lower left corner. So looking at the data from different directions determines whether the clusters are visible. It is therefore questioned whether there are other ways of looking at the data that reveal more structure.

1.2 Families of ship designs

In this paper families of ship designs are defined as being subsets of designs that share a clear similarity within design and performance attributes. These families should be clearly different when comparing designs between different subsets. An example is the middle plot in Fig.1, where two families are present. Another example is in *Droste (2016)*, where he defined different luxury levels for a cruise ship design. Examining the impact of these families in a performance space is shown in Fig.2. High luxury level causes a jump in both building costs and earning potential, creating two distinct families, clearly showing a tradeoff to be made. Identifying families of ship designs is thus very useful, especially when they correspond to certain regions of the performance space.

In contrast to these obvious families, which are defined by single discrete variables, families can be more complex. These complex families account for the inherent interaction between multiple design and performance features. These multi-dimensional families may be hard to identify and study using 2D plots. Looking for instance at the layout of a naval ship, there are numerous interactions between the compartments. Examples are: no machinery near accommodation due to noise and no accommodation near the bow due to seasickness. Thus, although the positions of objects are continuous variables, there might be discrete valid combinations of these variables, which results in clusters. A certain cluster might then for instance require a larger beam, corresponding to the part of the performance space with high resistance and high stability. But since the layout is depending on many features (such as x, y and z position of all compartments) these families are only detectable using the combination of the features.

An example of how this would look like from a data point of view is illustrated by the artificial dataset displayed in Fig.3. If we look at the data from the 2D plots (3a-c), there is no special structure present. But if we look at it in 3D space (3d), the data actually consists of two distinct families. These are exactly the type of structures that are sought in this paper, where it is hypothesized that they exist in higher than three dimensions.

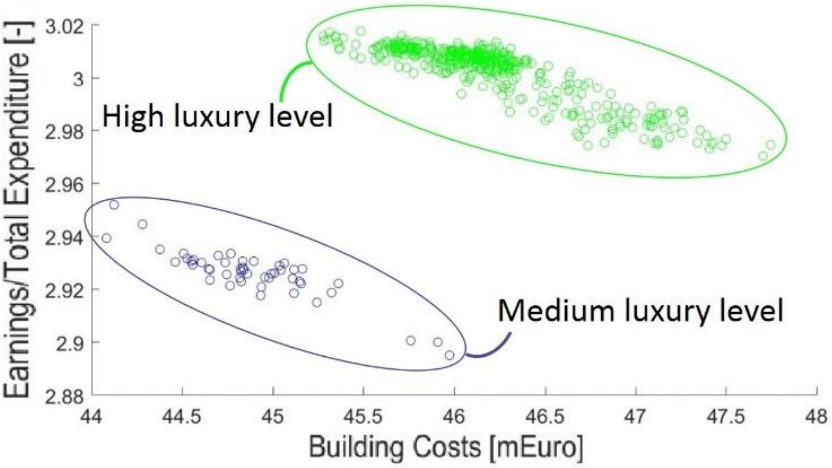

Fig.2: Various designs plotted in performance space, divided into families based on luxury level, *Droste (2016)*

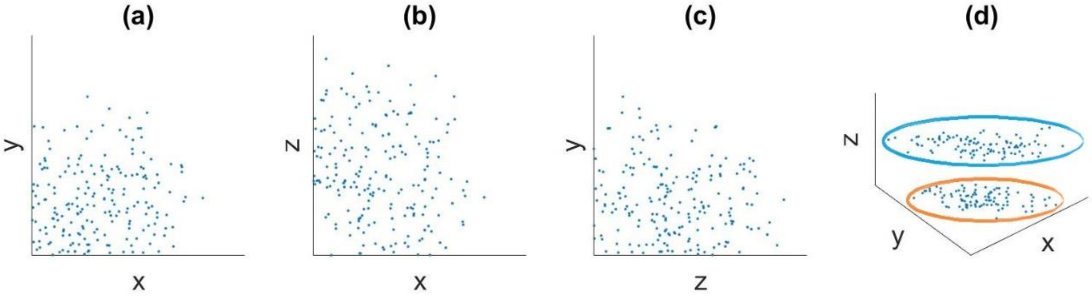

Fig.3: In this artificial dataset no clusters are detected by looking at 2d plots of (a), (b) and (c), whereas looking in 3d does reveal two clusters (d).

1.3. Clustering

In order to find these multidimensional families of ship designs, clustering algorithms from machine learning are proposed. These algorithms, as their name suggests, are devoted to find clustering structures in data. An example of their application is in companies as Facebook and Google where people are divided into clusters to achieve better assessment of which advertisement suits which person best *Schutt and O'Neil (2013)*. The analogy is that in this case the designs are divided into clusters to achieve better assessment of which design decisions suits which performance requirement best. The assumption is that the more distinct the clusters are, the more information they reveal about the relation between design and performance space.

A problem is however, that there is no clear notion of what 'being distinct' means. Studying for example the designs in Fig.4, there are various ways of comparing them. Looking at main dimensions designs A, B and C are similar, while design D is a bit longer. Whereas looking at the position of the working deck designs A and C have a working deck amidships, while at designs B and D it's positioned at the stern. Finally if assessing the main gun, only design A has one, while it is absent in the rest of the designs. These examples show that clustering is inherently a subjective science, as there is no single right or wrong way to cluster any given data *Theodoridis and Koutroumbas (2009)*. It is therefore important to investigate various sensible ways of clustering the set of designs.

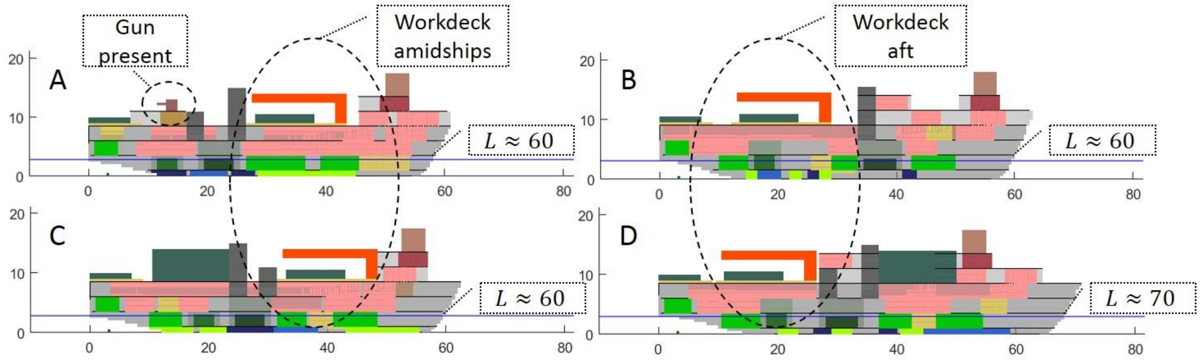

Fig.4: Four MCMV-designs resulting from the packing approach, where various differences and similarities are pointed out.

In this paper first the method for clustering is pointed out, including a more detailed description of the used techniques. Then this method is applied to find families of designs regarding the layouts of the MCMV.

2. Method

Due to the subjectivity of clustering, attention should be payed how to use the algorithms. The way you set up the problem partly determines which results you are going to find, and whether these results contain useful information. Clustering is a six step process (See *Theodoridis and Koutroumbas (2009)*):

1. Feature selection/creation: Select a set of features that are of interest. This may include all features, a subset of features, or new features. An example of a new feature is adding displacement, when L, B, T and c_B are available.
2. Proximity measure: Define how similarity between data points is measured by selecting a distance metric (such as Euclidean and Hamming distance).
3. Dimensionality reduction: Try to reduce the dimensionality of the data by using techniques such as Principal Component Analysis or Self-Organizing Maps. This improves the quality of the clustering algorithm as is shown by *Ding and He (2004)*. Furthermore the result can be used as initial investigation/visualization of the problem.
4. Clustering: If the remaining number of dimensions is more than three, apply a clustering algorithm, otherwise plotting data is possible. There are numerous clustering algorithms available.
5. Validation: Validate the clusters. This is not trivial since there are more than three dimensions, which makes it hard to visualize. Several metrics exist that indicate the quality of clusters.
6. Interpretation: When the result is valid, interpret it.

The specific algorithms used in this paper in steps 3, 4, and 5 are discussed in-depth more below.

2.1. Dimensionality reduction: Principal Component Analysis

This paper uses Principal Component Analysis (PCA) for reducing the dimensionality of the selected features. PCA is a valuable technique for exploratory analysis of high dimensional data. It rotates the original dataset in such a way that the first principal component (pc) corresponds to the direction with the highest variance, the second pc is orthogonal to the first pc and contains the second highest variance, and so on. A two-dimensional example is shown in Fig.5. This is useful for a number of reasons. Most important is that the amount of variance can be interpreted as being the amount of information *Linsker (1989)*. This reveals how PCA can be used for dimensionality reduction: Selecting and examining only those first couple of pc's that have the highest variance.

Since it is only possible to plot up to three dimensional data (higher dimensional plotting is technically possible (i.e. using colour and/or time), but the same argument holds.), a plot of the first three pc's will show you as much information as possible in one plot. On the other hand interpreting the content of the plot gets harder due to the complex values on its axis, since each pc is a linear combination of all input features. But the focus in this paper lies in identifying the multidimensional structure (clusters) in the data, which will still be visible in the plots. In fact, if there is a direction in space where clusters do show up, this direction has an increased probability of having a high variance, which makes it more likely to end up in the first three pc's *Ding and He (2004)*. This property is illustrated in Fig.6.

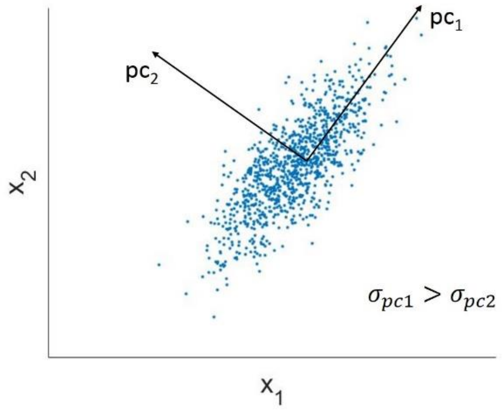

Fig.5: Illustration in 2D how PCA rotates the data. It makes it as "flat" as possible.

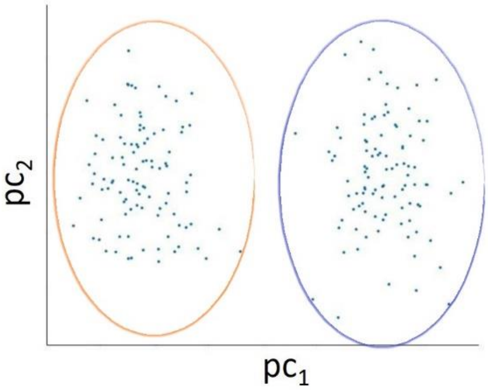

Fig.6: PCA applied to the data used in Fig.3. The first pc lies in the direction that reveals the clusters.

