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Rami Zghyer

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Doctoral thesis

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Norwegian University of Science and Technology
Thesis for the Degree of
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Department of Ocean Operations and Civil
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ISBN 978-82-326-5946-3 (printed ver.)
ISBN 978-82-326-5441-3 (electronic ver.)
ISSN 1503-8181 (printed ver.)
ISSN 2703-8084 (online ver.)

Doctoral theses at NTNU, 2023:23

Printed by NTNU Grafisk senter

NORWEGIAN UNIVERSITY OF SCIENCE AND TECHNOLOGY

DOCTORAL THESIS

The Role of Ship Simulators and Maneuvering Models in Maritime Operations

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A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

in the

National Joint PhD Programme in Nautical Operations

and the

Department of Ocean Operations and Civil Engineering

April 6, 2022

Declaration of Authorship

I, Rami ZGHYER, declare that this thesis titled, "The Role of Ship Simulators and Maneuvering Models in Maritime Operations" and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed:

Date:

"If you want something you've never had,
you must be willing to do something you've never done."

— Thomas Jefferson

NORWEGIAN UNIVERSITY OF SCIENCE AND TECHNOLOGY

Abstract

Faculty of Engineering

Department of Ocean Operations and Civil Engineering

Doctor of Philosophy

The Role of Ship Simulators and Maneuvering Models in Maritime Operations

by Rami ZGHYER

The concept of autonomy in the maritime domain is attractive from both the safety and efficiency points of view, as in other transportation domains. To investigate the payoffs of autonomy as automation levels increase on a ship's bridge, a literature review is presented. The concept hence is broken-down into two sides: the technology and human operator side. The technology side is limited to hydrodynamics, Guidance, Navigation, and Control (GNC). The operator side is limited to experiences by ship and airplane operators facing increased automation in their workplaces.

The literature review is distilled into the main functional challenges to be confronted in the pursuit of maritime autonomy. First, the uncertainties stemming from ship dynamics and environmental loads largely affect the performance of GNC technologies. Second, the alteration of human-machine interaction as automation increases introduces new sources of error. Human operators face serious challenges dealing with highly automated systems. The following were concluded:

- The accuracy of ship maneuvering models in calm waters and operational conditions is crucial for the advancements of maritime autonomy,
- The focus on remote control and the capabilities of remote operators rather than full autonomy and the capabilities of machines,
- The use of ship simulators for enabling research in both maneuvering models and remote control of ships.

The application of ship simulators and accuracy of ship dynamics therein merited further investigation. A comprehensive study to learn about ship simulators and their application in research and industry was conducted. This study includes a literature review, interviews, and a case study with the Norwegian Coastal Administration to identify the role of maritime simulators. Ship simulators are no longer merely used for the purpose of nautical education and training. The trends show an expanding scope of ship simulator applications. For example, they are used in the development and testing of autonomous ship controllers, underwater operations planning, and pilot recruitment.

Simulators must demonstrate an appropriate level of physical, behavioral, functional, and visual realism to achieve satisfactory suitability according to application objectives. Physical realism pertains to hardware and furniture settings that are comparable to the bridge of a real ship. behavioral realism is limited to the behavior of bridge equipment. Functional realism is concerned with the physics of a moving ship in water, whereas visual realism focuses on the resolution, size, and shape of the displays and content within. The standard for Maritime Simulator System (DNVGL-ST-0033) provides appropriate levels of physics and behavior realism, but does not recognize simulator applications other than for education and training. Moreover, the standard does not require objective assessments of ship dynamics, as in the flight simulation standard (CS-FSTD).

Thus, a minimum accuracy requirement is proposed to identify the level of functional fidelity in a simulator. In accuracy requirement level 1 (ARL 1) the ship 'feels realistic' while it maneuvers. In ARL 2, the ship maneuvers accurately in calm water. In ARL 3, the ship maneuvers accurately in operational conditions. Every application, based on its objectives, holds a minimum ARL. For example, a simulator training of nautical students requires ARL 1, however, a simulator training of experienced professionals requires a higher accuracy level.

Maneuvering models are essential for the functional realism of a simulator. They are also used in modern ship navigation systems as an additional input that can predict current and future ship states. The ever-growing scope of simulator applications raises questions about the accuracy and accessibility of maneuvering models. Maneuvering in calm water has been long investigated; this thesis uses the existing maneuverability standards of the International Maritime Organization (IMO) in calm water and extends them to investigate maneuvering in waves. Specifically, the author is addressing the accuracy of different maneuvering models and their suitability for various applications. The 355 meter-long Duisburg Test Case (DTC) benchmarking containership is considered herein for this study.

This study evaluates the accuracy of two different maneuvering models using an objective assessment. The first maneuvering model belongs to an industry-standard simulation provider. The second is a novel research simulation tool recently developed by the Marine Technology Department of the Norwegian University of Science and Technology (NTNU). Both models are compared against experiments performed earlier (in 2018 and 2019) in the Sintef Ocean Basin in Trondheim, Norway. The results show the differences between simulators and experiments in both calm water and several wave conditions. Results show that both simulators perform well in calm water, however, they perform differently in waves. The novel model compares more adequately to experiments in waves, appreciating the impact of waves on ship speed while maneuvering and turning.

In summary, this study provides an overview on the functional challenges in autonomous vessels from both the technological and the operator's perspectives. It also provides a comprehensive overview on ship simulator applications and their role in maritime autonomy. It introduces the accuracy concern and thus proposes a minimum accuracy level standard, the ARL. The ARL standard is an objective measure that identifies the functional realism of a simulator. Based on the application, a simulator with a known ARL is either deemed compliant or non-compliant. Finally, this study objectively evaluates the accuracy of two different maneuvering codes and discusses their suitability for various applications.

Acknowledgements

I would like to thank my supervisors, Associate Prof. Runar Ostnes and Associate Prof. Karl Henning Halse. Without them, this work would still be floating in the realm of my imagination.

I would like to thank my collaborators from the Department of Marine Technology at NTNU for the good work we have done together, and for sharing their experimental data of the Sintef Ocean Basin free-running model tests.

I would like to thank the rest of my collaborators from the simulator centers and interviewees for giving your time for this project. Thank you all.

I would like to thank my colleagues for their support, and the priceless moments we spent together throughout this journey.

I would like to thank my students, from whose energy I got charged, and from whose curiosity I learned a lot.

Finally, I would like to thank my dear family. I understand, what you've been through was challenging. Kudos to you!

Preface

This is a PhD within Nautical Studies. The vacancy was advertised by the Department of Ocean Operations and Civil Engineering. The position is funded by Markom2020 and is part of the joint PhD program in Nautical Operations. The workplace is at NTNU, Ålesund campus, the Shipping and Nautical group.

The author of this research is a Mechanical Engineer with an interest in offshore operations. After finishing his bachelor's degree in mechanical engineering, he pursued two master's degrees in energy engineering (with a focus on offshore gas fields) and offshore technology (with a focus on environmental loads on offshore structures).

This vacancy sparked the interest of the candidate because it was advertised as an open PhD position related to the "*Maneuvering of a semi-autonomous vessel close to a wall or two ships in close proximity - (a nautical challenge)*". The advertised position consisted of elements such as offshore operations, autonomous ship technology, operator interface, and simulator tests, which initially piqued the interest of the author.

The author, with his pure engineering background, thought that the research would take a technical path and be dominated by the testing of advanced navigation algorithms in simulators. However, as the "nautical operations" research started, and as the author learned more about the functional challenges of autonomy from both the technology and human operator sides, the research took a different path. The author appreciated the knowledge gathered along the way.

An example of values and their evolution during the research is how the author previously thought that autonomous vessels held the solutions to the safety and efficiency challenges and that the main barrier for realizing them was merely a technological one. However, the author has learned to appreciate the barriers from many other perspectives such as human factors, infrastructure, guidelines, and cybersecurity.

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List of Abbreviations

AIS	**A**utomatic **I**dentification **S**ystem
ARL	**A**ccuracy **R**equirement **L**evel
BRM	**B**ridge **R**esource **M**anagement
COG	**C**enter **o**f **G**ravity
COLREG	Convention on the International **REG**ulations for Preventing **COL**lisions at Sea
CW	**C**alm **W**ater
DOF	**D**egree(s) **o**f **F**reedom
DNV	**D**et **N**orske **V**eritas
DP	**D**ynamic **P**ositioning
DSS	**D**ecision **S**upport **S**ystem
DTC	**D**uisburg **T**est **C**ase
ECDIS	**E**lectronic **C**hart **D**isplay and **I**nformation **S**ystem
GMA	**G**eneral **M**ental **A**bility
HCD	**H**uman-**C**entered **D**esign
HCI	**H**uman-**C**omputer **I**nteraction
IMO	**I**nternational **M**aritime **O**rganization
KPI	**K**ey **P**erformance **I**ndicator
LOA	**L**evels **o**f **A**utomation
LNG	**L**iquefied **N**atural **G**as
LPG	**L**iquefied **P**etroleum **G**as
MASS	**M**arine **A**utonomous **S**urface **S**hips
MMG	**M**athematical **M**odel **G**roup (modular models)
MSC	**M**aritime **S**afety **C**ommittee
NCA	**N**orwegian **C**oastal **A**dministration
NCA PS	**N**orwegian **C**oastal **A**dministration **P**ilot **S**ervice
NFAS	**N**orwegian **F**orum for **A**utonomous **S**hips
NTNU	Norwegian University of Science and Technology
RPS	**R**evolution **P**er **S**econd
SME	**S**ubject **M**atter **E**xpert
STCW	**S**tandards of **T**raining, **C**ertification, and **W**atchkeeping
TRL	**T**echnology **R**eadiness **L**evel(s)
VHF	**V**ery **H**igh **F**requency
VR	**V**irtual **R**eality
VTS	**V**essel **T**raffic **S**ervices
WSM	**W**hole **S**hip (regression) **M**odel(s)

List of Definitions

Definitions of the main terms used in this thesis are listed alphabetically as follows:

Automation: The use of (GNC) technology for the control of machines. Automation is a state that can be described by the "levels of automation" hierarchy.

Autonomous ships: Ships that are designed and verified, under certain conditions, to be controlled partially or fully by automation, along with human monitoring, supervision and intervention.

Autonomy: The process towards increasing automation and reducing overall human presence.

behavioral realism: To what degree the simulator resembles real equipment in order to allow a learner to exhibit the appropriate skills. The realism shall include capabilities, limitations and possible errors of such equipment (DNVGL-ST-0033, 2017).

Broaching: The loss of stability while sailing in following seas where the kinetic energy of the ship along the forward axis transfers to roll motion and leads to strong heel, loss of heading, and even capsize.

Following sea: Incident waves moving in the same direction as the ship heading (coming from behind).

Functional fidelity: Functional fidelity is a simulator quality that considers the accuracy of ship dynamics in water.

Guidance, navigation, and control (GNC): The well-established term in control engineering where guidance is the system responsible for trajectory planning, collision avoidance, and conforming to protocol. Navigation is the system responsible for estimating own state (i.e. position and velocity), external situation (i.e. wave forces and water depth), and obstacle state. Control is the system responsible for translation of guidance into actuator instructions.

Head sea: Incident waves moving in the opposite direction of the ship heading (waves are coming against ship nose).

Hull fouling: The accumulation of marine growth, resulting in reduced vessel speed, increased bunker consumption and the accrual of cleaning costs.

Human factors: Reflections from human operators as more automation is introduced to their operations.

Hydrodynamics: In this thesis, the term hydrodynamics is limited to methods that describe the motions and responses of a ship moving in water using maneuvering and seakeeping theories in real time.

Learning (as a simulator application): Learning describes the use of simulators to understand the process of knowledge transfer (and skill transfer as well). This includes education science, the actions that contribute to learning, including the role of the instructor in briefing, debriefing, and/or during the exercise.

Maneuvering characteristics: Results from maneuvering trials are either test specific characteristics or general characteristics. The zigzag characteristics are: overshoot angles (first and second); and reach (distance and time). The turning circle characteristics are: tactical diameter, advance, and transfer. The general characteristics are position timeseries, velocity timeseries, and average speed.

Maneuvering models: Or also called in this context: Hydrodynamic models. Numerical codes used in simulators that solve ship motion in the time domain, in real-time, or faster, considering maneuvering theory, seakeeping theory, control inputs, environment loads and other physical phenomena.

Maneuvering performance: In this context holds the same meaning as "ship behavior", "maneuverability" and "maneuvering capability".

Maneuvering theory: Maneuvering is the study concerning a ship advancing or turning in calm water at constant speed. The in-plane motions: surge, sway and yaw are usually the main focus. In the maneuvering problem no wave excitations are taken into account and the radiation-induced forces are assumed frequency-independent.

Maneuvering trials: Such as zigzags and turning circles. They can be in the form of simulations (virtual trials) or experiments (physical trials, also referred to as free-running model tests).

Model-scale trials: Scaled model tests. These are trials performed using a model-scale ship in a large water tank/basin prepared as a laboratory for such experiments.

Objective testing: A quantitative assessment based on comparison with validation data.

Physical realism: To what degree the simulator looks and feels like real equipment. The realism shall include capabilities, limitations, and possible errors of such equipment (DNVGL-ST-0033, 2017).

Sea trials: Full-scale trials, but the term trials can be used to address virtual trials as well.

Seakeeping theory: Seakeeping is the study concerning a ship oscillating in waves at straight course, either at zero speed (the trivial case of station-keeping) or at constant speed. Wave excitations, frequency dependence, and memory effects are important considerations while usually, the vertical plane motions, heave, pitch and roll are the main focus in the seakeeping problem.

Standard maneuvers: The maneuvering trials described in the IMO standard for ship maneuverability are zigzag tests, turning circles, and crash stop tests (MSC.137(76), 2002).

Subjective testing: The evaluation by giving an opinion of an experienced officer based on relevant previous experience.

Training (as a simulator application): Training describes the use of a simulator for nautical students and experienced professionals to enhance some of their relevant skills.

Virtual trials: Simulations. In other words, they are computer predictions using mathematical models.