2.2. Clustering: k-means

K-means is a very popular clustering algorithm, mainly because of its elegancy and performance, *Jain (2010)*. The algorithm requires the amount of clusters, k, as input and uses the following steps:

- Initialize by selecting k distinct points $c_1, \cdots, c_k$ in space (Various initialization methods exist such as k-means++, which is used in this paper. The easiest is randomly selecting distinct positions as is used in the example of Fig.7.)
- Repeat until convergence:
  - Assign every data point to cluster i if it is closest to point c_i
  - Shift every c_i to the center of mass of the data belonging to cluster i

This process is illustrated in Fig.7. In Fig.7a the data itself and the random initialization of the centres is displayed. The first and second iterations are shown in respectively figures 7b and 7c, and finally convergence is reached in Fig.7d.

2.3. Validation: Dunn-index

There are a number of different metrics that give an indication of the quality of clusters. This paper seeks clusters based on physical attributes, which means that certain combinations of features result in infeasible designs. Thus, opposed to density clusters, there should be real gaps in-between the clusters. Therefore the Dunn-index is used, since it measures the size of the gap *Theodoridis and Koutroumbas (2009)*. It is defined as:

$$Dunn\ index = \min_{\forall i, \forall j \neq i} \left(\frac{d(C_i, C_j)}{\max_{\forall k}(diam(C_k))} \right)$$

Where $d(C_i, C_j)$ is the minimum distance between points from clusters C_i and C_j, and $diam(C_k)$ is the maximum distance between points from cluster C_k.

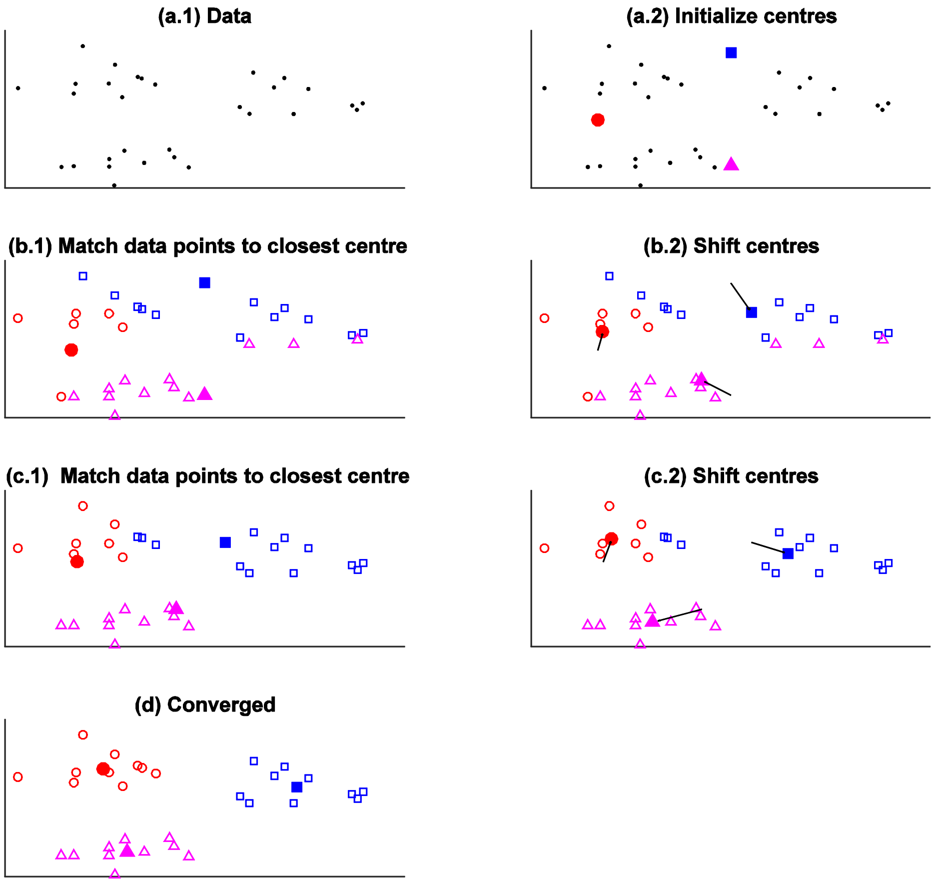

Fig.7: Illustration of how k-means converges on a 2D artificial dataset for k=3

To be more precise the Dunn-index is a measure that gives a lower bound for the distance between the clusters relative to the size of the clusters. A Dunn index of 1 or higher would therefore mean that the minimum distance between the clusters is higher than the diameter of the biggest cluster. In order to test whether the method in this section is able to elucidate families of designs from the data of the packing approach, it is applied to a test case in the next section.

3. Test Case: Mine-countermeasures vessel

The dataset of a MCMV as used in *Duchateau et al. (2015)* is used as test case. The set consists of over 17000 designs, with variations in global parameters (such as length, speed and range), optional objects (gun and Unmanned Surface Vessels (USV's)) and layout (position of the compartments and bulkheads). An example is displayed in Fig.8 including an explanation of its objects.

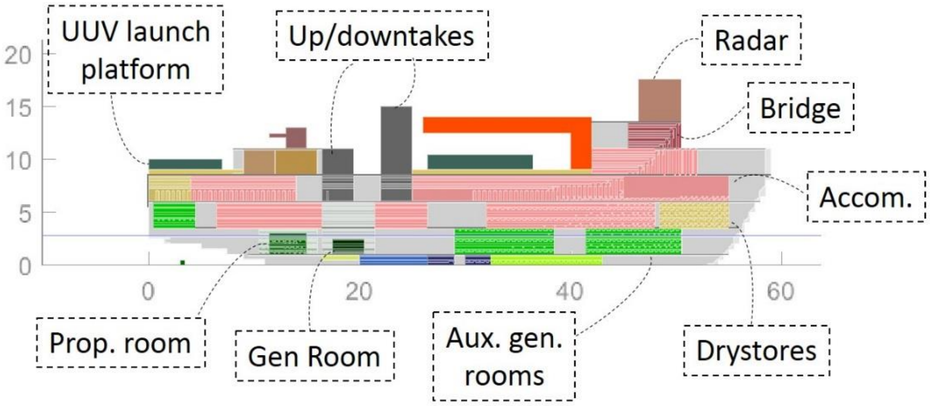

Fig.8: Example of a MCMV design from *Duchateau (2016)*

Since naval ships are complex designs that have many interactions between their compartments, the MCMV dataset is particularly interesting. The problem with this set is however that many of these interactions were omitted when initially developing the data set. This means that the compartments are more or less randomly stacked into the hull. Therefore, this section starts with selecting designs based on the quality of their layout. Then the proposed method is applied for finding multidimensional structures in the layouts of these selected designs. And finally, the results will be discussed.

3.1. Design selection based on designer rationale

The goal in this section is to select the 10% designs with the best layouts based on designer rationale. The layouts of the resulting subset of designs should then contain more structure than the remaining 90%. This enables verification of the hypothesis that this set consists of distinct families of designs.

In order to achieve this, first a metric is defined that quantifies if a design has a good layout. This is based on designer rationale captured by *Denucci (2012)*. He developed a Rationale Capture Tool (RCT) where designers could comment on automatically generated ship designs. These comments were structured and saved so that a resulting list of designer rationale emerged. All rationale applicable to the MCMV was extracted from that list and then quantified into a metric. The resulting ten comments and their corresponding metrics are listed in Table I.

Table I: Applicable designer rationale for the MCMV from *Denucci (2012)*, including the metrics representing the rationale. Every metric should be minimized.

#	Designer Rationale	Reason	Metric
1	The length of fuel piping must be minimized	Survivability/Cost	Sum distances between all tanks and generators
2	Shaft length should be minimized	Space/Weight/Cost	Distance between propulsor and propulsion room
3	High ranked officer accom[1] should be close to the bridge	Operability	Max. distance between high ranked officer accoms and bridge
4	accom shouldn't be near the bow	High accelerations	Negative min. distance between accoms and bow
5	High ranked officer accom shouldn't be below dcd	Survivability	Count number of high ranked officer accom below dcd
6	Drystores should be close to the galley	Logistics	Max. distance between drystores and the galley
7	Bridge shouldn't be near the bow	High accelerations	Negative distance between bridge and bow
8	Davit shouldn't be too high above the waterline	Operability	Davit height minus the draft
9	accom should be grouped	Atmosphere	Within cluster sum of squares (WCSS)[2] for k-means with k=2
10	accom shouldn't be close to heavy machinery	Noise	Negative min. distance between accom and generators, propulsion room and gun

The following step is to combine the ten metrics from Table I into one metric for the quality of the layout of the designs. First, since every metric has different values (the first metric is typically in the order of tens, while the third metric is in the order of thousands) they are first standardized by taking

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[1] For each design the 14 accom blocks are first sorted on whether they are above dcd and are then sorted on their distance to the bridge. The first 4 accom blocks are then assigned to high ranked officers.

[2] WCSS is equivalent to the sum of the Euclidean distances between every data point (accommodation) and its respective cluster center resulting from k-means.

their z-scores[3]. Then for the sake of simplicity it is assumed in this paper that every design comment is equally important, thus the quality of a layout is defined by the plain sum of these ten metrics without using a weigh factor. Finally the 10% designs with the lowest total objective value are the designs with the best layout, and are therefore combined into a subset which is investigated for clusters in the next section.

3.2 Apply method

3.2.1 Feature selection/creation

The dataset with included designer rationale is expected to consist of separated clusters regarding the layouts of the designs. Therefore the features regarding the positions of all objects in the layout are selected. In total the designs are packed with 43 objects. Since the designs are generated by 2.5D packing, x- and z-positions of all objects are selected, but y-positions are only deviating from the centreline for workshops and stores and are therefore omitted *van Oers and Hopman (2012)*. This results in a total of 86 selected features (or dimensions) which describe the designs.

3.2.2 Proximity measure

There are multiple criteria for down selecting a proximity measure. Since in this case the data is in Cartesian coordinates, and consist of continuous variables, Euclidean distance has been chosen as an appropriate metric.

3.2.3 Dimensionality reduction

The next step in the process is dimensionality reduction with PCA. An initial result is displayed in Fig.9, where the explained variance is plotted versus how many pc's are used (note that the pc's are sorted regarding the amount of variance they explain). The first pc does thus contain over 20% of the total variance. Furthermore it is interesting to see that 99% of the total variance is explained by using the first 33 pc's. This means that 86 – 33 = 53 dimensions can be discarded with very limited information loss. Fig.10 shows the data plotted regarding the first 2 pc's. From Fig.9 it is clear that this plot contains about 29% of the total variance. As discussed in section 2.1.1, clusters are likely to show up in this plot. Although there are no clear separate clusters visible, there is some structure present with regions that have a higher density. The presence of distinct clusters is further investigated in the next sections.