Visual fidelity: To what degree the simulator displays look and feel real. This is the part of physical realism concerned with the resolution, size, and shape of the displays and the content within.

To my family
who keep bearing with me and
supporting me throughout my endeavours

Chapter 1

Introduction

1.1 The Dream

I started my PhD fellowship in October 2017, the term "autonomous vehicles" was at the peak of inflated expectations according to the Gartner's Hype Cycle, but not anymore. Expectations of the capabilities of full autonomy in the maritime industry were exaggerated. For example the Maritime Unmanned Navigation through Intelligence in Networks (MUNIN) project, was a EUR 2.9 million collaborative EU-funded research project in maritime autonomous systems. The project aimed to develop a technical concept for an autonomous dry bulk carrier and assess its technical, economic, and legal feasibility. The project was based on the belief that unmanned and autonomous vessels can contribute to the goal of a more sustainable European maritime transportation industry, as they have the potential to: (1) reduce operational expenses, (2) reduce environmental impact, and (3) attract seagoing professionals.

The potential benefits of unmanned and autonomous shipping are enormous in both safety and efficiency. Also, since they are expected to have no crew at all, or at least, a reduced crew, then hotel loads are expected to be reduced, hence slow streaming becomes feasible. The power-speed relationship in ships is often described as $P \approx V^3$ hence, slow streaming is capable of achieving considerable fuel savings.

Unmanned and autonomous ships would be greener, because there will be no need for accommodation superstructures, and the ship is expected to be lighter and exposed to less air resistance. Electrification and smart routing technologies are developing in parallel with unmanned and autonomous ships aiming to reduce fuel consumption, reduce emissions, reduce environmental loads, and enhance energy efficiency.

Advanced navigation and collision avoidance systems are expected to provide significant safety benefits, mainly because they are designed to adhere to the rules of the way at sea (COLREG) and because these systems are free from the widely-used-cause of accidents, human error. The absence of crew onboard is perceived as a safety game changer by keeping human lives away from exposure to the weather, that can get rough sometimes.

Another project is *The Advanced Autonomous Waterborne Applications (AAWA)*, a EUR 6.6 million collaborative project, funded by Tekes (The Finnish Funding Agency for Technology and Innovation). The project aims to develop concepts for the next generation of advanced ship solutions considering technology, safety, legal, and economical aspects of remote and autonomous operations.

AAWA's initial conclusions included that the technologies needed to make autonomous ships a reality exist. The challenge is to find the optimal way to combine them reliably and cost effectively. In addition, remote and autonomous operations must be at least as safe as existing vessels. There is a potential of reducing human-based errors but new risks would emerge.

Yara Birkeland is the world's first fully electric and autonomous vessel with zero emissions. It is a 120 TEU container ship that is fully battery powered and prepared for autonomous and unmanned operation. It was planned to start operation in the second half of 2018. The aim of Yara Birkeland is to reduce diesel-powered truck haulage by 40,000 journeys per year, resulting in the reduction of exhaust emissions and improved road safety. Kongsberg is responsible for the technology development and Massterly, a joint venture between Kongsberg and Wilhemsen, operates the vessel from their monitoring and operation center in Horten.

NFAS, the Norwegian Forum for Autonomous Ships, was established in late 2016. The premise of NFAS is that unmanned ships will be an important part of the international transport system in the future. The emphasis on unmanned ships is based on the possibilities that fully unmanned ships offer, such as improved working conditions, lower damage-related cost, reduced crew costs, slow streaming, lower structural costs, new ship designs, and better environmental performance. Many of these possibilities resonate with the MUNIN's project expectations.

In 2017, the Maritime Safety Committee (MSC) of the International Maritime Organisation (IMO) included the issue of marine autonomous surface ships (MASS) on its agenda. IMO has a strategic goal of integrating new and advancing technologies in the regulatory framework.

1.2 The Challenge

With great power comes great responsibility. Although unmanned and autonomous ships would solve many of the safety and efficiency challenges in shipping, they would create new risks of their own. According to the MUNIN project, the limitations include the fact that fully autonomous ships, independent of a shore control center, are not cost-effective today. In addition, unmanned ships will need technical and operational infrastructure at ports and shore control centers. Also, unmanned ships need to be designed from scratch, the MUNIN reported, as retrofits are not a viable option.

The AAWA initiative stated that despite all the recent technological advancements in car navigation, a conclusive demonstration of a sufficiently reliable autonomous car in varying real-world conditions has not yet been presented. Solutions still struggle with unknown environments and unexpected events, thus requiring human intervention occasionally.

In the safety section (Section 4.2) of the AAWA's report, some human factor issues were introduced in remote operations and monitoring, including: weakened ship sense, information overload, mishaps during changeovers and handoffs, need for automation awareness, skill degradation, latency, cognitive horizon, boredom, and vigilance maintenance.

The COLREG rules and their translation to algorithms is another challenge, because some of the rules therein are subjective, mentioning terms such as "safe speed" that are case-specific and require experienced operators to interpret properly. In addition, in some situations, the COLREG rules are violated on purpose by operators to enhance the safety at specific circumstances of the trip, or even to make it possible at all. For example, two car ferries are crossing the fjord while a cruise ship is passing along. The two ferries would give way and cross to the stern of the cruise ship (one turns to the starboard side - conforming with the COLREG - and the other turns to the port side - non-conforming). Therefore, COLREG is not carved in stone, and it is challenging to quantify it in a way that is processed by machines as it is by human operators.

Other kinds of challenges are involved in autonomous shipping such as cybersecurity, economical and political. In this thesis however, the main concerns are ship dynamics under operational conditions and operator experiences as automation increases.

1.3 The Contribution

This study explores some of the main functional challenges inevitable in the pursuit of autonomous ships. This study focuses further on ship simulators, answering questions about the opportunities and challenges of their use and reviewing their applications for the past twelve years.

Such an overview of simulator applications raises an alarm regarding the accuracy of ship dynamics in simulators. Pointing to the question: "Are simulators fit-for-purpose?". This study compares the standards of maritime simulators with flight simulators and finds a serious missing requirement, in the maritime simulators, that is crucial to suitability of simulators to some applications.

This study proposes an accuracy (of ship dynamics) requirement level (ARL) standard that serves two goals: (1) ship specific, which defines the accuracy level of a simulator's ship model and (2) application specific, which defines the accuracy requirement level of an application. In addition, this study classifies the presented simulator applications with expected accuracy requirement levels and performs an objective evaluation of accuracy for two different simulators. Simulator maneuvering trials are compared to a recent benchmark. The benchmark consists of a number of basin free-running model tests performed in the Sintef Ocean Basin in Trondheim, Norway.

1.3.1 Scientific

The major contribution of this study to science is:

- Providing an overview of simulator applications using multiple data collection methods.
- Finding the "objective testing" gap in the maritime simulator standards in contrast with the airplane simulator standards.
- Providing insight into the maneuverability of the DTC containership in calm water and waves.
- Providing an example of "objective testing" for the accuracy of ship dynamics in simulators.

- Proposing the ARL classification standard that addresses the functional fidelity concern.
- Combining the ARL classification standard and the "objective testing" to alleviate the accuracy concern (a methodological contribution).

1.3.2 Industry

The main contribution of this study to the industry is:

- Demonstrating that the accuracy of ship dynamics in a simulator is a concern.
- Introducing ARLs for simulators and their applications. ARLs can help users in matching functional fidelity with application requirements to ensure suitability.

1.3.3 Society

This study does not directly impact society, however, it does indirectly contribute to safety in the sea. Simulators, whether used for training students or experienced navigators, for the design of a hull or a decision support system, all need to be subjected to scrutiny. The typical approach of "is this good enough?" or "does it feel realistic?" does not seem sound enough to continue, especially because the range of applications of simulators is growing rapidly.

The functional resemblance of simulators to the real-world can mean better training and preparedness to face day-to-day operations. It can also mean better decision-making in system development and operations planning. This work is largely focused on the role of simulators in paving the way for safer advanced ship operations and the suitability of simulators given limitations in ship dynamics.

The thesis is structured as follows: The next chapter is a research design chapter. It is followed by three content chapters on maritime autonomy, maritime simulators, and maneuvering models. Discussion and conclusions follow. Then comes the appendices that include a document on a maritime simulator background (in terms of physical modeling) and article attachments.

Chapter 2

Research Design

2.1 Philosophical Worldview

Worldview means "a basic set of beliefs that guide action." In this research, the postpositivist worldview is adopted: pursuing objective truth while acknowledging the effects of one's own biases on observations, interpretations and conclusions.

Biases resulting from the author's own values, background knowledge, and previous experiences are minimized using multiple strategies such as being continuously aware of potential biases, implementing mixed methods for data collection, and being active in scientific/industry-related events.

Even though one's own biases are minimized, they probably still have a considerable effect on the path and outcome of the research, therefore the author's own biases are made as transparent as possible in the Preface and in the Research Strategy sections.

The cornerstones of the philosophical postpositivist worldview are as follows:

1. Knowledge is conjectural. One can never find absolute truth. Established evidence in research can always be fallible.
2. Data, evidence, and rational considerations shape knowledge.
3. Methods and conclusions shall be examined for bias. Objectivity is essential.

The author believes in dual realities: an absolute reality and a relative reality. The absolute reality is one that exists independent of the mind. The relative reality however, is one that exists within the mind. Therefore, the ontological stance of the author is mainly dominated by realism, and flavored with a pinch of idealism. Meaning that the reality about the physical world and its digital counterpart, represented by mathematical models, exists independent of the mind. Whereas, human experiences and the knowledge borne therein, are strongly mind-dependent. Therefore, both the rationalism and empiricism epistemological views are adopted throughout this research. The former view inspired qualitative methods such as literature reviews and interviews, and the latter inspired experiments and simulations.

2.1.1 Pre-Assumptions

A priori assumptions of the author can be summarized in the following list. These assumptions were put under scrutiny and were severely challenged during the course of the author's work.

- Full-autonomy holds great potential for enhancing safety and efficiency in the maritime industry.

- Control is the main problem. Autonomous ships' main development challenge is merely a collision detection and avoidance problem.
- Hydrodynamic modelling of a ship moving on the surface of the water never occurred to the author as a crucial issue.

2.2 Methodology

2.2.1 Research Strategy

"A telescopic" research strategy was adopted herein with three cascading hypotheses (three levels), one giving birth to the next, starting with a broad scope and narrowing it down as the research progresses. The hypotheses guided the formulation of the research questions, and each hypothesis was investigated for failures. The three hypotheses are:

1. Full-autonomy is the way to go for maximizing the oceans potential.
2. Simulators are suitable laboratories for testing advanced ship technologies.
3. The accuracy of ship dynamics in simulators is 'good enough' for its applications.

Three research questions are inspired from the above hypotheses. Mixed research methods were selected to address the questions and provide adequate knowledge. The research questions and methods are described in the next sections.

2.2.2 Research Questions

On the paradoxes of the pursuit of maritime autonomy: how autonomous maneuvering technology is limited by the performance of human operators and real-time physics models?

The three research questions (RQ1, RQ2, and RQ3) are formulated as follows:

- RQ1: What are the main functional challenges in autonomous vessels?
  - What are the functional challenges from the technology side?
  - What are the functional challenges from the operator side?
- RQ2: How do maritime simulators contribute to shaping the future of maritime operations?
  - What are the opportunities and challenges in using simulators?
  - What are the applications of ship simulators?
- RQ3: How can the accuracy of maneuvering models and their suitability in simulators for various applications be addressed?

2.2.3 Methods

Both deduction and induction approaches are used for acquiring knowledge. Starting with the deduction mindset for learning from the body of knowledge that already exists and finding knowledge gaps, then switching to induction for observing specific variables and creating new knowledge.

A number of methods were used to conduct this research. First, a literature review on *autonomous vessels* was conducted. The term *autonomous vessels* was reduced to the following fields: hydrodynamics, guidance, navigation, and control (GNC) together with the human factors field. This literature review was conducted with the intention of learning about autonomous vessels technologies, their impacts on human operators, the knowledge gaps, and challenges that lie within their pursuit.

Three methods were performed to answer the second research question (RQ2). The first method was another literature review. This literature review searched for simulator applications in research. It was followed by a second method, a campaign of interviews with researchers and industry professionals, asking them about their use of simulators, the opportunities they see, and challenges they experience using ship simulators. The interview campaign was followed by a case study. The case study demonstrated how the Norwegian Coastal Administration is using, and planning to use, simulator technologies for safer pilotage operations. Data for this case study was collected in a webinar specially designed for this purpose. The webinar was planned and hosted by the author of this research.

The last method consists of simulations. Standard maneuvers were performed in simulators with different maneuvering models compared with experimental data. The experiments presented herein were conducted as part of a different study, however, they represented an appropriate benchmark. Further details about the methods and their properties can be found in Section 2.3. Table 2.1 lists the methods used in this research and the research question each method is addressing.

TABLE 2.1: Data collection methods overview

Method number	Method name	Addressing
1.1	Literature Review - A	RQ 1
2.1	Literature Review - B	RQ 2
2.2	Interviews	RQ 2
2.3	Case Study	RQ 2
3.1	Simulations	RQ 3

2.3 Method Description

This thesis is a paper-based thesis. The research work of the methods listed in Table 2.1 is peer-reviewed and published (or soon to be published). The work is summarized in the various chapters of this thesis. The following table, Table 2.2, links the methods with publications and their corresponding chapters.

TABLE 2.2: Links among: Methods - Publications - Chapters

Method numbers	Publication	Chapter
1.1	Zghyer et al., 2019	Chapter 3
2.1; 2.2; 2.3	Zghyer and Ostnes, 2019 & Zghyer et al., 2022a	Chapter 4
3.1	Zghyer et al., 2022b	Chapter 5

2.3.1 Identifying challenges for autonomous vessels

Method 1.1: Literature Review - A

This literature review was done for multiple objectives. The primary objective was to find challenges in the pursuit of autonomous vessels that are both grounded and relevant, grounded in literature and relevant to current industry practices. In addition, the review defined and documented the starting point of the research. Primarily, the review provided the broad background knowledge necessary for motivating and guiding the rest of this study.