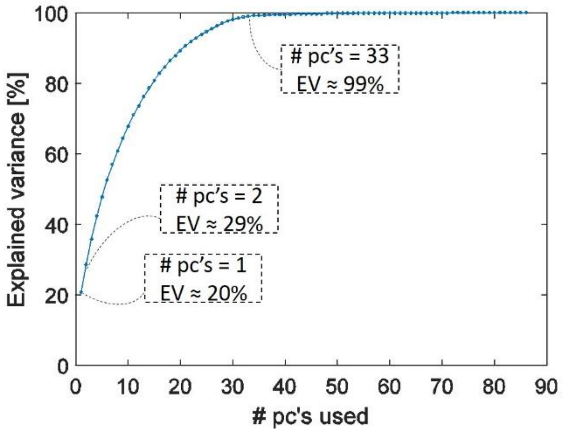

Fig.9: Explained variance vs. the number of pc's used for the MCMV dataset including designer rationale.

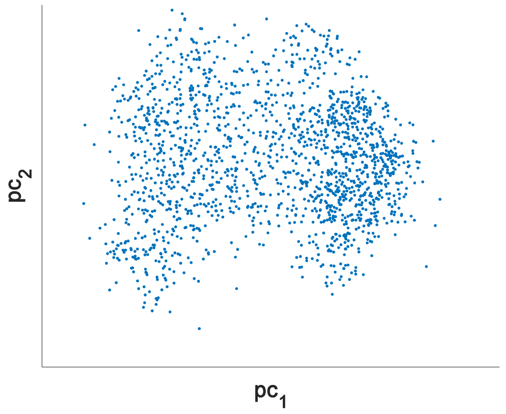

Fig.10: MCMV dataset including designer rationale plotted regarding its first 2 pc's.

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[3] Taking the z-score of a data array sets its mean to zero and its standard deviation to 1 with the following transformation: $z_i = \frac{x_i - \mu_x}{\sigma_x}$ for all data points x_i.

3.2.4 Clustering

Next the k-means algorithm is applied to the reduced 33-dimensional dataset for various values of k. Since the 33-dimensional clusters are still hard to visualize in a figure they are validated in the next section. A projection of the clusters for k = 3 into the first two pc's is shown in Fig.13a.

3.2.5 Validation

The Dunn indices calculated for the various cluster compositions from k-means are plotted in Fig.11. Instead of one value for k that corresponds to a high Dunn index, the Dunn index is approximately constant at a rather low value of about 0.18. This might indicate that there are no gaps in between the clusters. For further investigation, the Dunn index is calculated for 1000 random cluster compositions, Fig.12. The median of the resulting set equal 0.184, showing that there is roughly a 50% probability of a random cluster composition exceeding the cluster compositions from k-means. This means that there is no significant gap in between the clusters from k-means.

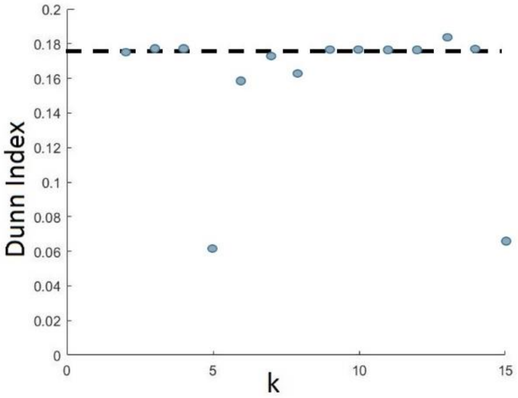

Fig.11: Validation of the results from k-means using the Dunn index

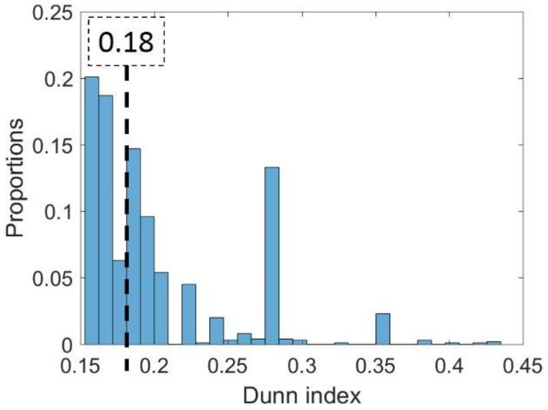

Fig.12: Histogram of Dunn index values for 1000 samples when the dataset is split into two groups by a random hyperplane[4].

3.2.6 Interpretation

Although the clusters are not separated by a significant gap, Fig.13a does show that the clusters correlate to certain regions with higher densities.

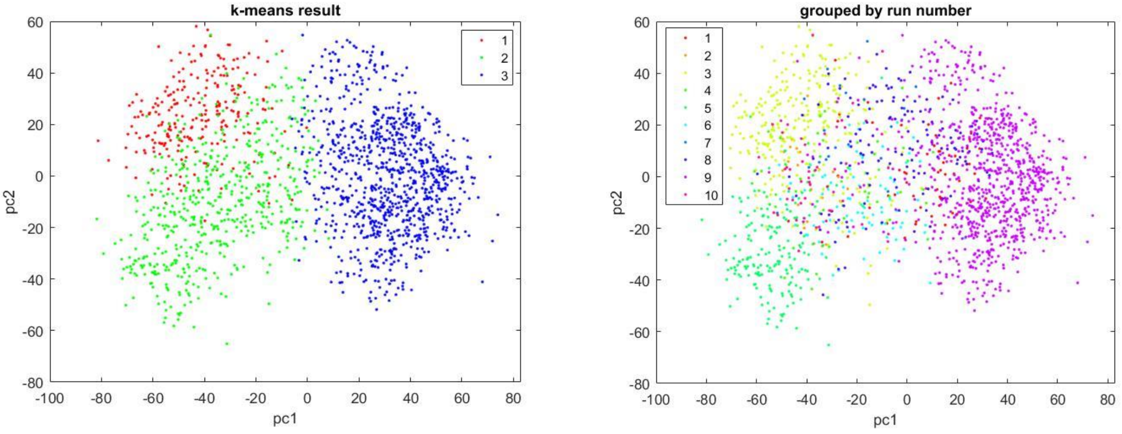

Fig.13: Data plotted in first two pc's clustered by: (a) the result of k-means for k=3 and (b) the run number in which the data was generated.

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[4] Hyperplane equidistant to two randomly selected data points.

The explanation for the visible structure lies in how the data was generated. The packing algorithm was run ten distinct times in order to compare it with another dataset. The results of these ten runs were combined to form the complete dataset. Colouring the data based off this run number, as shown in Fig.13b, and comparing this with the clusters found by k-means shows that the result is very similar:

- Cluster 1 corresponds to run number 3
- Cluster 2 corresponds to run number 5 (and 4,6,8 and 10 which are smaller)
- Cluster 3 corresponds to run number 9

This result suggests that every run searches a particular part of the design space, since every run forms its own cluster based on layout. This notion is further investigated in the next section.

3.3. Design space

In the packing approach every design is parametrized by a chromosome which can then be adjusted by the genetic algorithm. The genes in the chromosome do thus form the design space. In order to further investigate the influence of run number in the dataset at hand, PCA is applied to this design space of the full design set, and the result is plotted in Fig.14. This static figure shows clearly that every run converges to a different part of the space, which is even better visible when the figure is rotated.

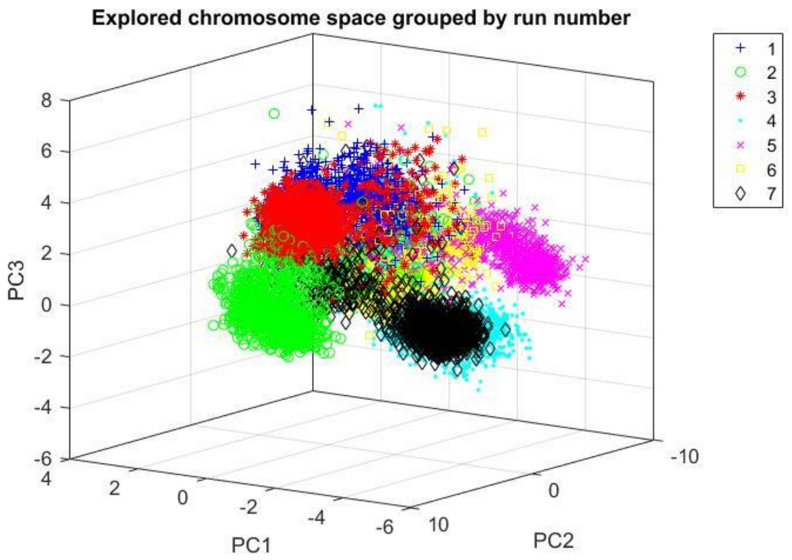

Fig.14: Input data plotted versus the first three pc’s obtained from the design space. For visualization purposes only the first 7 out of 10 run numbers are included.

4. Discussion & Future work

Although part of the problem for the lacking diversity lies in using a genetic algorithm as a search algorithm, it is suspected that it is amplified by the following effect: The objective of the NSGA II algorithm is to create compact designs (i.e. maximize packing density). When a design has a high packing density, it will therefore be higher graded than other designs. This causes the algorithm to keep trying to propagate this design. But in contrary this design is less likely to get a feasible child, since it is more difficult to pack the compartments in a denser design. The probability of having feasible children is then only higher if there are only minor changes applied, which causes convergence. Furthermore if the design does happen to get a feasible child, this is most probably the case due to increasing the size of the ship, which makes it of less quality then the original design. This suspicion can be tested by investigating the family tree of a run, including the designs that have failed to meet the constraints. Since this information is not included in the data yet, this is up for future work.

5. Conclusion

In this paper clustering algorithms were used to search for families of ship designs generated by the TU Delft packing approach. Therefore a clustering method was applied to a test case of layouts from a MCMV. Unfortunately the results seem to be dominated by the fact that the dataset was built by combining data from ten distinct runs of the packing approach.

Although families of ship designs based on physical aspects of the designs were not clearly visible, the techniques used in this paper did reveal information on how the model generated the data. It shows that despite the effort of using the NSGA II algorithm as a search algorithm by setting its mutation rate rather high *Duchateau (2016)*, the diversity for a single packing run is still limited.

It would have been difficult to ascertain this behaviour using other techniques. The clustering method allows to look at the data from a different point of view than ordinary plotting variables, and therefore creates new insights and hypotheses. The authors are therefore convinced that its application will remain useful, revealing information about both the model as the relation between design and performance space.

Acknowledgements

We gratefully thank Bijan Ranjbarsahraei for supporting us by sharing his wisdom on the various techniques and methods from the field of data science in regular meetings.

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Six Steps to using the IoT to Steer Ships into the Digital Future – Keeping Vessels “Ship Shape” with Predictive Maintenance Efficiency

Mary Etienne, Dell EMC, Paris/France, mary_etienne@dell.com

Abstract

Connecting vessels to the Internet of Things (IoT) has transformative potential for the maritime industry that goes beyond the shininess of technology. The passion brigade includes suppliers of industrial equipment and systems on vessels who are embracing the IoT as an enabler to deliver value. A key area our customers are exploring is predictive maintenance. PdM helps improve top operational challenges: reduce unplanned downtime for repairs, improve overall equipment effectiveness, reduce maintenance costs and increase return on assets. This paper outlines best practices for implementing PdM solutions with technology that connects to and accesses operational data and provides business analytics.

1. Introduction: The new normal is digitization

Technology moves in step changes. All the elements of computing power: processing chips, storage chips, software, networking and sensors tend to evolve as a group. As their collective capacities reach a certain maturity, they blend together to create a platform and that platform scales a new set of advances which becomes the new normal.

Today the new normal is digitization. The Internet of Things and Big (or “Smart”) data offer companies the ability to aggregate existing data sources, gain visibility into new data and identify patterns through analytics to make better business decisions.

Vessels operate a lot of “machinery” and can benefit from PdM enabled by sensor-generated data. Finding patterns that are early indicators that something is going to break or is becoming inefficient is called predictive maintenance (PdM). It is a fancy way of saying that you can maintain your vessels industrial systems on your terms, rather than being 100% reactionary. In many cases the system can predict its own impending failure. The biggest gain for this method is that you can plan for equipment downtime and maintenance to proactively make adjustments and repairs when it makes the most sense.

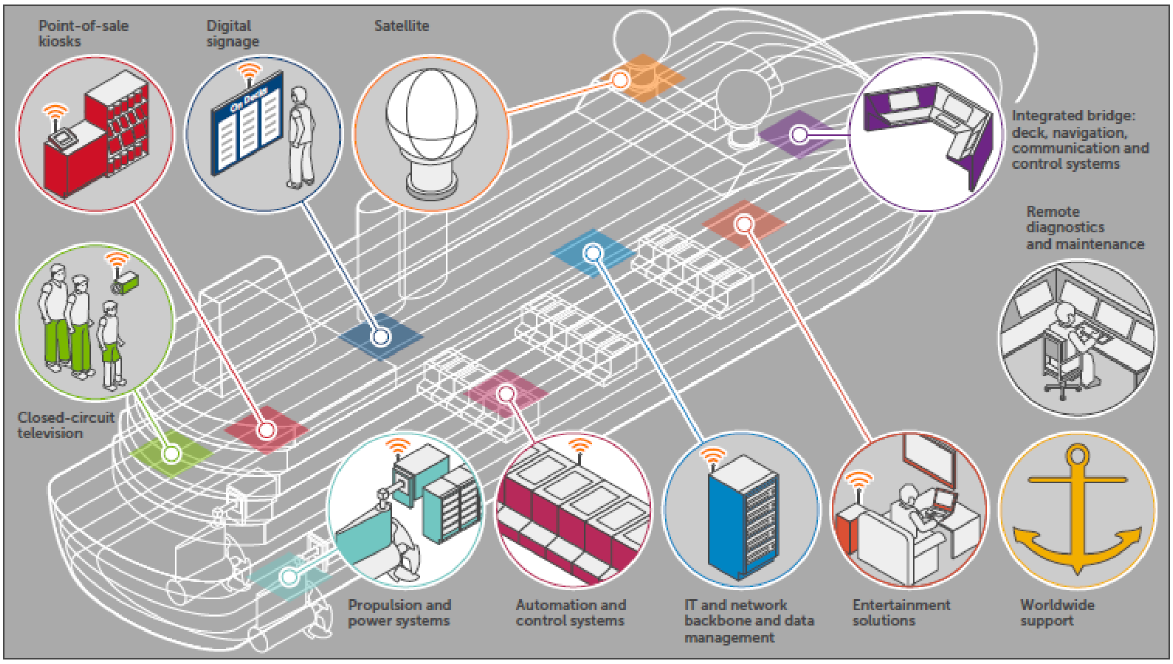


Fig.1: Onboard M2M remote diagnostics and predictive maintenance

2. Repairing Machine Failures on the Ocean

The cost to repair or replace a device or equipment can be significant. Reacting to machine failure is a very expensive proposition and can include both the costs of repairing or replacing the device as well as costs resulting from the unavailability of the device until it is repaired. Predicting when a device fails and performing intervening actions could avoid device repair or replacement, and associated downtime costs.

One approach to solve this problem is to perform periodic inspections and parts replacement based on a rigid maintenance schedule. This can be expensive and inefficient especially when the part being replaced is still in good working order. Another approach utilizes a predictive model that is executed in batch. The models are typically executed one or a few times a day. However when there is a sudden deviation in patterns that are indicative of impending failure, it would not be detected until the next execution of the predictive model.

One of the key components of our approach is the real-time detection of leading indicators of device failure. The leading indicator could be a threshold breach of a metric (i.e. temperature), an analytic (i.e., the average temperature over the last 5 minutes is on the rise), or the real-time execution of a predictive model (i.e., expect machine failure in 1 hour with 95% confidence).

3. PdM Comparison Example

The value over any other maintenance model is that PdM empowers maintenance and operation decision makers to predict when an asset will need intervention well in advance of its failure impacting personnel, operations or production.

PdM provides the highest possible visibility of the asset by collecting and analyzing various types of data to provide the following benefits:

- Identifying key predictors and determining the likelihood of outcomes.
- Optimizing decision-making by systematically applying measurable real-time and historical data.
- Planning, budgeting and scheduling maintenance repairs, replacements and spares inventory.

The example in Fig.2 illustrates the amount of time that it takes to detect a potential failure interval for each of the four maintenance models commonly used today. PdM enables you to save time and money by detecting the failure based on data sources before damage to the machine occurs.

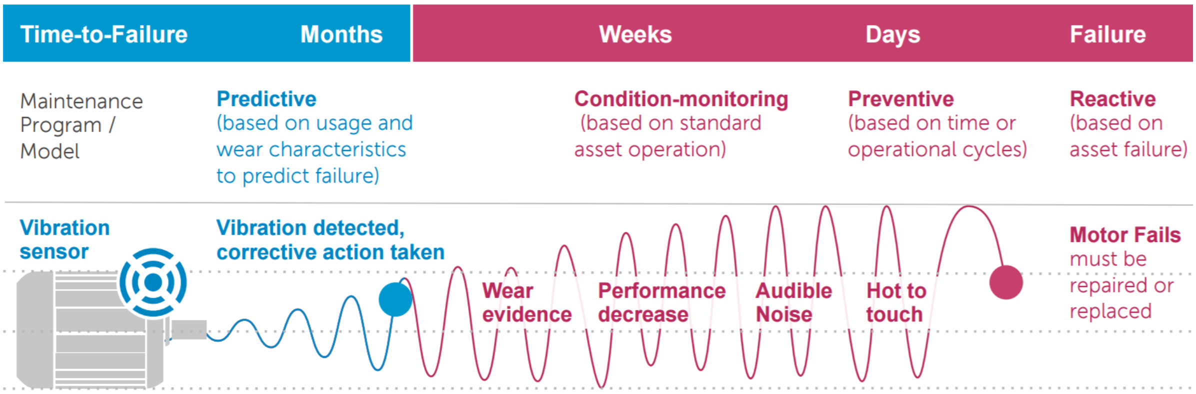


Fig.2: PdM motor vibration analysis example

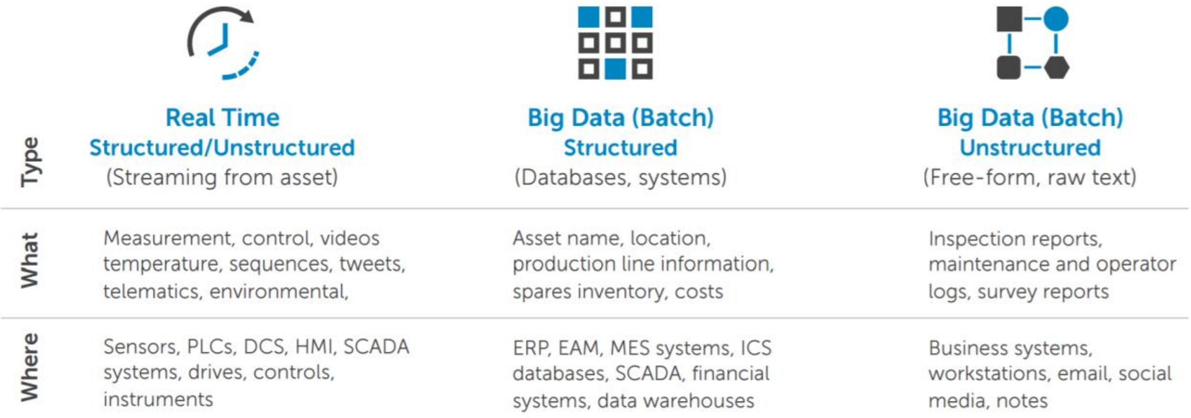
Step 1: Establish the business case for PdM

To make the case for a PdM implementation, the focus should be on the unique problems that affect optimizing operational and production impacts while managing risk. It is important to understand what metrics the organization is focusing on and which need to be improved. Consider these questions to identify key goals of your PdM project and ensure success:

- What critical assets are likely to fail? When and why do we believe they will fail?
- How would assets' failure impact personnel, operations or production costs? What does downtime cost?
- How can data driven decisions be integrated within the constraints of existing maintenance practices?

Step 2: Identify and prioritize data sources

The increase in asset connectivity and use of smart devices may have generated large amounts of available data. It is not needed or recommended to address this whole universe of possible data. Instead, begin to predict failures on a single asset by focusing on the usable, existing data sources related specifically to it. Fig.2 illustrates how capturing the real-time data from just one sensor resulted in avoiding costly damage, downtime and emergency response. Fig.3 shows a list of the various types of data sources available and where they are typically found.



Type	Real Time Structured/Unstructured (Streaming from asset)	Big Data (Batch) Structured (Databases, systems)	Big Data (Batch) Unstructured (Free-form, raw text)
What	Measurement, control, videos temperature, sequences, tweets, telematics, environmental,	Asset name, location, production line information, spares inventory, costs	Inspection reports, maintenance and operator logs, survey reports
Where	Sensors, PLCs, DCS, HMI, SCADA systems, drives, controls, instruments	ERP, EAM, MES systems, ICS databases, SCADA, financial systems, data warehouses	Business systems, workstations, email, social media, notes

Fig.3: Various types of data sources available

Step 3: Collect selected data

The selected data may reside in disparate locations from a device at the network edge to the server room to the enterprise cloud, including sensors, meters, enterprise asset management systems, and supervisory control and data acquisition (SCADA) systems. An Ideal PdM solution should be flexible enough to enable you to collect from all of these data sources to learn and continually make better, more informed business decisions. The Dell Edge Gateway is an industrial-grade, scalable solution for the Edge which works with a variety of critical protocols, data sources, and types of data, Fig.4.