In order to research *autonomous vessels*, the author assumed that this term can be broken down to technology and human factors. The technology portion can be further reduced to hydrodynamics, guidance, navigation and control. This literature review is not based on a keyword search, instead, it is based on relevance to the fields of interest. Therefore, the search sources consisted of advanced university courses and scientific databases with no date limitations or other specific filters. The size of the selected sample of references included herein is 59 texts. Table 2.3 summarizes the properties of Literature Review A.

TABLE 2.3: Properties of Literature Review - A

Properties of Literature Review - A	
Keywords	Not based on keywords. Based on fields
Selection criteria	Hydrodynamics: Simulator-fit models
	GNC: University courses (MR8500, TK8109)
	Human factors: University course (MFA-8010)
Date span	No limits
Sources	University courses; Scientific databases
Filters	No filters
Sample size	59 texts

The courses helped the selection immensely, since they are specialized courses. The MFA-8010 Maritime HTOI (Human-Technology-Organisation-Innovation) course helped in the selection of the human factors literature. The MR8500 PhD Topics in Marine Control Systems and TK8109 Advanced Topics in Guidance and Navigation helped in the selection of the GNC literature. In the hydrodynamics field, the researcher's interests were limited to simulator-fit models, models that can describe maneuvering and seakeeping in real-time. Hence, this was the criteria for literature selection of the hydrodynamics portion.

2.3.2 Identifying the role of maritime simulators

Method 2.1: Literature Review - B

The second literature review was completed for a more specific goal. Primarily, it was conducted to answer the question, "what are ship simulators used for?" and also, for gaining insight into opportunities, challenges, and literature gaps associated with simulators and their use. Table 2.4 lists the properties of Literature Review B.

A literature search was undertaken in the search engine "Oria" at the NTNU. It provides a search of the university's printed and electronic collections of internationally renowned scientific databases. Only literature reporting the use of navigation simulators were selected.

TABLE 2.4: Properties of Literature Review - B

Properties of Literature Review - B	
Keywords	Ship simulator; bridge simulator; mission simulator
Selection criteria	Research involves use of ship simulator
Date span	12 years (2009 - 2021)
Sources	Among others: INSPEC, Scopus, ProQuest, WMU, TransNav
Material type	Articles, journals, and conference proceedings
Filters	Publications not involving simulator experiments were removed
Sample size	80 texts (selected)

Method 2.2: Interviews

Subject matter expert (SME) interviews were conducted to give a deeper insight into the applications, opportunities, and challenges associated with maritime simulators. They were designed as semi-structured interviews with open-ended questions. Simulation centers were found using an internet search. 35 centers were identified, and a shortlist of contacts was made. Interview invitations were sent out by email to the shortlisted centers and ten positive responses were received. Nine interviews were performed. Interviewees were made aware of the purpose of the interviews, and they signed electronic consent forms. All personal data was kept confidential and the results were kept anonymous. The duration of the interviews was half-an-hour on average for each. Interviews included an introduction about the interviewers and their motivation for conducting this research before beginning.

The interviewees had different backgrounds; seven of them were engineers and two had social science backgrounds. They were filling different roles such as managers, professionals, and researchers. At the time, the interviewees were geographically located as follows: 5 were in Norway, 2 in Sweden, 1 in the Netherlands, and 1 in Canada. All the interviewees referred to maritime simulators in their interviews, most of them (seven out of nine) referred to full mission navigation training simulators (Class A: full mission) and the rest referred to offshore operation simulators (Class S: special task). This classification is based on the Maritime Simulator System Standard DNVGL-ST-0033 (2017). The interviews focused on, and started with, the interviewees' work and experience, shaping an interviewee-centred context throughout the conversation.

An inductive coding method was used for analyzing the collected data. The interview questions were as follows:

1. Tell us about yourself and your field of interest.
2. What opportunities do you think simulators provide for research (or for the industry)?
3. What challenges did you face during using simulators for your research (or for your work)?

The inductive coding process was performed on two levels: the general themes, and the more specific items, nested under the themes. Responses were compared across all interviewees for each question. Similarities among the answers were identified and labeled for the general themes they addressed. Answers of the second questions for example were labeled with: “research and innovation facilitator” and “developing industry standards”. There were three labels identified for each question. The labels described the general themes and provided a rough description of the interview results. A higher level of detail was needed to portray the picture the interviewees painted, therefore, specific items where identified and coded. Every labeled theme was then described by several coded items. For example, in the second question (about opportunities), nested under the label “research and innovation facilitator” the following codes were given: “innovation facilitator”, “multidisciplinary”, and “proof of concept”. The codes are, in most cases, self-explanatory, and provide an additional level of detail to the description of the interview results. The coded items aid the labeled themes in describing the content of the interviews, and together, they provide an answer to usage, opportunities, and challenges.

Method 2.3: Case Study

The case study was conducted as a scientific collaboration with the Norwegian Coastal Administration Pilot Service (NCA PS). The main purpose was to gain a deeper insight on how simulators contribute to a vital industry such as shipping. The case study provided insight on multiple dimensions such as:

- The everyday life of a pilot,
- Examples of challenging operations,
- Recruitment and other simulation applications,
- R&D strategies of the NCA,

The data was collected in a webinar that was designed for the purpose of this study. The webinar was held on 19th January 2020 and was named "Learning from the Pilots". It was a three-hour long event. The design of the webinar included long question/answer (QA) sessions. In addition, participants, who were mainly students and researchers, were encouraged to ask other questions. The active participation in the QA sessions was modest therefore the collection of data was mainly passive. The data is summarized and presented in Chapter 4 supporting the research question RQ2.

2.3.3 Identifying the accuracy of maneuvering models

Method 3.1: Simulations

The main purpose of the simulations method was to evaluate objectively the accuracy of ship dynamics in a simulator. The concept of this method was to compare simulations against an appropriate benchmark. There are multiple kinds of mathematical modelling techniques used for simulating ships moving in the sea. Therefore, two different simulators, with different mathematical models, were used for this study. An industry-standard simulator (used in desktop setting for research purposes) and a novel research model have been used. To investigate ship dynamics in a simulator, the maneuverability standard of the IMO (MSC.137(76), 2002) was used as a reference on maneuverability and its evaluation.

It is worth mentioning that five simulators were used for the Simulations method. Three simulators were excluded, this thesis is hence presenting the results of only two. The reasons for excluding the three simulators are related to ship modeling as follows:

- The first simulator was excluded because the DTC ship model was not available. The author tried to model it himself using the available tools, however the result was not meaningful. A model of a very similar ship was made available after some searching, *Maersk Edinburgh* ship model, and zigzag and turning circle simulations were performed, but for methodological reasons, and mainly because it is not the same ship, then it was decided to discard this simulator.
- The second simulator was excluded mainly because the modeling work of the DTC did not reach completion. The collaborator was not able, due to other restriction, to follow up with the delivery of the model to the simulator. This simulator is more inclined towards offshore operations rather than navigation. Nevertheless, this collaboration produced articles on rapid virtual prototyping of the research vessel Gunnerus (Major et al., 2020, 2021).
- The third simulator consists of a combination between ShipX (Veres) and Matlab Simulink. The DTC hull geometry file is available in a formal compatible with ShipX. The MSS toolkit workflow was followed for generating a ship model compatible with the MSS maneuvering simulator in Simulink (Fossen, 2008). Simulations were performed but the results were not good enough to be included in this study. The investigation of "why the results are so?" lead to the following remarks. Due to the linearized model of the MSS Toolkit, when the rudder execute is implemented, the rudder induces a drag that will decelerate the ship, but since coupling terms are neglected, equilibrium in the surge equation is reached quickly. A turning circle is strongly non-linear, hence linearized models cannot be expected to perform satisfactorily. The MSS toolkit must be modified to provide an appropriate behavior. The nonlinear damping functions and the B11 element, which is missing from the 2D potential theory, must be calibrated. The toolkit uses a nonlinear crossflow drag function and an ITTC resistance curve in addition to the linear damper (potential plus viscous damping). This might be too much, hence damping must be calibrated and the resistance curve for the surge motion must be selected for the particular ship to provide a desired behavior. The MSS toolkit is typically used for design of control systems. It is a very simplified unified model that is based on a linearized equation system, with no coupling considerations between surge and sway-yaw. The MSS could be suitable for control design only, even for testing of control systems, the accuracy of the MSS is questionable.

The investigation of ship dynamics includes a multitude of variables such as sea state and metocean conditions (wave height, wave period, wind and current speeds and directions), water conditions (water depth, salinity, density, temperature, etc..), ship heading and relative direction to waves, winds and currents, ship characteristics (dimensions, hull geometry, hull surface roughness, loading condition, mass distribution, topside volumes and areas), and ship systems (propulsion and steering systems). The interdependence is a complex problem, therefore, limitations had to be made. In this study the following variables were taken into consideration and the rest were assumed to be constant:

- Calm water: calm water maneuvering trials for both simulations and experiments were performed to enable a baseline comparison.

- Waves: several irregular wave conditions were used in the maneuvering trials, in both simulations and experiments, to enable comparisons of maneuvering characteristics as wave height increases.
- Wave directions: two directions have been considered. Trials started with either initial head waves (where the ship was moving against the incoming waves) or initial following waves (where the ship was moving along the wave in the same direction) to enable the understanding of the effects of direction on maneuverability.

According to the maneuverability standard of the IMO (MSC.137(76), 2002), the maneuverability of a ship can be studied using standard maneuvering trials. Thus, zigzags and turning circle tests were used to evaluate ship maneuverability. Simulations were performed in both calm water and waves. In calm water, trials have been performed in both directions, however, in waves, trials have been performed with the first rudder action to the starboard side. Standard trials have been performed in several wave conditions. Two trials in two different initial headings were performed for each wave condition, a head on trial (ship is facing the incoming waves) and a following wave trial (ship is moving in the same direction as the wave). The properties of trials are described in Table 2.5. Wave conditions are defined in Table 2.6. The waves were generated from a Jonswap spectrum with a peakedness factor of $\gamma = 3.3$. The first three waves (ID 80000; 80010; 80020) were performed as simulations only, the rest of the waves, highlighted in green, were performed as simulations and experiments.

TABLE 2.5: Properties of maneuvering trials

Trial	**Zigzags**	**Turning circles**
Rudder angle	20°\20°	35°
Rudder direction	starboard	CW: starboard; port side Waves: starboard
Test speed	16 kn	16 kn
	(at constant propeller speed RPS)	
Sea state	CW and waves (according to Table 2.6)	
Wave direction	0°for head sea; 180°for following sea	
Ship model	DTC	DTC

CW: calm water
RPS: revolution per second
DTC: the Duisburg Test Case banchmarking container ship

TABLE 2.6: Irregular wave conditions

Wave ID	T_p [s]	H_s [m]	
		Target	Meas.
80000	8.0	-	1.0
80010	10.0	-	4.0
80020	15.0	-	10.0
85000	9.97	3.12	3.45
85010	11.97	3.18	3.56
85020	11.97	4.97	5.43
85030	13.96	4.33	4.71
85040	11.97	8.0	8.57

The ship considered in this study is a benchmarking containership named the Duisburg Test Case (DTC). Particulars of the DTC hull are shown in Table 2.7. The benchmark data was collected primarily for another study (Rabliås and Kristiansen, 2019). Access was given to us in the form of a scientific collaboration. The benchmark data was collected in the Sintef Ocean Basin in Trondheim, Norway with a DTC model performing free-running trials. The main purposes of the experiments were to gain a better understanding of the maneuverability of such a hull in waves, and to use the results as a benchmark in the evaluation of a research maneuvering model. The following article has additional information on the experimental campaigns (Rabliås and Kristiansen, 2022).

TABLE 2.7: Particulars of the DTC hull

Particulars		Ship	Model
L_{pp}	$[m]$	355	5.577
B	$[m]$	51	0.801
d	$[m]$	14.5	0.228
Δ	$[kg]$	173468000	673.27*
C_B	$[-]$	0.661	0.661
x_G**	$[m]$	174.059	2.721*
y_G	$[m]$	0	0
KG	$[m]$	19.851	0.311*
GM	$[m]$	5.100	0.081*
I_{44}	$[kgm^2]$	7.148E+10	41.51***
I_{55}	$[kgm^2]$	1.322E+12	1294.2*
I_{66}	$[kgm^2]$	1.325E+12	1268.4
L_{bk}	$[m]$	14.85	0.23*

* Measured values.
** Relative to aft perpendicular.
*** Estimated from measured natural roll period and numerical added mass.

Where,
L_{pp} - length between perpendiculars
B - Breadth
d - Draft (draught)
Δ - Submerged mass
C_B - Block coefficient
x_G - X-coordinate of the COG
y_G - Y-coordinate of the COG
KG - Height of the ship's center of gravity the above Keel
GM - Metacentric height
I_{xx} - Moments of inertia
L_{bk} - Length of each bildge keel segment.

The results of the maneuvering trials are plotted and presented in charts. Maneuvering trials result in maneuvering characteristics and timeseries. The characteristics (overshoot angle or tactical diameter, for example) are plotted in scatter-like charts showing the characteristic on the y-axis and wave height on the x-axis. Timeseries plots, however, are dedicated to a specific wave height and have the variable on the y-axis and time on the x-axis. Both characteristics and timeseries plots show three datasets overlaid on the same chart: the experiment datasets (labeled as Exp), the

Industry-standard simulator datasets (labeled as Sim A), and the research simulator datasets (labeled as Sim B). Table 2.8 summarizes the labels of the presented results.

TABLE 2.8: Simulation datasets and their labels

#	Dataset	Label
1	Experiment data	Exp
2	Industry-standard simulator	Sim A
3	Research simulator	Sim B

Descriptions of the mathematical background of both simulators are presented in Chapter 5. The brand name of Sim A is undisclosed herein. The mathematical background of Sim A is described to a degree that maintains its supposed confidentiality. The mathematical background of the latter is described herein and reference is made to other publications that describe it more thoroughly.