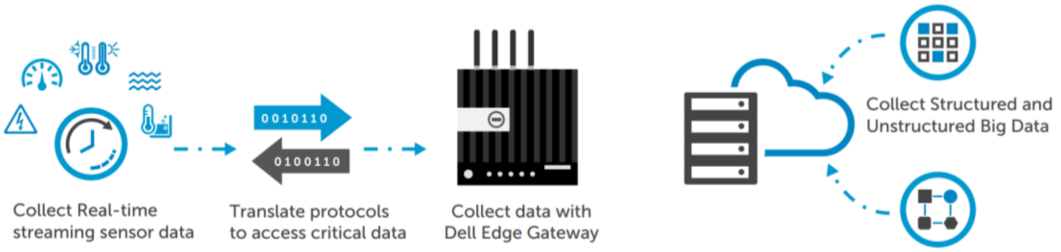


Fig.4: Basic principle of Dell Edge Gateway

Step 4: Determine where to run your analytics

Establish an advanced analytics foundation based on your specific operation. For example, Edge (or local) and Cloud analytics can be balanced to reduce the burden of streaming perishable PdM data on your cloud deployment. A distributed approach enables you to detect and respond to local events at the edge as they happen, taking action immediately on streaming data, while simultaneously integrating additional data sources in the cloud. The Dell Edge Gateway can analyze streaming data in memory for real time response and filter out unnecessary data rather than relaying it to the cloud, Fig.5.

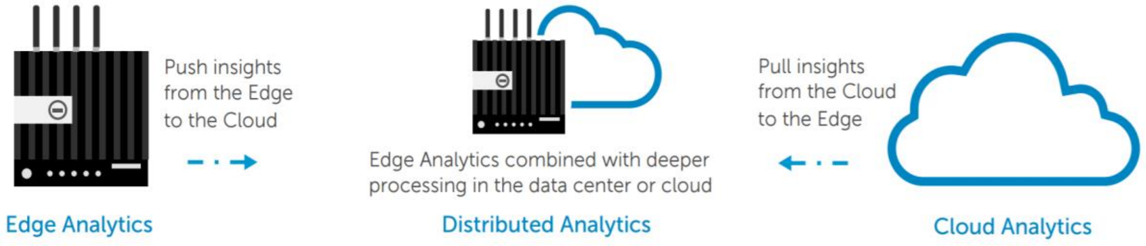


Fig.5: Edge analytics vs. cloud analytics

Step 5: Combine and analyse data to gain precise insights

Start by analyzing available data to define the parameters of normal operation for a machine. This enables the creation of rules through condition monitoring for analyzing the real-time data coming directly from machine sensors on the Dell Edge Gateway. With the Edge Gateway, analytics can happen as close to the machine as possible with the native I/O to collect data from industrial equipment and the ability to operate in harsh environments. After analyzing the real-time data, add historical and third party data such as reliability models and logs to uncover meaningful correlations, patterns and trends with the anomalies generated by the real-time data rules, to signal potential failures. The patterns can be used to further refine your rules and offer actionable insights in real time.

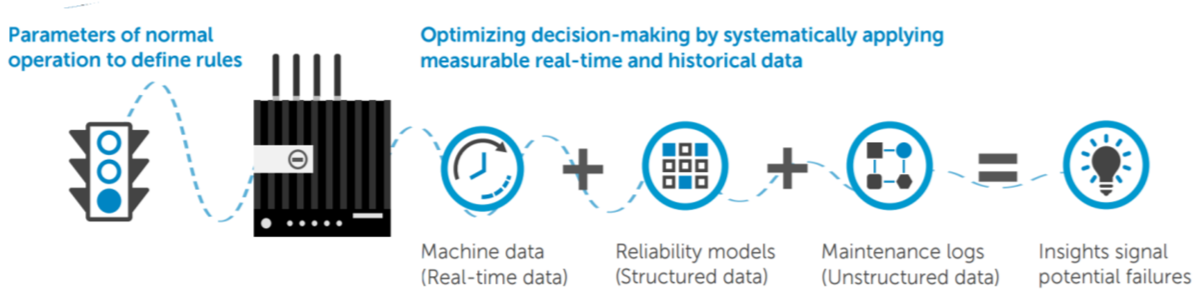


Fig.6: From analytics to insight and business decision

Step 6: Operationalize and take action

Turn insights into action by integrating an aggregated risk assessment for all assets into your operation through a single dashboard. For example, when a potential problem is uncovered the Dell Edge Gateway triggers an event that allows you to send out automated alerts to concerned parties, such as location, estimated replacement parts and recommended corrective action to avoid a catastrophic event. Then, by capturing wear characteristics data from the replaced parts, you are able to continuously refine your PdM models and learn from performance insights. Finally, explore additional uses for your PdM data such as automating inspection reports and enhancing component supplier evaluation.

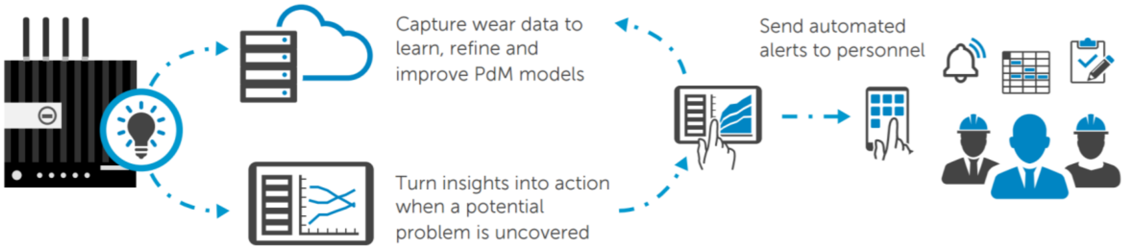


Fig.7: Operationalize and take action

4. Conclusion: A seafarer’s intuition

Seafarers repeatedly tell us, the highway of the sea is a ferocious environment, digital or not. It’s quite a responsibility to be on the deck in time of stress, doing the thinking that will guide tons of steel through a few million tons of wind and waves. The captain and crew measuring their knowledge of what the vessel can endure against the blows being stuck at her.

Think about it, a seafarer’s intuition about how a ship is operating comes from 30 years of navigating and being able to detect a slightly different sound coming from a flow meter on a pump telling them something might not be exactly right. Now with sensors, weak signals can be detected without intuition. All the data that is being gathered inside a ship from engines, pumps, turbine fans, pieces of oil & gas equipment can all report to the captain how they are feeling every minute. If the power systems, fans, pumps, or an engine is on the “sick list”, the sensors will broadcast it.

Suddenly you can tell how fast the vessel is travelling, when the brakes are applied, or how much time the engine has spent idling vs time in motion. A vessel enabled with sensors can sense and broadcast the height of the waves; it can calculate the force of the current and how much energy it needs to cover a nautical mile, putting on the engines a little less when it is smooth sailing and generally maximizing fuel efficiency or velocity to get it from point “A” to point “B”. Cameras can monitor how captains/crew are operating engines at every crest of the wave and the engine manufacturer will know that if the engines have to run at 120% on a hot day, certain parts will need to have their predictive maintenance moved up.

Crew or technicians on the ship or on shore can monitor equipment in real time to remotely service products via the Internet so parts can be swapped out at the next port of call, avoiding operational down time and costly delays.

As sensors become smaller, more robust and cheaper to acquire, we predict that they will be everywhere, in the hull, main engine, and auxiliary machinery and even attached to smaller equipment items, gathering and collecting data for analysis. Whether ships and the equipment on them are operated locally or by remote control, operational decisions will be data driven.

References

NN (2016), *Predictive Maintenance Solution Brief*, Dell IoT Solutions, http://i.dell.com/sites/doccontent/shared-content/data-sheets/en/Documents/DELL_PdM_Blueprint_Final_April_8_2016.pdf

Appendix: Predictive Maintenance Solutions Blueprints

Dell EMC has developed flexible architectures around the Edge Gateway 5000 with qualified partners for complete PdM solutions. For more detailed information on our Predictive Maintenance Reference Architectures, see:

Dell | SAP IFM PdM Reference Architecture
http://en.community.dell.com/techcenter/blueprints/m/resources/20442877

This document is intended for both Information Technology and Operations Technology audiences in asset intensive industries such as manufacturing, transportation, energy, and others. It is ideal for audiences exploring how IoT-enabled predictive maintenance could be effectively deployed in their environment. Readers who have some familiarity with concepts including IoT, device protocols, streaming analytics, and predictive analytics will gain a deeper understanding of how these concepts can come together to increase maintenance efficiencies in your business.

Dell Software AG Kepware PdM Reference Architecture
http://en.community.dell.com/techcenter/blueprints/m/resources/20442878

Big Data Streaming Analytics at the Edge for Predictive Maintenance Reference Architecture. This paper presents a reference architecture for a Predictive Maintenance solution that runs on a Dell Edge Gateway 5000 and associated best practices in leveraging this architecture. The architecture leverages Kepware’s KEPServerEX® connectivity platform for device protocol translation and Software AG Apama for streaming analytics and real-time predictive model execution.

Big Data – Processing Global AIS in Real Time to Produce Market Insight

Mark Deverill, Genscape Vesseltracker, London/UK, mdeverill@genscape.com

Abstract

This paper presents how Genscape Vesseltracker process 500 million daily AIS messages in real time, filtering for all types of ship events, merging the information with a detailed geographical database of maritime locations and facilities, and filtering against databases of ship, terminal and company information to provide unique, actionable market insight.

1. Introduction

Vesseltracker, www.vesseltracker.com, has been pushing the boundaries of how AIS data can be used to gain business advantage for over 10 years. While running probably the biggest commercial AIS network for tracking ships globally, we recognise that AIS alone is no longer enough to gain the best business advantage from ship tracking. Vesseltracker is now part of Genscape Maritime utilising machine learning and the expertise of Genscape's market analysts. Genscape's new ship events engine enables building market orientated views to mine specific information relevant to fleets and markets, www.genscape.com/maritime, www.genscape.com/blog.

2. Ship Events based products

Genscape Vesseltracker parses AIS data in real-time to create a stream of ship events in a new suite of products called Periscope. Periscope products provide detailed insight into specific market activities from the past, present, and future. The history of these events is used to recognise trends and provide insight to future market activity.

2.1. Events Processing Engine Overview

The Ship Events Engine parses the real-time stream of AIS and other data to identify events such as floating storage, ship bunkering and other ship-to-ship (STS) transfers. This history of different events builds a concise and readily available summary of the ship's activity. The Events Processing Engine consumes 500,000,000 daily AIS position and voyage messages, referencing a database of 150,000 ships and a geographical database of 3,400 ports. 1,900 ports have specific terminal or anchorage information. The Events Processing Engine outputs more than 2,200 polygon events per minute and more than 100 STS events per minute.