The simulations method enables the objective evaluation of the performance of simulators. The comparison of the maneuvering trials of simulators against those of experiments opens up the opportunity to quantitatively assess the ship dynamics in simulators. Such quantitative assessments reveal the following:

- Accuracy of maneuvering in calm water
- Accuracy of maneuvering in waves
- Trends of maneuvering characteristics as wave height increases

2.4 Data Management Plan

Various kinds of datasets were used in this research. Datasets in the form of literature, such as journal articles, conference proceedings, and MSc or PhD theses were used. The interview dataset consists of audio recordings, text transcriptions, and a coding table. The case study dataset consists of a webinar recording, text transcription, and a reviewed summary. Simulations consists of three datasets. The experiment datasets include the zigzag and turning circle trials in separate files. Each file includes the properties of a single trial in a single row. The number of rows in the file structure is equal to the number of trials. The Industry-standard simulator dataset includes every trial in a separate file. The format is rearranged to Matlab structures .mat format to match that of the experimental dataset. The research simulator dataset is similar in format of the experimental dataset.

Literature data were collected using popular search engines and Oria, the digital library of the NTNU. Interview data were collected after invitation letters were sent by email to a shortlist of relevant candidates. Acceptance replies were delivered and consent forms were signed. In addition, in the beginning of every interview, the interviewer asked the interviewee: "Do you allow me to record?". After the second consent, the recorded interview started. The case study data were collected after it was made clear, in the beginning of the webinar, to the presenters and the attendees alike, that the event would be video recorded.

The experimental dataset was collected in two campaigns, using the data infrastructure of the Ocean Basin that is equipped with sensors, cameras, and controllers to facilitate the logging and monitoring of data. The author of this research participated in one of the campaigns in January 2020. Data were sent from the Ocean Basin to our collaborators from the Marine Technology department of the NTNU. Access was granted to the author of this research as a form of scientific collaboration. Ownership of the data belongs to the collaboration partners.

The Industry-standard simulator dataset was logged using the simulator tool, to which the author was given access. The firm modelled the hydrodynamics of the DTC container ship and created simulation scenarios according to the request of the author. The author ran multiple simulations and requested the data. The firm delivered the logged data to the author. The ownership of the data belongs to the firm.

The research simulator dataset was collected by the research collaborator who is developing the novel maneuvering model. The dataset, was created by the collaborator and then delivered to the author of this research. Ownership of this dataset belongs to the collaborator.

Formatting, structuring, post-processing, visualizing, and interpreting the data was done by the author of this research. An overview of the data involved in this research is found in Table 2.9.

TABLE 2.9: Overview of the research datasets

#	Dataset	Type	Ext.	Size	Ownership
1	Literature - A	Text documents	.pdf	$\sim$ 100 MB	Publishers
2	Literature - B	Text documents	.pdf	$\sim$ 130 MB	Publishers
3	Interviews	Audio recordings	.mp3	$\sim$ 420 MB	Interviewees
4	Webinar	Video recording	.mp4	$\sim$ 1.3 GB	NTNU (IHB) & NCA
5	Experiments	Quantitative data	.mat	$\sim$ 5.2 GB	NTNU (IMT)
6	Simulations - Sim A	Quantitative data	.npz	$\sim$ 10 MB	The Simulator Company
7	Simulations - Sim B	Quantitative data	.mat	$\sim$ 20 MB	NTNU (IMT)

Chapter 3

Maritime Autonomy

This chapter provides a summary of the results of Method 1.1, Literature Review - A (Zghyer et al., 2019). The term *autonomous ships* is defined herein as: ships that are designed and verified, under certain conditions, to be controlled partially or fully by automation, along with human monitoring, supervision and intervention. Therefore the literature review divides this study of the field of autonomous vessels into two, the automation technology field and the human operators. The term *automation* is defined as: The use of (GNC) technology for the control of machines, therefore this review is conducted on the fields of hydrodynamics and GNC (representing the technological side of autonomous ships), and the field of human factors (representing the human experiences as automation increases in their workplace). Figure 3.1 shows the signal flow of the GNC systems in relation to each other, and Figure 3.2 shows the ship maneuvering (hydrodynamics) and human factors in relation to the GNC fields. At this level, the review has a broad scope to achieve the following objectives:

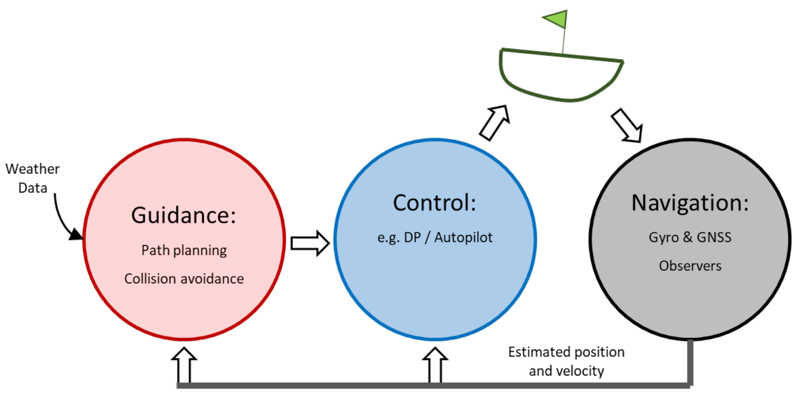

FIGURE 3.1: GNC systems signal flow diagram

- Learn about autonomous vessels technologies
- Learn about the impact of increased automation on human operators
- Identify the knowledge gaps and challenges towards pursuing autonomous ships
- Define the continuation of this research

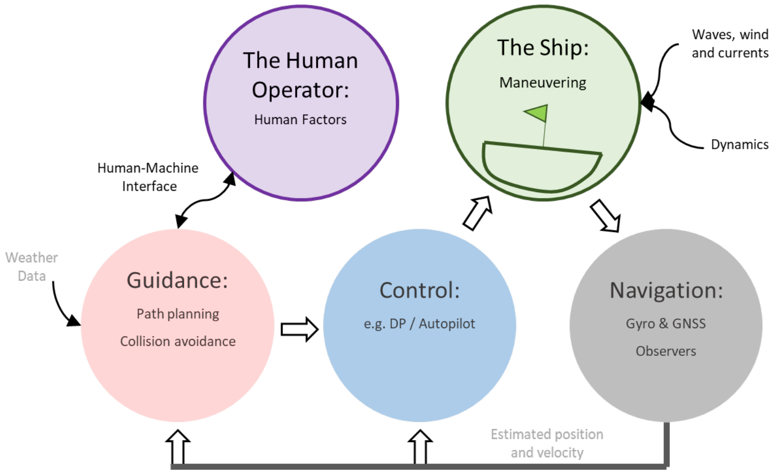

FIGURE 3.2: Relation of ship maneuvering and human factors to the GNC systems

The broad exposure helped me learn about the opportunities and challenges of autonomous ships from different, often conflicting, points of view. The technological fields mainly over-confirm the capabilities of developing ships that can observe-orient-decide-act on their own, without any input from the human operator. Whereas the human factors field mainly confirms the incapability of human operators to perform under systems with high levels of automation.

3.1 State-of-the-art

A summary of the main literature follows in the next subsections.

3.1.1 Hydrodynamic models

Hydrodynamic models of interest are the models that can be used in ship simulators. In other words, they must satisfy the following conditions:

- Solve ship motion in the time domain.
- Demand low processing power, meaning that they can run in real-time or faster.
- Predict ship maneuvering given control inputs and environmental conditions.
- Appreciate seakeeping and maneuvering theories simultaneously, such as, wave excitation forces, environmental loads, and control inputs.

The maneuvering theory is the study of ship motion of a moving ship in calm water. The concern with the maneuvering theory is mainly on the horizontal-plane motions, assuming that there is no wave excitation and that hydrodynamics are frequency independent. The seakeeping theory, however, is the study of the ship motion of a standing-still ship, or a ship moving at constant speed in straight course in waves. The concern with the seakeeping theory is mainly on the vertical-plane motions, assuming linear wave induced oscillation. Unified models are models that consider the effects of both maneuvering and seakeeping theories simultaneously.

Extensive literature on ship hydrodynamics is published by Newman (1977) and Faltinsen (1990), solving the seakeeping and maneuvering problems in the frequency domain by applying a 2D strip theory for obtaining good estimates of the hydrodynamic coefficients. Bailey et al. (1998) are the first to formulate a unified model solving seakeeping and maneuvering simultaneously. Examples of unified hydrodynamic models that satisfy the above conditions are the unified model by Fossen (2011) and the two-time scale method by Skejic and Faltinsen (2008). The former model is formulated as follows:

$$\dot{\eta} = J_{\Theta}(\eta)\nu \tag{3.1}$$

$$M\dot{\nu} + C_{RB}(\nu)\nu + C_A(\nu_r)\nu_r + D(\nu_r)\nu_r + \mu + G\eta = \tau_{control} + \tau_{wind} + \tau_{wave} \tag{3.2}$$

Where $\eta = [x, y, z, \phi, \theta, \psi]'$ (′: transpose) and $\nu = [u, v, w, p, q, r]'$ are the position (including orientation) and velocity vectors respectively. Eq. 3.1 is the kinematic transformation equation between two different reference frames: the body-fixed frame $\{b\}$ and the inertial North-East-Down $\{s\}$ frame. On the left hand side of Eq. 3.2 are the rigid body forces, hydrodynamic, and hydrostatic forces, while on the right hand side lie the control, wind, and wave-induced forces. Where,

$M = M_{RB} + M_A$ - system inertia matrix (including added mass)
$C_{RB}(\nu_r); C_A(\nu_r)$ - Coriolis-centripetal matrices (Rigid body and added mass)
$D(\nu_r)$ - damping matrix
μ - fluid memory effects
$G\eta$ - vector of hydrostatic forces and moments
$\tau_{control}$ - vector for control inputs
τ_{wind} - vector of wind forces
τ_{wave} - vector of wave-induced forces.

This model includes both the maneuvering and seakeeping effects in the time-domain. The basis for the time domain transformations is the famous articles by Cummins (1962) and Ogilvie (1964). The maneuvering theory is based on the assumption that the hydrodynamic potential coefficients and radiation-induced forces are frequency independent. In the maneuvering theory, the equations of motions are described relative to the body-fixed frame $\{b\}$. The seakeeping theory includes a dissipative force known as *fluid memory effects* that is captured using the convolution integrals (Cummins, 1962). Radiation forces and (frequency dependent) wave excitation forces are computed as part of the seakeeping forces. In the seakeeping theory, the equations of motion are described relative to $\{s\}$, the frame fixed to an equilibrium virtual craft that moves at a constant speed and heading corresponding to the actual motion of the actual craft. The unified model is usually represented in the $\{b\}$ frame, therefore, the seakeeping terms must be transformed from $\{s\}$ to $\{b\}$, creating Coriolis and centripetal force terms between $\{s\}$ and $\{b\}$ (Fossen, 2011).

The latter model of Skejic and Faltinsen (2008) is formulated as follows in the 4-DOF (surge, sway, roll, and yaw) equation, Eq. 3.3. In this method, the time domain of the maneuvering simulation is split into two time scales: one is slowly varying and the other is rapidly varying, associated with maneuvering and seakeeping, respectively. The maneuvering system provides slowly varying forward speed U and heading ψ to the seakeeping problem that is activated based on prefixed differences in the ship heading $\Delta\psi_C$. The main advantage of this method is the prediction of the mean second-order wave loads (drift forces) that are solved using four different theories covering the whole range of important wavelengths (selection based on hull and wave characteristics). Wave forces highly depend on the linear unsteady flow fields, namely, on the wave-induced ship motions and forward speed U. Better predictions of drift loads result in better maneuvering performance in incident waves, where the drift loads heavily influence the maneuvering behavior.

$$
\begin{bmatrix} M & 0 & 0 & 0 \\ 0 & M & 0 & 0 \\ 0 & 0 & I_{44}-Mz_g^2 & -I_{46} \\ 0 & 0 & -I_{64} & I_{66} \end{bmatrix}
\begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{p} \\ \dot{r} \end{bmatrix}
+ \begin{bmatrix} 0 & -Mr & 0 & 0 \\ 0 & 0 & 0 & Mu \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}
\begin{bmatrix} u \\ v \\ p \\ r \end{bmatrix} =
$$
$$
+ \begin{bmatrix} X_{\dot{u}} & 0 & 0 & 0 \\ 0 & Y_{\dot{v}} & Y_{\dot{p}} & Y_{\dot{r}} \\ 0 & K_{\dot{v}} & K_{\dot{p}} & K_{\dot{r}} \\ 0 & N_{\dot{v}} & N_{\dot{p}} & N_{\dot{r}} \end{bmatrix}
\begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{p} \\ \dot{r} \end{bmatrix}
+ \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & Y_v & Y_p & Y_r \\ 0 & K_v & K_p & K_r \\ 0 & N_v & N_p & N_r \end{bmatrix}
\begin{bmatrix} u \\ v \\ p \\ r \end{bmatrix}
$$
$$
+ \begin{bmatrix} 0 & -C_{TN}Y_{\dot{v}}r & -Y_{\dot{p}}r & -Y_{\dot{r}}r \\ 0 & 0 & 0 & X_{\dot{u}}u \\ 0 & 0 & 0 & 0 \\ 0 & -X_{\dot{u}}u & 0 & 0 \end{bmatrix}
\begin{bmatrix} u \\ v \\ p \\ r \end{bmatrix}
- \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}
\begin{bmatrix} \int_0^t u dt \\ \int_0^t (v + z_g p + u\psi) dt \\ \phi \\ \psi \end{bmatrix}
$$
$$
+ \begin{bmatrix} X_R \\ Y_R \\ 0 \\ N_R \end{bmatrix}
+ \begin{bmatrix} -R(u) + (1-t)T(u) \\ 0 \\ 0 \\ 0 \end{bmatrix}
+ \begin{bmatrix} 0 \\ Y_{CF} \\ K_{CF} \\ N_{CF} \end{bmatrix}
+ \begin{bmatrix} \overline{R_X} \\ \overline{R_Y} \\ \overline{M_X} + z_g \overline{R_Y} \\ \overline{M_Z} \end{bmatrix}
\tag{3.3}
$$