2.2. Ship-to-Ship Events

Ship-to-Ship (STS) events capture includes:

- STS transfers
- Bunker deliveries STS
- Bunker tanker loadings from floating storage
- Tug activity
- Pilot Boat engagements
- Supply and service ships

2.3. Voyage Periscope & Voyage Events

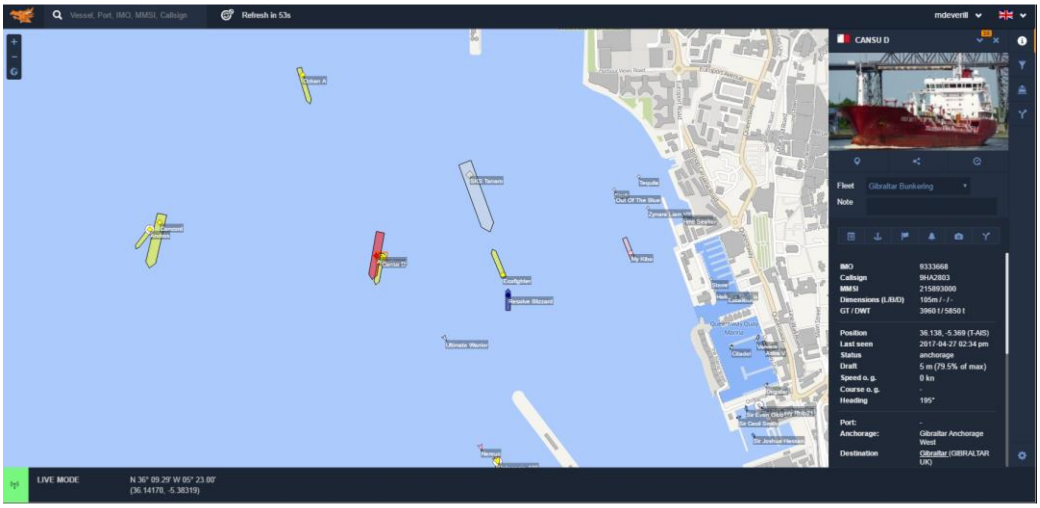
- Ships calling at detailed locations
- Changes in voyage information, destination, estimated times of arrival
- Changes in draft – deriving ballast or laden status - leading to delivery or loading at ports

- Knowledge of ship technical details to indicate cargo volumes from draft changes
- Entry and exit from trade areas, SECA zones, and geographical regions
- Ships calling at detailed locations
- Ports and terminals
- Anchorages, pilot areas

3. Bunkering Events

Research into specific bunkering providers' ships, bunkering locations and a consolidation of base events allows us to produce accurate records of STS bunkering as well as reloads of bunker vessels. Unique machine learnt logic recognises continuous events even when there are gaps in AIS reporting. The end result is a record of STS events, location, duration and ships involved with estimates of bunkered volumes.

Fig.1: Video replay of AIS monitored bunkering of LNG ship



CANSU D

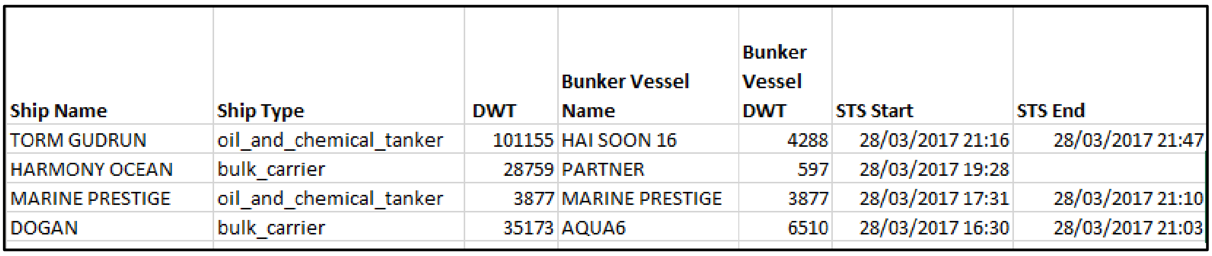
Fleet: Gibraltar Bunkering
Note:
IMO: 9333668
Callsign: 9HA2803
MMSI: 215893000
Dimensions (L/B/D): 105m / - / -
GT / DWT: 3960 t / 5850 t
Position: 36.138, -5.369 (T-AIS)
Last seen: 2017-04-27 02:34 pm
Status: anchorage
Draft: 5 m (79.5% of max)
Speed o. g.: 0 kn
Course o. g.: -
Heading: 195°
Port: -
Anchorage: Gibraltar Anchorage West
Destination: Gibraltar (GIBRALTAR UK)

N 36° 09.29' W 05° 23.00'
(36.14170, -5.38319)

Fig.2: STS Bunkering events observed in AIS

3. BunkerPeriscope

Backtesting the combined bunkering activity with estimates of bunkering volumes proved within 5% of official figures for total port bunkering activity. Bunkering events link to the ship information database, allowing bunker traders to see the client base by manager or operator of ships. Lastly, the BunkerPeriscope product includes predictions for bunkering port calls and a future bunker market emerges.

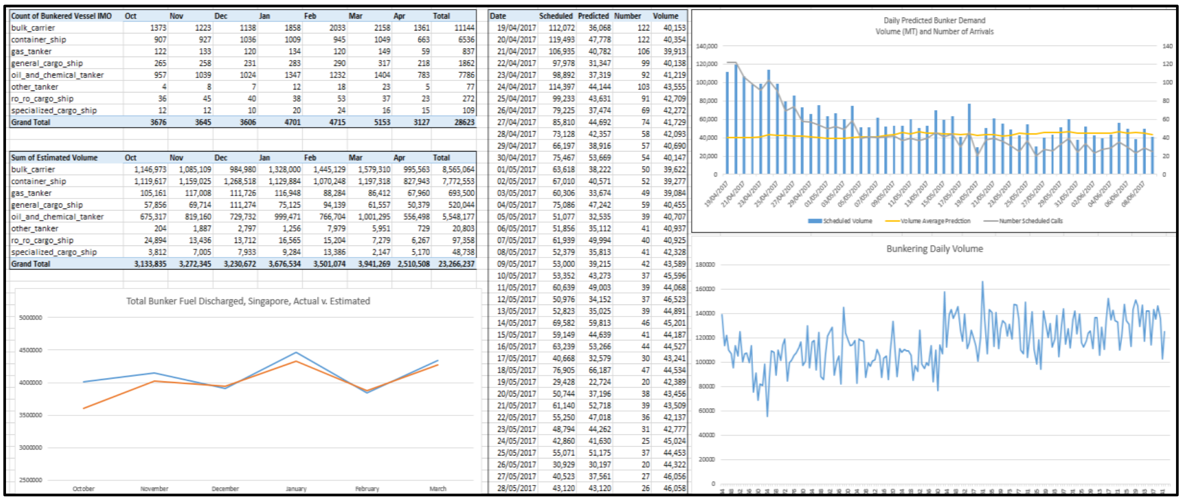


Ship Name	Ship Type	DWT	Bunker Vessel Name	Bunker Vessel DWT	STS Start	STS End
TORM GUDRUN	oil_and_chemical_tanker	101155	HAI SOON 16	4288	28/03/2017 21:16	28/03/2017 21:47
HARMONY OCEAN	bulk_carrier	28759	PARTNER	597	28/03/2017 19:28	
MARINE PRESTIGE	oil_and_chemical_tanker	3877	MARINE PRESTIGE	3877	28/03/2017 17:31	28/03/2017 21:10
DOGAN	bulk_carrier	35173	AQUA6	6510	28/03/2017 16:30	28/03/2017 21:03

Fig.3: Sample STS & Bunkering data

BunkerPeriscope builds on all areas of data and knowledge regarding ship to ship bunkering to produce a unique insight into the bunkering market. BunkerPeriscope provides bunker traders details of all market activity and an idea of the future market for growing their business by proactively approaching potential bunker clients before requests for bunkers are received. Logic built using events history, routing and distance calculations provide insights into the bunkering market including the following:

- Bunkering history of ships
- Calculations of bunker volumes
- Breakdown of bunkering activity by bunkering ship operator
- Historic bunkering activity and linkages to bunker providers, terminals, and refineries
- Distance travelled since last bunkering
- Distance likely before next bunkering
- Bunkering requirements for fleet approaching ports
- Future demand for bunkers in bunker hubs



Count of Bunkered Vessel IMO	Oct	Nov	Dec	Jan	Feb	Mar	Apr	Total
bulk_carrier	1373	1223	1138	1858	2033	2158	1361	11144
container_ship	907	927	1036	1009	945	1049	663	6536
gas_tanker	122	133	120	134	120	149	59	837
general_cargo_ship	265	258	231	283	290	317	218	1862
oil_and_chemical_tanker	957	1039	1024	1347	1232	1404	783	7786
other_tanker	4	8	7	12	18	23	5	77
ro_ro_cargo_ship	36	45	40	38	53	37	23	272
specialized_cargo_ship	12	12	10	20	24	16	15	109
Grand Total	**3676**	**3645**	**3606**	**4701**	**4715**	**5153**	**3127**	**28623**

Sum of Estimated Volume	Oct	Nov	Dec	Jan	Feb	Mar	Apr	Total
bulk_carrier	1,146,973	1,085,109	984,980	1,328,000	1,445,129	1,579,310	995,563	8,565,064
container_ship	1,119,617	1,159,025	1,268,518	1,129,884	1,070,248	1,197,318	827,943	7,772,553
gas_tanker	105,161	117,008	111,726	116,948	88,284	86,412	67,960	693,500
general_cargo_ship	57,856	69,714	111,274	75,125	94,139	61,557	50,379	520,044
oil_and_chemical_tanker	675,317	819,160	729,732	999,471	766,704	1,001,295	556,498	5,548,177
other_tanker	204	1,887	2,797	1,256	7,979	5,951	729	20,803
ro_ro_cargo_ship	24,894	13,436	13,712	16,565	15,204	7,279	6,267	97,358
specialized_cargo_ship	3,812	7,005	7,933	9,284	13,386	2,147	5,170	48,738
Grand Total	**3,133,835**	**3,272,345**	**3,230,672**	**3,676,534**	**3,501,074**	**3,941,269**	**2,510,508**	**23,266,237**