Where,

$\begin{bmatrix} M & 0 & 0 & 0 \\ 0 & M & 0 & 0 \\ 0 & 0 & I_{44}-Mz_g^2 & -I_{46} \\ 0 & 0 & -I_{64} & I_{66} \end{bmatrix}$ - is the system inertial matrix that includes ship mass and moments of inertia,

$\begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{p} \\ \dot{r} \end{bmatrix}$ & $\begin{bmatrix} u \\ v \\ p \\ r \end{bmatrix}$ - are the generalized acceleration and velocity vectors, respectively,

$\begin{bmatrix} X_{\dot{u}} & 0 & 0 & 0 \\ 0 & Y_{\dot{v}} & Y_{\dot{p}} & Y_{\dot{r}} \\ 0 & K_{\dot{v}} & K_{\dot{p}} & K_{\dot{r}} \\ 0 & N_{\dot{v}} & N_{\dot{p}} & N_{\dot{r}} \end{bmatrix}$ & $\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & Y_v & Y_p & Y_r \\ 0 & K_v & K_p & K_r \\ 0 & N_v & N_p & N_r \end{bmatrix}$ - are the hydrodynamic coefficients matrices: added mass and damping matrices, respectively, evaluated from the 2D BVP at $w_e = 0$,

$$\begin{bmatrix} 0 & -C_{TN}Y_{\dot{v}}r & -Y_{\dot{p}}r & -Y_{\dot{r}}r \\ 0 & 0 & 0 & X_{\dot{u}}u \\ 0 & 0 & 0 & 0 \\ 0 & -X_{\dot{u}}u & 0 & 0 \end{bmatrix}$$

- are frequency dependent response impulse functions (retardation functions) where C_{TN} - is a reduction coefficient,

$$\begin{bmatrix} \int_0^t u dt \\ \int_0^t (v + z_g p + u\psi) dt \\ \phi \\ \psi \end{bmatrix}$$

- is the position vector identical to $[\eta_1, \eta_2, \eta_4, \eta_6]'$, and the previous term in the equation, C_{44}, is a restoring coefficient,

$$\begin{bmatrix} X_R \\ Y_R \\ 0 \\ N_R \end{bmatrix}$$

- is the rudder force vector,

$$\begin{bmatrix} -R(u) + (1-t)T(u) \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

- is the resistance and propulsion vector. Total calm water resistance accounts for friction, hull form, appendage, wave resistance, and additional bulb bow pressure,

$$\begin{bmatrix} 0 \\ Y_{CF} \\ K_{CF} \\ N_{CF} \end{bmatrix}$$

- is the non-linear viscous loads vector using the cross-flow principle and,

$$\begin{bmatrix} \overline{R_X} \\ \overline{R_Y} \\ \overline{M_X} + z_g \overline{R_Y} \\ \overline{M_Z} \end{bmatrix}$$

- is the wave forces and moments vector.

The four methods that are used to calculate the wave loads are listed as follows:

- The conservation of energy method (based on the 1^{st} law of thermodynamics) named Generalized Energy Method (Loukakis and Sclavounos, 1978).
- The conservation of momentum (based on Newton's 2^{nd} law of motion) named Hull Pressure/Momentum Method (Salvesen, 1974).
- Direct Pressure Integration method (Faltinsen et al., 1980).
- Short Wavelength Asymptotic theorem (Faltinsen et al., 1980).

Both hydrodynamic models presented above, Eq. 3.2 and Eq. 3.3, are vectorial-unified models that adopt the principle of superposition in their formulation. They are linear models that constitute non-linear terms, such as the viscous terms. Potential theory based programs can be used for computing the hydrodynamic coefficients (frequency-dependent hydrodynamic added mass M_A, potential damping D_P, and the hydrostatic matrix G). In addition, they are also used for computing the hydrodynamic coefficients of the zero encounter frequency condition that resemble the frequency independent coefficients used for the maneuvering theory computations.

The most common potential theory based numerical methods for calculating the hydrodynamic coefficients are:

- Strip theory: a 2-D linear theory that divides the submerged part of the ship into a finite number of strips. Coefficients are calculated for each strip then integrated along the length of ship. Strip theory assumes that flow variation in the longitudinal section is much smaller than that of the cross-section (Salvesen et al., 1970). An example of a computer code using this approach is the seekeaping module in ShipX (Veres) by SINTEF Ocean (ShipX, n.d.).
- Panel method: a 3-D theory that uses panel discretization of the surface of the ship. An example of a computer code using this approach is WAMIT (WAMIT, n.d.).

The cross-flow principle can be used to account for the non-linear viscous load. The principle is summarized as follows:

- The flow separates due to cross-flow past the ship hull.
- The longitudinal velocity components do not influence the transverse forces on a cross section.
- The transverse force on each cross section is mainly due to separated flow phenomena effecting the pressure distribution along the ship hull.
- The cross-flow principle is appropriate at large drift angles β and low forward speed U.
- The drag coefficient is assumed constant; the dependence of drag on speed is neglected.

Such models represent an example of state-of-art ship maneuvering models that are deployed in navigation training simulators. Several examples of unified models have been published in the last few decades. Here is a summary of the recent progress: the method of Skejic and Faltinsen (2008) was verified and validated for calm water. It was further developed to include ship-to-ship hydrodynamic interaction effects in regular waves. The method highlights critical maneuvering situations and still requires experimental validation (Skejic and Berg, 2010). In 2013, the two-time scale model was applied to irregular seas and validated for a container ship (Skejic and Faltinsen, 2013).

Hermundstad and Hoff (2009) published a time domain unified model on submarines and compared it with experimental results, concluding that the used unified model did not describe the diving maneuvers correctly because the depth dependency of the coefficients was not incorporated. Another method was published using the two-time scale approach for ship motion simulation that derives 6-DOF equations of motion for the high frequency seakeeping problem and 4-DOF equations of motions for the low frequency maneuvering problem, where the predictions of the turning circle maneuvers of the container ship hull S-175 resulted in rough agreement with model tests (Yasukawa and Nakayama, 2009).

Based on the strip theory published by Adnan and Yasukawa (2007), Yasukawa et al. (2010) compared numerical estimates of hydrodynamic forces and wave-induced motions taking into account lateral drift, with experiments showing that drift effects are not negligible and that the method is able to capture them. Seo and Kim (2011) extended the WISH (computer program for nonlinear wave induced load and ship motion analysis) by coupling the maneuvering and seakeeping models, and verifying it by comparing it with published experimental data in calm water and regular waves. The simulations showed fair agreement of the overall tendency in maneuvering trajectories.

Besides lateral drift, another challenge for the hydrodynamic models is the broaching phenomenon. Broaching is the loss of stability while sailing in following seas where the kinetic energy of the ship along the forward axis transfers to roll motion and leads to strong heel, loss of heading, even capsizing (Wu et al., 2010). Generally, maneuvering in waves is a challenge for both experimental and numerical modelling. For simulating ship motion in waves, forces and hydrodynamic coefficients need to be calculated dependent on wave frequency, ship heading, and angle of attack (the angle between wave direction and ship heading), (Kim et al., 2014).

There are multiple hydrodynamic phenomena affecting ships, the majority are associated with restricted water sailing. In this research, only open water maneuvering and the effects of environmental loads, mainly waves, are concerned. Nevertheless, here is a list of common hydrodynamic phenomena affecting the maneuverability of ships:

- Ship-to-ship interaction
- Interaction with another structure (such as sailing in a tunnel)
- Bank effects
- Shallow water effects
- Restricted water effects
- Lateral drift
- Broaching
- Hull fouling

Maneuverability is a high-uncertainty process involving many (interacting) variables. As shown in Eq. 3.2 and 3.3 above, such maneuvering models are modular and can be extended to account for additional effects, however, they do not include most of the phenomena above by default.

3.1.2 GNC

The term GNC refers to guidance, navigation and control, the well-established control engineering (and cybernetics) term. It is broken down into the following terms and definitions:

- Guidance: the brain of the robotic controller that is responsible for trajectory planning, collision avoidance, and protocol conformance, such as to COLREG (Fossen, 2011).
- Navigation: the module responsible for estimating the ship's own position as well as position of target ships and other obstacles. This module, in highly automated ships, is also responsible for environment perception (Farell, 2008).
- Control: the translation of the guidance plan (desired trajectory) into actuator instruction that results in an actual trajectory as close as possible to the desired one while maintaining the stability of the vessel (Pérez, 2005).

The guidance system is responsible for path planning and collision avoidance. Fossen (2011) defines the motion objectives of the GNC system as one of the following categories:

1. Setpoint regulation: the heading angle is constant with no consideration of time, such as a traditional heading autopilot.
2. Path following: the heading angle is variable, following a path with no consideration of time.
3. Trajectory tracking: the heading angle is variable, following a trajectory in both space and time.
4. Maneuvering: considers the overall feasibility of the path, considering space and time.

Maneuvering prediction capabilities are necessary for the GNC system objective categories 3 & 4, where time considerations and the whole feasibility of the path become important.

The guidance system tasks can be split into two groups: the global and local path planning. The global approach is the deliberate part of the system that is planned in advance. It is a multi-objective path optimization problem from the start to the end of the trip including information about traffic, weather, own ship, target ships, land, water depth, currents, and buoy locations. The local planning approach is the reflexive part of the guidance system that takes charge of real-time local deviations from the global plan.

Polvara et al. (2018) published a review of global and local path planning methods, concluding that almost all of the reviewed methods did not consider uncertainties due to environmental loads and vehicle dynamics. Such a statement stresses the role of maneuvering models in advanced GNC systems. The authors stated:

"It has been concluded that almost all the existing methods do not address sea or weather conditions, or do not involve the dynamics of the vessel while defining the path. Therefore, this research area is still far from being considered fully explored"

Dixit et al. (2018) published a review on the trajectory planning and tracking methods for autonomous driving systems and they concluded that even the most advanced GNC systems, with today's available sensor technology work well under regulated environments, adding that, the consideration of vehicle dynamics and environmental loads increases the effectiveness of such systems.

LaValle (2011, p.108) in his renowned path planning tutorial stated:

"The basic problem of computing a collision-free path for a robot among known obstacles is well understood and reasonably solved; however, deficiencies in the problem formulation itself and the demand of engineering challenges in the design of autonomous systems raise important questions and topics for future research"

The navigation system is traditionally responsible for positioning, however, the role of the navigation system in unmanned ships expands to two main tasks: state estimation and environment perception. State estimation consists of information about the ship's motion, mainly position and velocities. State estimation in an unmanned ship would include states of own ship and that of target ships. Environment perception consists of evaluating weather information, wind, waves, currents, water depths, and information about the surroundings waters and lands.

The navigation system analyzes data from multiple sources for achieving the required accuracy. Data sources that could be involved in a navigation system are:

1. Inertial measurement unit (IMU) is an onboard three-dimensional sensor that comprises three mutually-orthogonal accelerometers and three gyroscopes to give the position, velocity, and altitude of own ship. IMU is often used with (and aided by) satellite positioning to provide drift-free positioning. If IMU is used on its own, without satellite correction, small errors in positioning would accumulate over time, causing a drift between the estimated position and actual position.

2. Automatic Identification System (AIS) is a very high frequency communication system used by ships to transmit their identity, position, velocity, destination, and other information and, in return, they receive information on nearby ships. Even though AIS is mandatory for commercial vessels, not all boats have it onboard! Not to mention the leisure boats and the small fishing boats that roam the coastal waters in summers, neither is required to have an AIS onboard.

3. GNSS is a global positioning solution system. It transmits radio signals from satellites orbiting the planet to ships. There are a number of GNSS solution providers including GPS, GLONASS, BeiDou and Galileo. Satellite systems are used to correct the drift caused by the IMU position estimates. Despite being a crucial positioning data source, satellite signals suffer from attacks such as spoofing and jamming that result either in a weak signal or a wrong position estimate.

4. Radar, an acronym for radio detection and ranging, uses radio waves to detect ships and obstacles within a long range, but its capability of detecting small moving targets is limited. Radar wavelength passes through fog and rain and provides nearly all-weather data imagery.

5. Lidar, an acronym for light detection and ranging, is a high resolution and accuracy object detection sensor for the near-range.

6. Sonar, an acronym for sound navigation ranging, detects submerged objects such as reefs, sunken ships, and submarines. The sonar transmits ultrasonic pulses, receives the reflected echoes, and displays a picture of the detected objects.

7. Other types of sensors and tools are used for navigation purposes such as cameras, infrared sensors, compass systems, navigation lights, and ship whistles.

Kalman filtering is the most common method for navigation data fusion. Traditional fusion happens between the IMU and GNSS signals. Modern systems include the maneuvering model signal as well, aka "model-based navigation" (Bryson and Sukkarieh, 2006; Crocoll et al., 2013; Khaghani and Skaloud, 2016). The Kalman filter, invented by Kalman in 1960, is a real-time Bayesian estimation algorithm that uses all available measurements over time, and uses knowledge of the deterministic and statistical properties of the system's parameters in order to provide an optimal minimum-error state estimation (Groves, 2013). Recent navigation filter technologies include the eXogenous Kalman filter (XKF) (Johansen and Fossen, 2017), the Inverted Kalman filter (IKF) (Motwani et al., 2013), the Unscented Kalman filter (UKF) (Peng et al., 2009), and the Extended Kalman filter (EKF) (Caccia et al., 2008).

The control system is responsible for translating guidance system information into actuator commands. Ship actuators such as propellers, thrusters, and rudders receive commands from the control system to produce forces and moments approaching the ship's desired state. In addition to sending control commands, the control system is responsible for ensuring the commands are practical given actuator limitations and ship dynamics. Control literature is rich with control design approaches ranging from classical proportional-integral-derivative (PID) controllers to the more advanced artificial-intelligence (AI) based controllers.