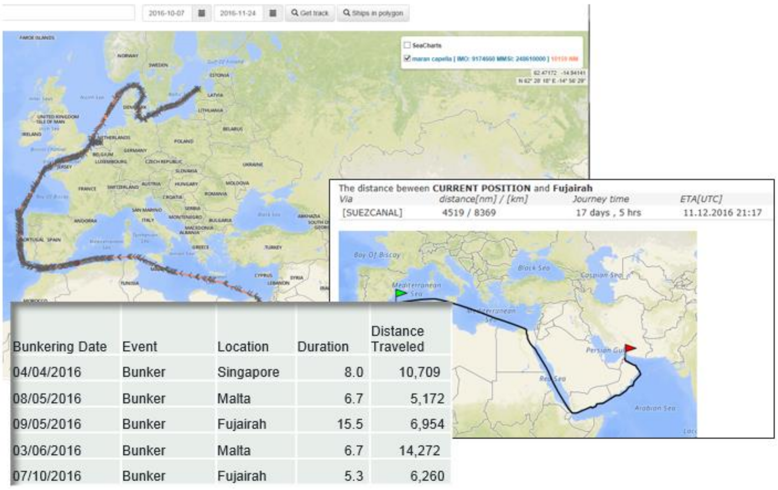
Date	Scheduled	Predicted	Number	Volume
19/04/2017	112,072	36,068	122	40,153
20/04/2017	119,493	47,778	122	40,354
21/04/2017	106,935	40,782	106	39,913
22/04/2017	97,978	31,347	99	40,138
23/04/2017	98,892	37,319	92	41,219
24/04/2017	114,397	44,144	103	43,555
25/04/2017	99,233	43,631	91	42,709
26/04/2017	79,225	37,474	69	42,272
27/04/2017	85,810	44,692	74	41,729
28/04/2017	73,128	42,357	58	42,093
29/04/2017	66,197	38,916	57	40,690
30/04/2017	75,467	53,669	54	40,147
01/05/2017	63,618	38,222	50	39,622
02/05/2017	67,010	40,571	52	39,277
03/05/2017	60,306	33,674	49	39,084
04/05/2017	75,086	47,242	59	40,455
05/05/2017	51,077	32,535	39	40,707
06/05/2017	51,856	35,112	41	40,937
07/05/2017	61,939	49,994	40	40,925
08/05/2017	52,379	35,813	41	42,328
09/05/2017	53,000	39,215	42	43,589
10/05/2017	53,352	43,273	37	45,596
11/05/2017	60,639	49,003	39	44,068
12/05/2017	50,976	34,152	37	46,523
13/05/2017	52,823	35,025	39	44,891
14/05/2017	69,582	59,813	46	45,201
15/05/2017	59,149	44,639	41	44,187
16/05/2017	63,239	53,266	44	44,527
17/05/2017	40,668	32,579	30	43,241
18/05/2017	76,905	66,187	47	44,534
19/05/2017	29,428	22,724	20	42,389
20/05/2017	50,744	37,196	38	43,456
21/05/2017	61,140	52,718	39	43,509
22/05/2017	55,250	47,018	36	42,137
23/05/2017	48,794	44,262	31	42,777
24/05/2017	42,860	41,630	25	45,024
25/05/2017	55,071	51,175	37	44,453
26/05/2017	30,929	30,197	20	44,322
27/05/2017	40,523	37,561	27	46,056
28/05/2017	43,120	43,120	26	46,058

Fig.4: Example of bunker periscope insight

Bunker Periscope identifies the need to bunker and likely bunkering locations using:

- History of recognised bunkering events for a ship
- Tracking of distance and speed travelled since last bunkering
- Monitoring voyage and destination
- Recognising route and possible bunkering locations
- Calculating possibility of bunkering in locations on route, judging from history and immediacy of bunkering requirement

Fig.6 shows the processing engine estimating bunker loadings for Singapore. Using actual bunker details to verify our generated data, version 1 of the engine is ~90% accurate on individual ship bunker volume estimates.



The distance beween **CURRENT POSITION** and **Fujairah**

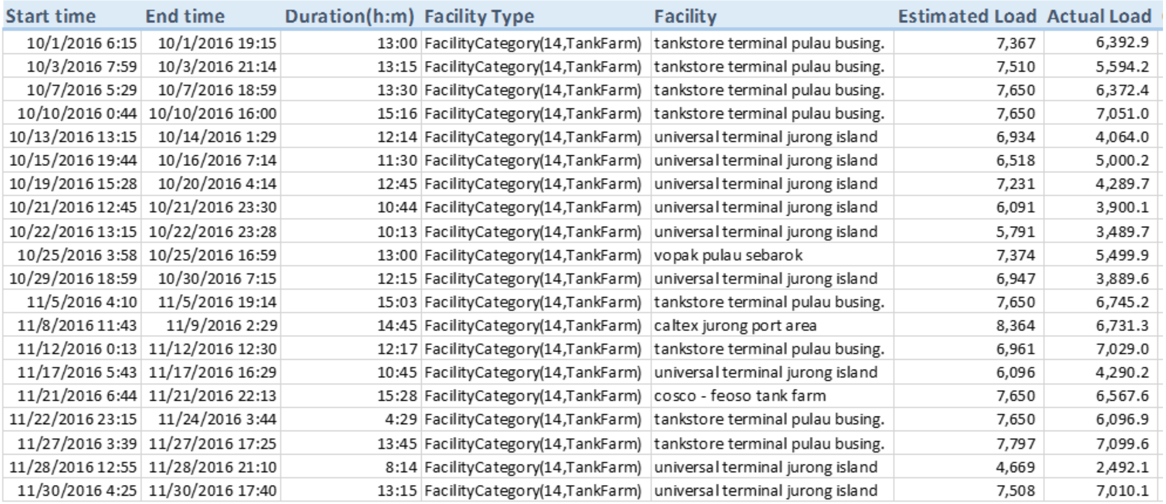
Via	distance[nm] / [km]	Journey time	ETA[UTC]
[SUEZCANAL]	4519 / 8369	17 days , 5 hrs	11.12.2016 21:17

Bunkering Date	Event	Location	Duration	Distance Traveled
04/04/2016	Bunker	Singapore	8.0	10,709
08/05/2016	Bunker	Malta	6.7	5,172
09/05/2016	Bunker	Fujairah	15.5	6,954
03/06/2016	Bunker	Malta	6.7	14,272
07/10/2016	Bunker	Fujairah	5.3	6,260

Vessel travelled 10159 Nm since last bunkering in Fujairah.

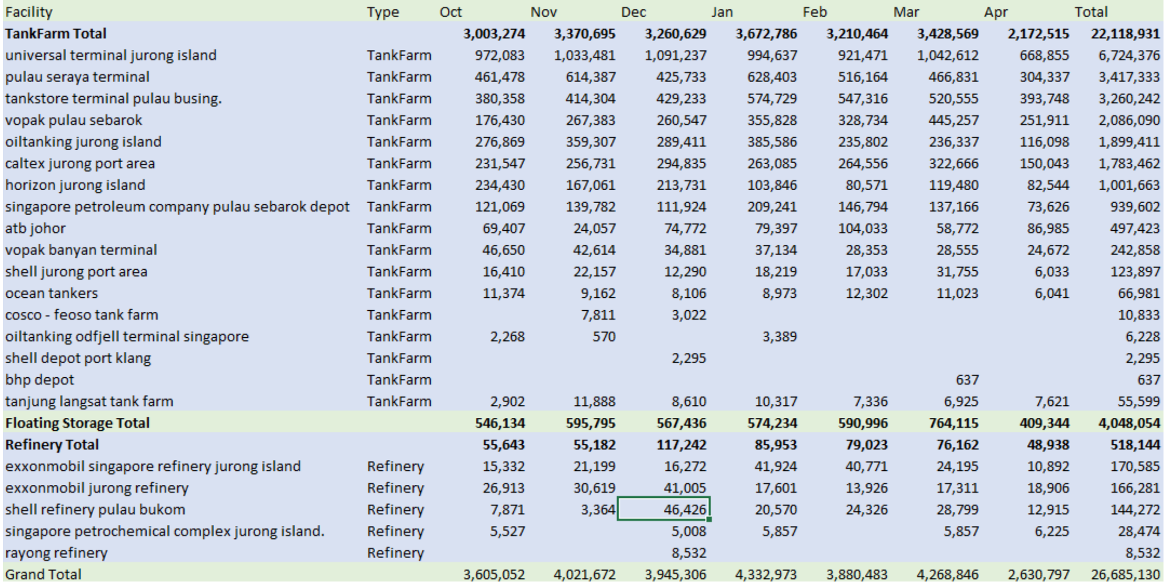
Bunkering History & Routing Distance Predicts Bunkering in Malta 27/28 Nov.

Fig.5: BunkerPeriscope predicts when vessels will need bunkering



Start time	End time	Duration(h:m)	Facility Type	Facility	Estimated Load	Actual Load
10/1/2016 6:15	10/1/2016 19:15	13:00	FacilityCategory(14,TankFarm)	tankstore terminal pulau busing.	7,367	6,392.9
10/3/2016 7:59	10/3/2016 21:14	13:15	FacilityCategory(14,TankFarm)	tankstore terminal pulau busing.	7,510	5,594.2
10/7/2016 5:29	10/7/2016 18:59	13:30	FacilityCategory(14,TankFarm)	tankstore terminal pulau busing.	7,650	6,372.4
10/10/2016 0:44	10/10/2016 16:00	15:16	FacilityCategory(14,TankFarm)	tankstore terminal pulau busing.	7,650	7,051.0
10/13/2016 13:15	10/14/2016 1:29	12:14	FacilityCategory(14,TankFarm)	universal terminal jurong island	6,934	4,064.0
10/15/2016 19:44	10/16/2016 7:14	11:30	FacilityCategory(14,TankFarm)	universal terminal jurong island	6,518	5,000.2
10/19/2016 15:28	10/20/2016 4:14	12:45	FacilityCategory(14,TankFarm)	universal terminal jurong island	7,231	4,289.7
10/21/2016 12:45	10/21/2016 23:30	10:44	FacilityCategory(14,TankFarm)	universal terminal jurong island	6,091	3,900.1
10/22/2016 13:15	10/22/2016 23:28	10:13	FacilityCategory(14,TankFarm)	universal terminal jurong island	5,791	3,489.7
10/25/2016 3:58	10/25/2016 16:59	13:00	FacilityCategory(14,TankFarm)	vopak pulau sebarok	7,374	5,499.9
10/29/2016 18:59	10/30/2016 7:15	12:15	FacilityCategory(14,TankFarm)	universal terminal jurong island	6,947	3,889.6
11/5/2016 4:10	11/5/2016 19:14	15:03	FacilityCategory(14,TankFarm)	tankstore terminal pulau busing.	7,650	6,745.2
11/8/2016 11:43	11/9/2016 2:29	14:45	FacilityCategory(14,TankFarm)	caltex jurong port area	8,364	6,731.3
11/12/2016 0:13	11/12/2016 12:30	12:17	FacilityCategory(14,TankFarm)	tankstore terminal pulau busing.	6,961	7,029.0
11/17/2016 5:43	11/17/2016 16:29	10:45	FacilityCategory(14,TankFarm)	universal terminal jurong island	6,096	4,290.2
11/21/2016 6:44	11/21/2016 22:13	15:28	FacilityCategory(14,TankFarm)	cosco - feoso tank farm	7,650	6,567.6
11/22/2016 23:15	11/24/2016 3:44	4:29	FacilityCategory(14,TankFarm)	tankstore terminal pulau busing.	7,650	6,096.9
11/27/2016 3:39	11/27/2016 17:25	13:45	FacilityCategory(14,TankFarm)	tankstore terminal pulau busing.	7,797	7,099.6
11/28/2016 12:55	11/28/2016 21:10	8:14	FacilityCategory(14,TankFarm)	universal terminal jurong island	4,669	2,492.1
11/30/2016 4:25	11/30/2016 17:40	13:15	FacilityCategory(14,TankFarm)	universal terminal jurong island	7,508	7,010.1