It is observed from the reviewed literature that path planning technology is well understood and reasonably solved, however, maneuvering modelling technology, which accounts for ship motion behavior under operational metocean conditions is a bottleneck in the development of the guidance system of the future. It is also observed that multiple data sources with varying qualities and frequencies exist for aiding the positioning estimates. However, the main sources suffer from challenges such as the onboard inertial sensors suffering from drifting errors and the global satellite signals suffering from attacks. This knowledge is key for the calibration of trust between the human operators and information they get on their charts. In addition, this knowledge can be used in the design of modern navigation systems for unmanned ships.

3.1.3 Human factors

Human factors of interest to this study are those connected to the experiences and reflections of human operators as they are introduced to high levels of automation in their operations. This section starts with a reflection on Levels of Automation (LOAs) and proceeds with summarizing the main human factors involved in pursuing high levels of automation.

The term Levels of Automation (LOAs) was coined by Sheridan and Verplank (1978). Since then, multiple versions of LOAs have been published. In shipping, LOA proposals exist from various sources such as Bureau Veritas, Lloyd's Register, the Norwegian Forum for Autonomous Ships (NFAS), Rolls-Royce, and others. Table 3.1 shows an example of the LOAs according to the NFAS. General agreement exists among the different LOA definitions as they range from traditional human-operated vessel to fully autonomous vessel. Explicitly and surprisingly, the different variations of LOA definitions, agree that, on the highest level of automation, the machine decides and acts on its own, requiring no communication with the human.

The intention of increased automation is to increase the safety and efficiency of operations, however, in complex tasks such as dynamic environments with many variables involved, automation changes the nature of the human role in the task. Automation can alter the workload and cognitive demands of operators. The overall outcome of increased automation may actually be more complex than otherwise anticipated. The impacts of automation are qualitative in context rather than quantitative and uniform (Woods et al., 1996). The main human factors are summarized in four categories as follows:

1. Responsibility: As automation increases, more decisions are delegated to machines. Can responsibility be delegated to machines as well? The calibration of trust between human operators and machines, and the way operators perceive responsibility, are crucial to safe autonomous operations (Muir, 1987). Jordan (1963, p. 164) stated:

TABLE 3.1: LOAs as proposed by NFAS (Rødseth and Nordahl, 2017)

Degree	Label	Description
Degree one	Automated processes and decision support	Seafarers are on board to operate and control shipboard systems and functions. Some operations may be automated and, at times, be unsupervised but with seafarers on board ready to take control.
Degree two	Remotely controlled ship with seafarers on board	The ship is controlled and operated from another location. Seafarers are available on board to take control and operate the shipboard systems and functions.
Degree three	Remotely controlled ship without seafarers on board	The ship is controlled and operated from another location. There are no seafarers on board.
Degree four	Fully autonomous ship	The operating system of the ship is able to make decisions and determine actions by itself.

"We can never assign them any responsibility for getting the task done; responsibility can be assigned to man only".

Billings (1991) suggested that human operators bear the ultimate responsibility for operational goals. They must be in command, well involved, and well informed about ongoing autonomous activities.

2. "Automation surprises": As automation increases, it can be difficult for human operators to follow up and understand the basis of the decisions of the autonomous vehicle. Once the actions of the machine are not the same as what the human operator would do if placed in the same situation, then the human will lose track and probably fail to predict next steps. An experiment was carried out to examine a pilot's mode awareness confirmed that "automation surprises" are experienced even by operators with an extensive amount of line experience. As expected, the experiment showed that in non-normal situations, more problems related to "automation surprises" occurred (Sarter and Woods, 1994). A survey of B-757 pilots showed that 55% of respondents were still being surprised even after more than a year of line experience on the aircraft (Wiener, 1989).

   Norman (1988) referred to the phenomenon of losing track (of the machine's series of actions) as a *"breakdown in mode awareness"*, which has been linked strongly to: automation surprises, increased error possibilities, new cognitive demands, and failure to intervene appropriately. The surprise is not limited to the operators according to Norman, it also affects the designers and owners, especially if such an autonomous system fails to behave as intended.

3. Management by exception: A remote operator, whether monitoring or supervising, is in a double bind dilemma with the machine, a dilemma between trust and takeover. Dekker and Woods (1999) explained that supervisory control places the human operator in a decision-making situation, a trade-off between intervening too early, before enough evidence is collected about the situation,

and intervening too late, after it escalates into an irreversible crisis. Operators therefore, even in supervision roles, are required to assess the criticality of the situation at every moment in time, and decide whether to intervene or not. Late decisions are catastrophic while early decisions are hard to justify. In such cases decision aids and prediction tools may be required, but how much should they be trusted? (Sheridan, 2000).

Increased automation is changing the human-machine interaction in nature. It reduces workload in normal times and increases it dramatically in non-normal times. In non-normal times, the surprise factor, attention demands, and cognitive demands are higher, leading to less situational awareness (SA) and intervention capabilities. Thus, safety is a concern in non-normal times. Sarter et al. (1997, p.6) defined the term mode awareness as:

> *"the ability of a human operator to track and anticipate the behavior of automated system"*

Endsley (1995, p.36) defines the term situational awareness as:

> *"the perception of the elements in the environment within a volume of space and time, the comprehension of their meaning, and the projection of their status in the near future"*

4. Communication: For example, the grounding of the Royal Majesty is referred to as a loss of situational awareness problem, a communication problem because of increased automation. Among other factors, the GPS failed, positioning information was incorrect, autopilot used the faulty information, and the ship drifted, which was not obvious to the crew. They believed that the sailing was on route, however, it lead to a grounding (Lützhöft and Dekker, 2002). Researchers emphasized the value of communication and collaboration with the machine for safer autonomous navigation. Effective communication and coordination between humans and machines is believed to be necessary for successful operations (Sarter et al., 1997).

   Another example, in some situations, is when operators do not follow the COLREG on purpose. Operators violate procedures for different reasons, as shown by research that collected 1262 questionnaires from tankers and bulk carrier crew (Oltedal, 2011). Machines must account for cases where the regulations are compromised in favor of the overall safety. Besides, COLREGS rules include subjective terms, such as safe speed/distance, that are not easily translated to algorithms.

3.2 Discussion

According to a review on the developments and challenges of unmanned ships, Liu et al. (2016), stated that the GNC systems of an autonomous vehicle work by interacting with each other. Imperfections in one system lead to performance concerns for the whole system. Ship hydrodynamic models are an integral part of GNC systems. They are being used in model-based navigation systems and support the advanced GNC system objective categories that require consideration of time in addition to space, and consideration of the feasibility of the whole path. Therefore, GNC systems that perform path planning or collision avoidance require (accurate) trajectory prediction methods. Suggesting that as ships become more advanced, the dependence on maneuvering models increases for fulfilling GNC system objectives.

Even though dependence on maneuvering models increases, literature shows that maneuvering models describing ship motion, including the effects of waves, winds and currents, is a research area still far from being considered fully explored. It is interesting to investigate the accuracy of ship maneuvering models that exist in navigation simulators.

Multiple data sources, with varying qualities and frequencies, exist for aiding the positioning estimates. However, the main sources of data suffer from challenges. For example, the onboard inertial sensors suffer from drifting errors and global satellite signals suffer from attacks. This knowledge is key for the calibration of trust between the human operators and information they get on their charts. In addition, this knowledge can be used in the design of modern navigation systems for unmanned ships.

Despite the LOA and the ability of a ship to decide and act on its own, there remains a need for managing the remote assets. The explained human factors stress the importance of communication between the ship and human operators. Communication must be thorough and transparent, enabling operators to asses the criticality of the situation at every moment, empowering their intervention capabilities.

The reviewed literature is conducted to answer the question *"is full-autonomy the way to go towards maximizing the ocean potentials?"*. The short answer is: the term full-autonomy brings autonomy to the center of attention. Autonomy is perceived as the process towards machines that are able to decide and act on their own without the need of human intervention. Human operators should remain "in the loop" regardless of the capabilities of machines, therefore, it is remote-control, the way to go towards maximizing ocean potentials. Automation technologies are the enablers of remote-control, however, it is important to keep the focus operator-centered instead of automation-centered. Therefore, it can be seen that remote control technology needs to be developed and matured, enabling remote operators the appropriate intervention and situational assessment capabilities. Such capabilities can be further investigated and developed in ship simulators.

3.3 Takeaways

The key points of this chapter are summarized in the following list:

I The progress of automation along the scale of LOAs results in higher capabilities of the autonomous ship to decide and act on her own, nevertheless, it still requires human monitoring, supervision, and intervention capabilities.

II Ironically, as automation increases, demand on superhuman skills (in non-normal times), such as workload, attention, cognitive demands, and intervention capabilities, increases as well.

III Hydrodynamic models are an integral part of GNC systems, and their role increases in importance as the vehicle systems increase in the level of automation.

IV *Ship dynamics* and *environmental loads* are the main functional challenges for autonomous vessels from the technology side.

V Maneuvering models: The capability of the state-of-art models to predict ship motion (in operational conditions) is far from being considered fully understood, and is crucial in the development of autonomous ships.

VI Remote control: The capability of operating ships remotely is necessary, regardless of the level of autonomy. Operation can be in the form of control, monitoring, or supervision. The infrastructure and technology enabling remote operators to better perform their tasks are crucial in the development of autonomous ships.

VII Ship simulators: Simulators enable research in both maneuvering models and remote ship operations. Therefore, they are needed in the development of autonomous ships. This point needs further investigation.

VIII It is of importance to know how capable and fit are ship simulators as labs for the research and development of maritime operations.

Chapter 4

Maritime Simulators

This chapter is a summary of the results of the three methods 2.1, 2.2, and 2.3 (Zghyer and Ostnes, 2019; Zghyer et al., 2022a), focusing on maritime simulators and their applications in industry and research.

- Method 2.1 is Literature Review - B, conducted to review simulator applications.
- Method 2.2 is an interview campaign, conducted to learn about the applications, opportunities, and challenges of ship simulators.
- Method 2.3 is a case study investigating how the NCA is using and planning to use simulator technology for pilotage operations.

4.1 State-of-the-art

The results of the three methods are combined and presented in the following sections. Section 4.1.1 Opportunities and Challenges provides information that is collected solely from interviews. Section 4.1.2 Applications in Industry and Research provides information that was collected from the three methods combined. Section 4.1.3 Case Study: NCA Simulator Applications provides information collected solely from the case study.

4.1.1 Opportunities and Challenges

Simulators offer important proof of concept capabilities to innovations in ship-bridge design, port design, and research ideas. Simulators are convenient for human factors and sociocultural diversity research. Nevertheless, the research and development of autonomous vessels will depend largely on simulator experiments. This section will start with a brief discussion about simulator advantages to lay the foundation for their opportunities.

The advantages of simulators are massive and are listed as follows:

- First, simulators bring the human "in the loop", literally. The human users are central elements of simulator trials. For the case of ship-bridge simulators, the human is the one observing, perceiving, and interacting with the navigation equipment and surroundings to achieve the desired maneuvers.
- Second, in the same manner, simulators bring hardware "in the loop" as well. Real and up-to-date hardware is required to be installed in the simulator for delivering the expected experience of realism. This requirement is valid for

all interaction hardware, such as rudder and thruster controllers, seats, bridge furniture, radar, and ECDIS.

- Third, simulators provide (users/researchers) full control of the situation. A simulator is a safe lab to practice risky operations in harsh conditions.
- Fourth, simulators are more feasible. Running a demanding operation in a simulator is dramatically more feasible than actually executing the operation itself. Instead of simulating the complete actual operation, concentrated chunks can be simulated to investigate or train the users for a particular skill, thus saving time and resources.
- Fifth, simulators are more flexible. The simulators offer flexibility in setting the environment conditions such as winds, waves, and currents. In addition, they also offer flexibility in setting scenario specifications such as traffic, and time of day/night. However, the flexibility is limited to designed flexibility. For instance, if the researcher requires enhancing the level of autonomy for the target ships, this cannot be done without further programming and software development.
- Sixth, simulators are fast. some of them have the capability of running faster than real time, and this advantage opens up prediction and augmentation opportunities.
- Seventh, simulator operations are reproducible; this is a key advantage for research. The researcher is able to reproduce the conditions, for example the wave conditions, and perform the experiment over and over again.
- Finally, simulators open new frontiers. They can simulate operations in very harsh and rare weather conditions. They can achieve goals that are hardly possible to achieve in real life, such as planning iceberg management or optimizing seismic survey ship scan routes.

- Opportunities -

The advantages of simulators, as listed above, lay the foundation for the opportunities connected with their use. The opportunities of using simulators far exceed their traditional use: navigation training. A brief list of opportunities follows:

Proof of concept

Simulator trials turn out to be useful in the ability to validate or refute concepts regarding ship and port design. They are not only valuable for proof of concept, but also for further developments and training. According to an interviewee, simulator runs can be used to train people, algorithms, and procedures. Research ideas can be validated in a simulator. For example, a researcher with their own hypothesis: "separated traffic schemes will enhance safety in the sea" can structure a simulator experiment to investigate the very existence of a relationship between the variables (and obstructs) of interest: travel schemes, and safety.

Training of algorithms

Algorithms can be trained in and by simulators. Some of the artificial intelligence algorithms require training datasets. Datasets are able to train the algorithms on how things work in certain conditions. Simulators can provide valuable training datasets for such algorithms. Then, the performance of the trained algorithm can be put under investigation in a simulator experiment, in settings different than the training settings.

Usability studies

Usability studies are two-fold opportunity. On the one hand, simulator trials are used to verify and validate the performance of a piece of hardware or software and whether it delivers the actions as expected. On the other hand, an interviewee mentioned that the learning curves of novice and experienced users could be investigated in a simulator to evaluate the ease and user-friendliness of a certain piece of equipment.

Port studies

Simulators are fit for the purpose of evaluating existing and new port designs. Pilots can run trials into and out of ports in a simulator with different ship sizes and test geometrical port features and capacities.

Ship design

Simulators can be used early on in the process of ship design. From maneuvering capabilities to bridge technologies, most parts of ship design can be investigated with the operator-in-the-loop in the simulator. Simulators are the place to test interface items risk free such as controllers, visuals, and bridge layouts for evaluating the impact of new designs on the performance of seafarers.