Fig.6: BunkerPeriscope using AIS data to forecast bunker demand



Facility	Type	Oct	Nov	Dec	Jan	Feb	Mar	Apr	Total
TankFarm Total		**3,003,274**	**3,370,695**	**3,260,629**	**3,672,786**	**3,210,464**	**3,428,569**	**2,172,515**	**22,118,931**
universal terminal jurong island	TankFarm	972,083	1,033,481	1,091,237	994,637	921,471	1,042,612	668,855	6,724,376
pulau seraya terminal	TankFarm	461,478	614,387	425,733	628,403	516,164	466,831	304,337	3,417,333
tankstore terminal pulau busing.	TankFarm	380,358	414,304	429,233	574,729	547,316	520,555	393,748	3,260,242
vopak pulau sebarok	TankFarm	176,430	267,383	260,547	355,828	328,734	445,257	251,911	2,086,090
oiltanking jurong island	TankFarm	276,869	359,307	289,411	385,586	235,802	236,337	116,098	1,899,411
caltex jurong port area	TankFarm	231,547	256,731	294,835	263,085	264,556	322,666	150,043	1,783,462
horizon jurong island	TankFarm	234,430	167,061	213,731	103,846	80,571	119,480	82,544	1,001,663
singapore petroleum company pulau sebarok depot	TankFarm	121,069	139,782	111,924	209,241	146,794	137,166	73,626	939,602
atb johor	TankFarm	69,407	24,057	74,772	79,397	104,033	58,772	86,985	497,423
vopak banyan terminal	TankFarm	46,650	42,614	34,881	37,134	28,353	28,555	24,672	242,858
shell jurong port area	TankFarm	16,410	22,157	12,290	18,219	17,033	31,755	6,033	123,897
ocean tankers	TankFarm	11,374	9,162	8,106	8,973	12,302	11,023	6,041	66,981
cosco - feoso tank farm	TankFarm		7,811	3,022					10,833
oiltanking odfjell terminal singapore	TankFarm	2,268	570		3,389				6,228
shell depot port klang	TankFarm			2,295					2,295
bhp depot	TankFarm						637		637
tanjung langsat tank farm	TankFarm	2,902	11,888	8,610	10,317	7,336	6,925	7,621	55,599
Floating Storage Total		**546,134**	**595,795**	**567,436**	**574,234**	**590,996**	**764,115**	**409,344**	**4,048,054**
Refinery Total		**55,643**	**55,182**	**117,242**	**85,953**	**79,023**	**76,162**	**48,938**	**518,144**
exxonmobil singapore refinery jurong island	Refinery	15,332	21,199	16,272	41,924	40,771	24,195	10,892	170,585
exxonmobil jurong refinery	Refinery	26,913	30,619	41,005	17,601	13,926	17,311	18,906	166,281
shell refinery pulau bukom	Refinery	7,871	3,364	46,426	20,570	24,326	28,799	12,915	144,272
singapore petrochemical complex jurong island.	Refinery	5,527		5,008	5,857		5,857	6,225	28,474
rayong refinery	Refinery			8,532					8,532
Grand Total		3,605,052	4,021,672	3,945,306	4,332,973	3,880,483	4,268,846	2,630,797	26,685,130

Fig.7: Monitoring Bunker Tanker Loadings in Detail (Loading monitored by facility type)

The tool has a feature for predicting bunkering demand based on vessels known to be on route to a bunkering hub, with a moving window of accuracy as schedules become known, Fig.8.

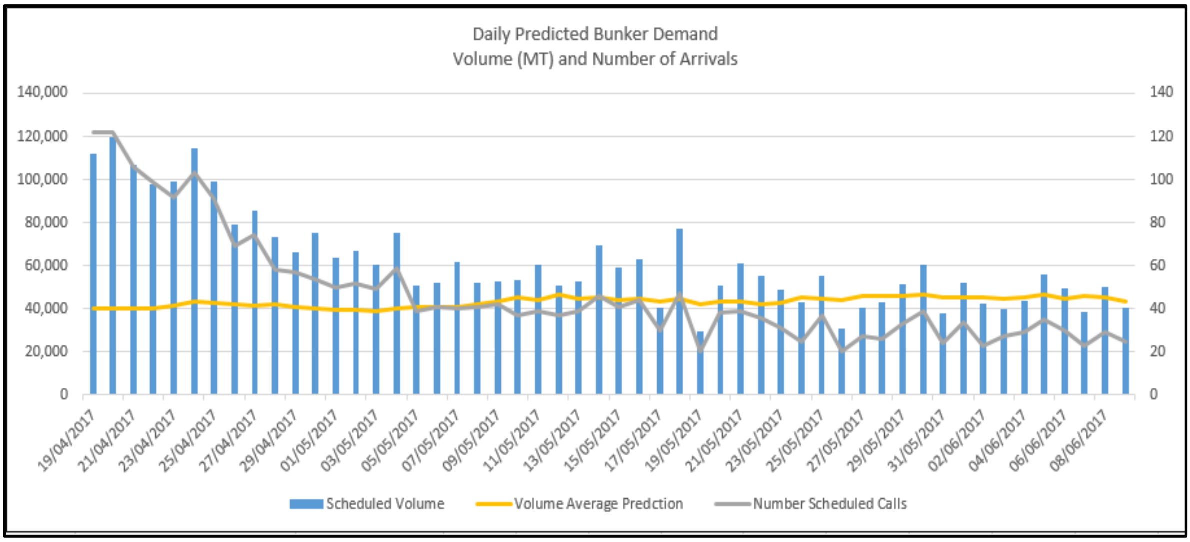


Fig.8: Predicting approaching Ships likely to need bunkering

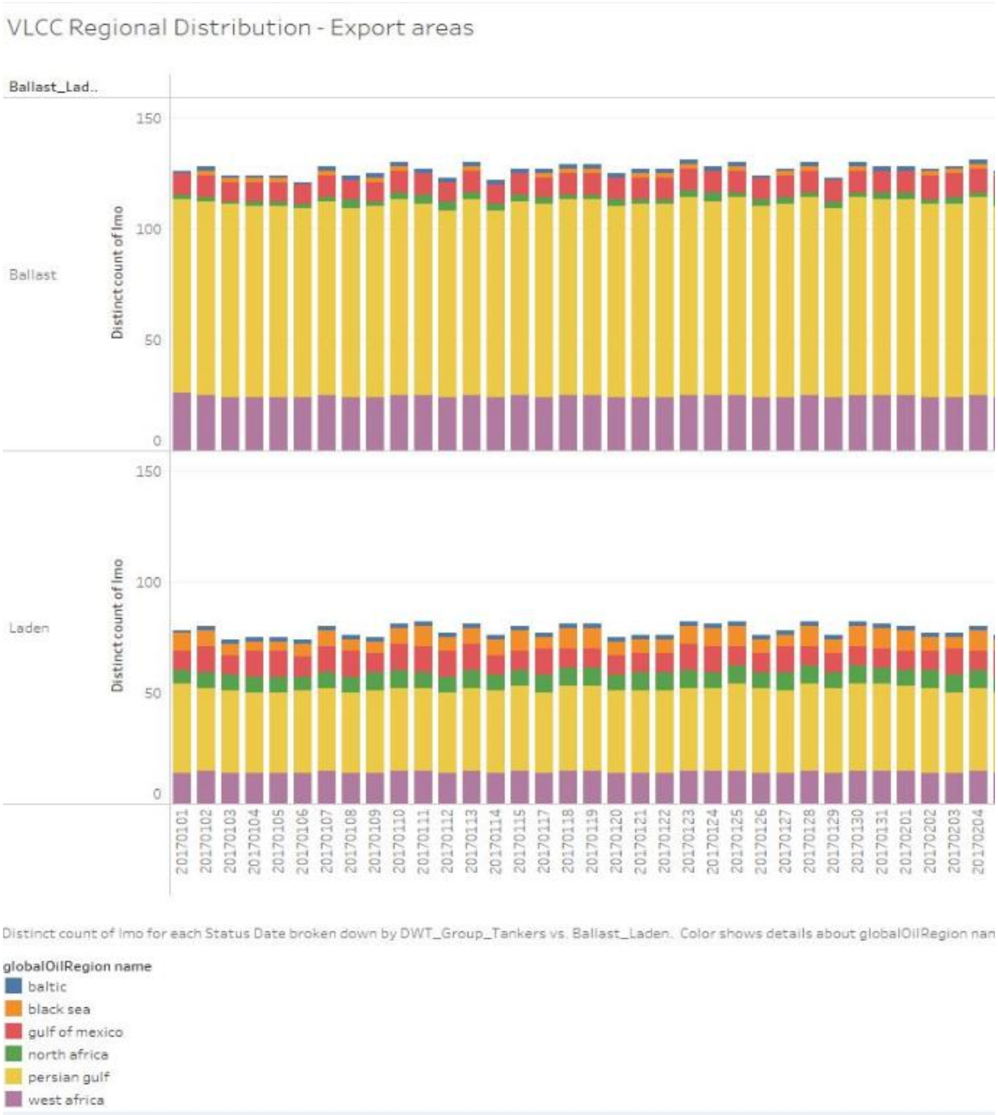


Fig.9: Summary of VLCC in Oil Export regions

4. Ship Status Events

The events engine builds up a detailed minute by minute history of all information and can provide a current status covering all areas of ship activity at any specified time. This can be used to query current status across multiple types of data not previously viewed together and also to take an aggregation of this information across global or specific market regions and produce analysis of fleet activity, distribution and deployment trends, Fig.9.

5. Summary

This approach to building business intelligence and market insight using all sets of available maritime information for tracking, ships, companies, and facilities is proving highly valuable to the bunkering sector.

All event engine based data sets are available through API services for integration to corporate information systems.

Genscape believes that equal value can be created for other sectors of the maritime world, varying from service providers such as tug companies, fleet operators, and bunker buyers.

Genscape also sees opportunities for port and national authorities to monitor maritime activity at a detailed level, both for planning purposes and compliance checks.

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Venue: The conference will be held at the Castello di Pavone in Pavone (near Turin/Italy)

Format: Papers to the above topics are invited and will be selected by a committee.

Deadlines:

anytime	Optional “early warning” of intent to submit paper
19.12.2017	First round of abstract selection (1/3 of available slots)
20.1.2018	**Final round of abstract selection** (remaining 2/3 of slots)
25.3.2018	Payment due for authors
25.3.2018	Final papers due (50 € surcharge for late submission)

Fees:

600 € / 300 €	regular / PhD student – early registration (by 25.3.2017)
700 € / 350 €	regular / PhD student – late registration

Fees are subject to VAT (reverse charge mechanism in Europe)
Fees include proceedings, lunches, coffee breaks and conference dinner

Sponsors: Aveva, DNV GL, Sener, SSI (further sponsors to be announced)

Information: www.compit.info