Human factors research

Simulators provide an opportunity to investigate group dynamics and interactions in a maritime operational setting. According to an interviewee, sociocultural variables can be considered and investigated in research such as gender, cultural, experience, and age differences. Simulators can be arenas for research of "teamwork in critical operations." Simulator experiments also make observing experts possible. Observation is an important data collection method for designers and researchers aiming to learn how experts really use and interact with the machine.

Development of methods

According to an interviewee, simulator involvement in different industry processes, for example, in the process of ship design, is disrupting the conventional industry practices and workflows. In line with the human-centered design (HCD) philosophy, the simulator becomes a regular meeting point among the designer, owner, and operator. Simulators can combine the experience from the operator and the desires from the owner into the design process early on. This provides transparent exposure and understanding among project partners, creating a paradigm shift in industry methods.

Autonomous vessels

In regards to investigating the safety and efficiency of different levels of autonomy, simulators happen to be havens for running a number of scenarios and cases with different kinds of traffic mixtures involving remotely controlled ships and conventionally-controlled commercial vessels including leisure boats and small fishing boats. Simulators can also be suitable labs for testing different guidance, navigation, and control (GNC) algorithms.

Virtual ocean

As the numbers of simulators increase and their demand increases as well, there is an opportunity to connect simulator centers and create a digital model of the world's oceans, including coastlines and ports, into a shared ocean space for different kinds of ocean economy related research. Simulator centers can access the shared space and perform operations for research, training, and technology development purposes.

When linking the advantages of simulators with the opportunities, the indications of what simulators can do and how they can contribute to the industry are immense. On the one hand, the scope of simulator usage is expected to grow significantly in the future, but on the other hand, simulators come with a range of challenges of their own. The challenges section follows.

- Challenges -

Simulators are technology driven. They advance with technology in computer processing power, graphics, visual systems, and real-time hydrodynamic models. Despite being the state-of-the-art, technologies have their pitfalls occasionally. The challenges are based on the experiences of the interviewed experts, and are summarized in this section. Part of the challenges is practical and related to the setup, equipment, and participants. The other part is philosophical, and is attached to the fact that a simulator is a simulator, whereas, reality is something else. Ironically, the philosophical challenges are closely related to the advantages of simulators. A brief list of challenges follows:

Availability

The main challenge is availability. Simulators are physical rooms and some requirements need to be met before an experiment is ready to be conducted. According to most interviewees, availability is a general challenge that can be broken-down into a number of challenges. The availability sub-challenges follow.

- Availability of simulator facilities

First, the availability of simulator facilities is a challenge. Researchers usually need to wait for long periods in order to have a time slot for their simulator experiments.

- Availability of participants

Second, the availability of experienced participants is a challenge. It is not simple to book experienced seafarers for simulator experiments. They are not always available. This challenge is connected to the validity of simulator research when participants are novices (students) rather than experienced navigators.

- Availability of technical support

Third, there is a challenge regarding the availability of technical support. An expert technician is required, in most cases, to help researchers manage the scenario setup, data flows, and logging. Support is also necessary to implement modifications on simulation configurations including scenario location, target ships, traffic, time, weather, and equipment functionalities.

- Availability of hardware

Fourth, the availability of up-to-date interaction hardware is a challenge. In order to maintain a feeling that the experience is as realistic as possible, full-scale up-to-date hardware must be installed, calibrated, and connected to the simulator system and be ready for use.

Data management

Big data can be collected from a simulator experiment. Research infrastructure is required to enable researchers to collect the data they seek, otherwise it is very challenging to setup and achieve the desired data collection. Multiple data sources are available, including the following examples.

1. The ship data: this is mainly the data from the simulation software that holds quantitative information about the position and motion timeseries of the ship(s) (i.e. position coordinates, course, heading, speeds, roll, pitch, yaw, and other motions timeseries).
2. The navigation aids data: this include Radar images, ECDIS, and AIS data.
3. The human-machine communication data: this is the record of all human control inputs including thrusters, rudder, and other control input instructions.
4. The human-human communication data: this includes communication among the bridge team, or communication between the bridge and others vessels, instructors, or VTS. This data type is conducted via various channels, mainly the very-high-frequency radio (VHF).
5. Physiological sensor data: this includes data from eye-trackers, heart-rate sensors, Electrocardiography (ECG), Electroencephalography (EEG), Electromyography (EMG), respiration sensors, and temperature sensors. Note that wearing the physiological sensors on the body and keeping the wires connected is not only challenging, but also heavy and motion restricting; thus participants wearing wired sensors will be limited in motion and perhaps not feel comfortable.
6. Video data: video recordings of the simulator session include the bridges and instructor rooms that could be utilized as a valuable source of data for education, learning, and collaboration research fields.

Realistic physics

With the real-time constraint, the accuracy of the physics is not guaranteed in a simulation. The hydrodynamic models at the core of the simulator software have underlying assumptions and simplifications. In some conditions where such assumptions are physically invalid, the uncertainty in the computed ship response becomes high, thus, the simulator experience becomes less realistic. Below are a few examples of less realistic simulator experiences:

1. The last meter in a docking operation: as the ship is approaching a dock, the behavior of the ship in the simulator gets less realistic. This is also true with approaching any other structure, that can be resembled in operations such as ship-to-ship operations or sailing in a tunnel.

2. Co-simulation: for example, the co-simulation of an offshore crane operation. The crane is mounted on the ship. The ship is moving in waves and the crane is lifting a load. The motion of the ship is affecting the motion of the load and vice versa. The information exchange among the various simulation models is a non-trivial problem to solve. Therefore, the simulator experience could deviate from that of the real world.

3. Shallow water navigation effects are not appreciated in a simulator, because one of the underlying hydrodynamic assumptions is that the ship is sailing in deep water. Recently, however, there have been developments of shallow water hydrodynamic models to bridge this gap.

Software is software

Simulators, comprised of hardware and software, might have periodic problems, bugs, and shutdowns occasionally. According to interviewees, one expert technician per facility is required to maintain the simulators and perform both corrective and preventive maintenance measures. System updates increase the realistic functionality and feel, however, it is typical with every update to encounter an issue that requires troubleshooting and fixing. The maintenance of a simulator facility is costly.

Philosophical challenges

Simulator experiments are not identical to real-life operations, yet they are designed to resemble them. The philosophical challenges are rooted in the differences between real-life operation and simulator exercise conditions. For instance, the duration of the operation in real-life is long, it includes the round trip to the location and duration of the operation itself in which the operators live onboard for the whole period. However, in simulator exercises, the participants would have a much shorter exercise, after which they can go and relax in the comfort of their own homes. Real-life operators work longer shifts, feel the ship rolling even when they sleep, and develop feelings of isolation and longing for life back on shore. The duration, location, motion, severity, and overall feelings and thoughts of operators would be different. This difference is related to the rather challenging question of the validity of simulator experiments.

4.1.2 Applications in industry and research

A summary of the "simulator applications" results of the three methods, 2.1, 2.2, and 2.3, is presented in this section. A wide range of simulator applications are found. Figure 4.1 presents a mindmap with an overview of the variety of simulator applications. The applications are hence categorized in 6 groups as such: i) Education and Training; ii) Operator Training; iii) Assessment; iv) Development and Testing; v) Research and Innovation and vi) Digital Twins.

FIGURE 4.1: Simulator applications mindmap

Where,
AIS: Automatic identification system
DP: Dynamic positioning
HCD: Human centered design
HCI: Human-computer interaction
LNG: Liquified natural gas
LPG: Liquified petroleum gas

Figure 4.1 shows that simulators are not only used for maritime education. Simulators are becoming more vital in industry processes such as design and operations. Simulators are multidisciplinary labs that can gather expertise within a variety of roles for achieving specific purposes, challenging the harsh and remote offshore environment. The involvement of maritime simulators in both academia and industry is becoming more visible. The following are examples of national and international collaborations involving the use of simulators for advancing maritime operations:

- SFI MOVE: a Center for Research-Based Innovation for Demanding Marine

Operations is using a simulation-oriented approach to solve some of the most pressing challenges in the offshore industry. The center has been running for several years. This center is an example of academy-industry collaboration for solving real-world problems using research in simulators (SFI MOVE, 2016).

- EU project AutoShip: simulators will be upgraded to better support the testing, commissioning, training, and operations of autonomous ships (AutoShip, 2019).
- SFU COAST: A center of Excellence in Maritime Simulator Training and Assessment envisioning the innovative potential of the best simulator practices in maritime education (SFU COAST, 2020).

According to the Maritime Simulator System Standard (DNVGL-ST-0033, 2017), ship simulators are classified into four groups: Class A (full mission), B (multi-task), C (limited task), and S (special task). In addition to the classes, different types of ship simulators exist based on the type of functions they simulate. The types are listed in Table 4.1. A brief summary on simulator application categories follows.

TABLE 4.1: Ship simulator types

Ship simulator types based on type of operation (DNVGL-ST-0033, 2017)			
1	Bridge operations	2	Machinery operations
3	Radio communication	4	Cargo handling
5	Dynamic Positioning (DP)	6	Safety and security
7	Vessel traffic services (VTS)	8	Survival craft and rescue boat
9	Offshore crane & Remotely operated vehicles (ROV)	10	Fishery operation

Education and Training

Ship-bridge simulator-based training practices are well established in maritime education. The International Convention on Standards of Training, Certification, and Watchkeeping of Seafarers (STCW) of the IMO regulates the standards of training. The main purpose of the Convention is to promote the safety of life and property at sea and protect the marine environment to ensure that future professional mariners can operate properly and safely in their work practice. This convention emphasises the use of simulators for both training and assessment (STCW, 1995).

For example on the use of simulators for maritime education, the set of simulator-based training courses offered by IMO for both novice and experienced participants includes, but is not limited to, the following simulator courses that are listed in Table 4.2.

Operator Training

This group, operator training, comprises various examples of training applications for professionals in the field, demonstrating the potential of simulators in the training of operators to achieve higher levels of safety and efficiency. The main distinction between this group, operator training, and the previous one, education and training, is that the former is concerned with academic training for navigation students and

TABLE 4.2: Simulator-based courses

Some of the simulator-based courses offered by the IMO (STCW, 1995)			
1	Ship simulator and bridge team-work	2	Liquefied petroleum gas (LPG) tanker cargo
3	Liquefied natural gas (LNG) tank-er cargo	4	Oil tanker cargo + Ballast Handling (BH)
5	Chemical tanker cargo + Ballast Handling (BH)	6	Automatic Identification System (AIS)

the latter is concerned with operational training for professionals in the field. Operator training could be customized to aim for different purposes such as:

- Training for navigation with higher energy-efficiency and lower emissions.
- Training for navigation on specific maneuvers such as the man-overboard Williamson turn.
- Training for navigation in specific conditions such as shallow water maneuvering.

For example, Benedict et al. (2014) presented their development of an innovative simulator that presents future projections of a ship's path according to present conditions. This could be classified in the development group, however, they emphasised the value of their developed simulator in training, elaborating that it can be useful in briefing and debriefing sessions for ship handling simulator training, and that it can be used as a training tool on board ships. Jensen et al. (2018) presented a proof-of-concept of a training that is helpful in saving fuel. They stated that the fuel-efficiency of ships is not merely a technical concern. Their research showed that factors such as awareness, knowledge, and motivation are also important parameters in determining the overall fuel consumption. Lastly, Formela et al. (2015), used a maritime simulator to train candidates on two different man-overboard maneuvers. Their investigation concluded that the Anderson Turn is more efficient than the Williamson Turn.

Assessment

The assessment group includes simulator applications that could have significant implications on organizational decisions. This group includes emerging (simulator application) subgroups such as risk analysis, objective performance assessments, and port and harbor studies. The risk analysis subgroup applications use the simulators in their studies to focus on safety. The use of statistical methods for calculating collision probabilities is common here. For example, Popov et al. (2021) held an investigation in a ship simulator based on a reconstruction of the Ever-Given grounding incident in the Suez Canal. Gende et al. (2019), alternatively, proposed a set of practices for reducing ship strike risk as an active whale avoidance strategy and tested its feasibility in the simulator.

Development and Testing

The Development and Testing group is using the simulator as a step toward the development or evaluation process of a product, procedure, new technology, or new design. Most of this group is developing programs/algorithms that enable autonomous maneuvering, and they are using the simulator to present their developments, or to evaluate them using the human-in-the-loop concept. In June 2015, after a series of EU projects from 2009, the IMO approved the “Guideline on Software Quality Assurance and Human-Centered Design (HCD) for e-Navigation”. The objective of the e-Navigation concept is to harmonize the collection, integration, exchange, presentation, and analysis of marine information by electronic means to enhance the operations and their safety. IMO considers e-Navigation to be driven by the user rather than technology. HCD methods require heavy involvement of seafarers and operators in the design and development process of navigation aid tools. From 2015 on, the IMO recommends that HCD should be used in the development of new navigation equipment (MSC, 2015).

As the HCD guideline encourages the involvement of users in the design process, it also, indirectly, encourages the use of simulators in that process. The simulators can play the role of labs, for testing out the new product being under development, measuring the user experience and user satisfaction while using the product, and measuring the performance of the user in a virtual operation using the product. Thus, simulators can be used for the testing and validation of design concepts, enabling effective HCD processes.

For example, Ari et al. (2013) developed a path planning algorithm that is length-optimized and feasible regarding the turning radii of given ship. They demonstrated a proof-of-concept for their algorithm using a ship simulator experiment. Varela and Soares (2015), on the other hand, developed a simulator program that is built specifically for training on ship-to-ship offloading maneuvers. They used navigation simulators to present the development works and test the final product.

In the literature, the development group is not limited to products (such as programs/algorithms), it also includes the development of procedures and specifications. For example, Hareide and Ostnes (2017) developed a navigation procedure that is inspired by a simulator experiment. They performed a simulator experiment with eye tracking devices. They identified efficient scan patterns and developed scan patterns, for maritime navigators that maximize safety. Lastly, it is observed that virtual reality (VR) navigation simulator developments and testing studies are emerging (Jinlong, 2019; Lauronen et al., 2020).

Research and Innovation

This group is for research and innovation types of applications. Covering a wide scope of research areas, where simulators might prove useful. This group takes place mostly in academic and research institutes and is split into several subgroups such as: ocean engineering, naval engineering, control engineering, human-computer interaction, human factors, and learning science. The main subgroup is the "human factors" research subgroup. This subgroup is mainly researching the human operator inside the simulator, focusing on either the human experience or performance. More than half of the literature reviewed in this group used physiological monitoring as part of their data collection methods. They measured either heart rate or brain signals to gain understanding of the workload or stress level the operators were experiencing in real-time.

For example, Hontvedt (2015) introduced a study that examined the experience of professional maritime pilots in a simulator training exercise using Azipod propellers to navigate in high winds. The participants reflected on their experience in debriefings. The interaction analysis performed by Hontvedt shows that simulator training has distinct advantages, however, the pilots experienced a lack of photorealism and graphical fidelity in the used simulator and this could have compromised the effectiveness of the training. Orlandi and Brooks (2018) also evaluated the experience of marine pilots in a berthing operation exercise. They used both qualitative data, such as the self assessment scales, NASA TLX, and Likert scale, and quantitative data from Electrocardiography (ECG), Electroencephalography (EEG), and eye tracking. They demonstrated that they could indirectly monitor levels of mental workload as they developed over time in a demanding operation.

Lastly, Nilsson et al. (2009) presented a study similar to Orlandi's, evaluating the performance of marine pilots, in two different bridges: one with more advanced instruments and the other with less advanced technology on board. They used several data collection methods, both qualitative (questionnaires and expert opinion) and quantitative data (physiological sensors and response times). They concluded that performance is not clearly correlated with the level of technology on board, however, if the mariners' experience is taken into consideration, they found a link between experienced navigators performing better in less advanced bridges and less experienced navigators performing better in more advanced bridges.

"Learning" is the second largest subgroup in this category. This application subgroup is using the simulators in research to focus on learning. The difference between training and learning in this context is as follows:

- Training describes the use of a simulator for nautical students and experienced professionals to enhance some of their relevant skills.
- Learning describes the use of a simulator to understand the process of knowledge transfer (and skill transfer as well). This includes the actions that contribute to learning, including the role of the instructor in briefing, during the exercise, and debriefing.

For example, Hontvedt and Arnseth (2013) researched the learning in a simulator. They investigated the context in which students and instructors collaborated to achieve learning goals. The study showed that collaboration and meaning making of students is an important entity to address in the design of simulator exercises. In addition, Sellberg (2018) performed an ethnographic study to investigate the instructor role in a simulator exercise. The research shows that continuous instructional achievement, from briefing to in-session instructions to debriefing, is highly important to facilitate learning in a simulator.

Digital Twins

The sixth category, Digital Twins, is an emerging umbrella of applications that can "naturally" be performed in a simulator. In digital twin applications, the ships on the (simulator) screens would be representing real assets in an operation. Simulators can be used to manage these assets, or as could be expected, to remotely control, monitor or supervise them.

"A digital twin is a virtual representation of an asset, used from early design through building and operation, maintained and easily accessible throughout its lifecycle" (Smogeli, 2017).

According to DNVGL (Smogeli, 2017), digital twins include multi-layered models such as: analytical models for structures and hydrodynamics, information models for systems and components, 3D visualization models of components, time-domain models of components and systems, sensor and process data from the real vessel, software-driven control algorithms and virtualized communication networks.

4.1.3 Case study: NCA simulator applications

This section lists simulator applications according to the Norwegian Coastal Administration Pilot Service (NCA PS). Five simulator applications according to the NCA PS are listed below:

1. During the preparations of a special pilotage operations, for example, the pilotage of the Sleipner platform into Haugesund port. The Sleipner is a huge offshore semi-submersible platform that needs to be maneuvered within tiny margins in and out of port. Part of the training for this operation took place at the Heerema simulator center.

2. In the process of recruiting pilots, simulators are used as the last step for testing candidates' performance, in tests called "final cut assessments." Since 2018 the NCA is using, among other tools, simulators at NTNU campus Ålesund to achieve this objective. They use general mental ability (GMA), personality, ability and skill, and stress tests, in addition to structured job interviews and simulator exercises. In the simulator exercises, factors such as blackouts, lack of GPS, gyro errors, and ocean currents are inserted into the scenarios to make them as challenging as they can possibly be in reality. The NCA is using a panel that consists of: pilots, pilot director staff members, an HR consultant, and the leader of the pilot district. The panel forms a widely exposed assessment group. Correspondence between previous tests and real time impressions are checked. Much is revealed about the candidates, and simulators create a suitable environment for research. The NCA's practical experience with simulators for the final cut assessments is that simulators are well suited because they unveil the candidates' strengths and weaknesses. Still, the NCA would need to develop objective ways of measuring candidates' conditions (pulse/stress/forms) and assessing their overall performance.

3. Simulators are used for safety-critical port operations. The case can be simplified by assuming that ports are staying the same in size and ships are increasing in size. Weather conditions can be harsh sometimes, so simulators can be used to test the external limits operations face that may have previously been deemed too risky. Simulator port studies consist of:

   - Risk assessments: define a given risk for a vessel upon arrival or departure under various meteorological conditions.
   - Mooring analysis: identifies mooring opportunities towards the harbour, the risk associated with this, and the outer meteorological limits of the mooring. For example: "can MS Iona at 340 m length berth in Stavanger with 35 knots wind?"

4. Simulators are used for operational training (demanding operations). This can be general or specific training. Training can focus on technical skills, coordination, cooperation, leadership, and/or communication. It can be general training such as ship handling, tug courses, VTS, or bridge resource management (BRM) courses. It can also be specific training on predefined assignments such as entering and leaving the Nexans Aurora cable layer in Halden. The training can also aim to distribute learning across the organization or focus on organizational culture, and safety culture.

5. Finally, simulators can be used for ship handling training through virtual reality simulators. The NCA is developing a VR simulator with generic configurable ship models for pilotage training in advance of the real operation. Additionally, this tool can be used for BRM, teamwork, and risk assessment studies.

4.2 Accuracy requirements

The broad scope of ship simulators' applications is raising validity concerns. In this thesis, the validation concern is limited to functional fidelity. Functional fidelity is a simulator quality that considers the accuracy of ship dynamics in water (Hontvedt and Øvergård, 2020). Although most ship simulators included in this study are developed for education and training purposes, they are actually used for a much wider application elsewhere. In the maritime industry, ship models undergo subjective validations. Subjective testing is essentially the acceptance of an experienced officer, which is an important consideration. However, the introduction of objective testing in the certification of simulators or ship models is crucial. Objective testing is a quantitative assessment based on comparison with validation data. Validation data is an appropriate benchmark, derived either from full-scale sea trials done with the same ship as the simulator model, or from free-running basin trials (model tests).

The airline industry, according to the Certification Specifications for Aeroplane Flight Simulation Training Devices (CS-FSTD, 2018) of the European Aviation Safety Agency (EASA), is addressing accuracy concerns. The concerns are addressed within the certification specifications. Qualification guidelines include objective testing in addition to pilot acceptance (subjective testing) and functional testing. The objective testing covers a range of plane behavior details including flight dynamics, the response of the airplane to drag, thrust, attitude, altitude, temperature, and center-of-gravity. In addition, test categories also cover ground effects, wind shear effects, simulator computer capacity, aerodynamic modelling, stall characteristics, icing, and mass properties.

Taking the full flight simulators (FFS) as an example, they are classified in four levels, A, B, C, and D (level D has highest functionality), according to their functionalities and match fitness against validation data, given defined tolerances. The maritime industry should account for such certification specifications for ship models, taking into consideration maneuvering behavior in calm water and with environmental effects.

In the maritime industry, a DNV Standard exists for Maritime Simulator Systems that gives the requirements of the performance of maritime simulator systems. The objective of this standard is to provide appropriate levels of physics and behavior realism in accordance with training and assessment objectives (DNVGL-ST-0033, 2017). Beyond the list of simulator types in Table 4.1, this standard recognizes additional types of simulators such as crisis management, oil spill, mobile offshore units, high-speed crafts, and other simulator types, but does not provide certification specifications per type. Type specific requirements can be acknowledged separately using compliance statements.

This standard lists requirements related to behavioral realism, physical realism, operating environment, and dynamic behavior. A few of the general requirements specified that are relevant to ship dynamics are summarized as one's own ship shall be based on a 6-DOF mathematical model. The model shall realistically simulate its own ship hydrodynamics in open water conditions including the effect of winds, waves, tidal streams, and currents. Class A simulators, in addition, are required to simulate realistically their own ship hydrodynamics in restricted waterways, including shallow water effects, bank effects, interactions with other ships and direct, counter, and sheer currents.

An appendix is added to the standard version of 2017 for the documentation specifications of mathematical and hydrodynamic models used in simulator systems. This includes the documentation of speed data, tactical diameter, and crash stop distance. The mentioned data shall be modelled, documented and verified.

It is obvious that the standard aims to provide 'fit-for-purpose' simulators and touches upon ship behavior and hydrodynamic modelling specifications. Despite that, it is also observed that the standard has two main shortcomings:

- First, the standard recognizes only education and training types of simulator applications. It complies with the STCW conventions. The other application categories, presented in Figure 4.1, are not taken into consideration.
- Second, the standard requires the verification of maneuverability indicators such as full speed and tactical diameter. This set of indicators is not elaborate enough to describe maneuverability of a ship and does not comply with the indicators specified in the maneuverability standards of the IMO (MSC.137(76), 2002).

In addition, the standard does not specify how to verify the given indicators, since it does not require "objective testing". The verification of physical modelling is indeed a challenge and therein lies the core of the matter concerning the objective of such simulator standards: "providing appropriate levels of physics and behavior realism..."

4.3 Discussion

Simulators are no longer mainly used for nautical education. The offshore industries are rapidly growing with examples such as bottom-fixed wind turbines, floating wind farms, fish farming, subsea completions, bridges, tunnels, and the ocean surveying industry. Together with the growth of the quantity and quality of offshore operations, the challenges imposed by distance-to-shore, environmental loads, weather, and the IMO energy efficiency regulations force the industry to evolve into a safer and more efficient one. Therefore, the industry methods for collaboration, design, and training must evolve. There is a need for a development medium and simulators naturally fill this gap, and give professionals the potential to "sit in the same room" with their various roles from management to operations, and from design to research.

In this sense, simulators can be viewed as the enablers of operations that are usually deemed as impossible. The need for simulators is believed to continue to rise. Simulators will help in the design of the ships of tomorrow. They will help in the remote control of surveying robots that will explore the ocean's depths. Simulators will help enhance the way floating wind turbines are installed and will help enhance port infrastructure and waterway designs. They will help in pilotage operations of huge containerships with autonomous tugboats. Simulators will train teams to work together, with their different roles, languages, and cultures. Likewise, simulators will help operators manage their risks and achieve more with what they have.

"Realistic physics" in simulators was indicated by one of the interviewees as a challenge. This challenge was turned into a concern after reviewing the simulator standard requirements. It was identified that the maritime simulator standards do not require "objective testing" for the certification of ship models, while the airplane flight simulator standards do require that.

Simulators are used for a wide range of applications, where some applications require higher functional fidelity than others, for example, the application of training nautical students probably requires a more relaxed functional fidelity than that of pilot recruitment assessments. Connecting the identified concern with the application extent, the functional fidelity concern is raising an alarm regarding the fitness-of-purpose of the various simulator applications, creating an urge to investigate the hydrodynamic models used in simulators and their accuracy.

Moreover, simulators prove crucial in the development towards maritime autonomy. Simulators contribute to the developments of collision avoidance and path planning systems for autonomous vessels (Ari et al., 2013; Cheng and Zhang, 2018; Mizuno et al., 2016; Xu et al., 2018; Zaccone and Martelli, 2020). Simulators also contribute to autonomous vessels in different ways, for example, Miyake et al. (2013) is demonstrating the effectiveness of a decision support system (DSS) that automatically exchanges the navigational intentions between encountered ships. Olindersson et al. (2017) demonstrates the feasibility of a safety index that takes into consideration probability of grounding and probability of collision to quantify safety in real-time.

As learned from the literature review in the previous chapter, Chapter 3, ship motion prediction is a cornerstone in collision avoidance and path planning systems for autonomous vessel. Uncertainties in the prediction of ship dynamics would manifest themselves in the overall performance of the control system. Such control systems, given their objectives in Section 3.1.2, are supposed to operate in real-world conditions, and thus, they require maneuvering models that perform accurately in operational conditions. The accuracy of maneuvering models becomes more important in such high technology readiness level (TRL) systems, as well as in the simulator testing of such high TRL systems.

4.4 Takeaways

The key points of this chapter are summarized in the following list:

I The need and potential of maritime simulators are significant. The wide range of simulator applications confirms the need, and the list of advantages of simulators confirms the potential.

II The scope of simulator applications is growing beyond both the intentions of manufacturers and certification requirements.

III Functional fidelity is a concern. According to the standards in the airline industry, simulators are subject to "objective testing", however, in the maritime industry, they are not.

IV Questions have been raised regarding how accurate the hydrodynamic models used in simulators are. A method for evaluating their accuracy is needed.

Chapter 5

Maneuvering Models

This chapter is a summary of the results of Method 3.1, Simulations (Zghyer et al., 2022b), where standard maneuvers are performed in two different simulators and the simulator data is compared with experimental data. The objectives of this method are as follows:

- To evaluate the accuracy of maneuvering models used in simulators.
- To address the suitability of simulators for various applications.

5.1 State-of-the-art

Initially, ship dynamics was split into two theories, calm water maneuvering and seakeeping. The former theory addresses horizontal plane motion of a ship moving and turning in water, assuming calm water conditions. The latter however, addresses wave-induced motions for a ship at zero or constant speed in a straight course. Seakeeping calculations are often done in the frequency domain by potential flow theory.

For maneuvering, there are two dominating mathematical models: the whole ship (regression) models (WSM), also referred to as Abkowitz models (M. A. Abkowitz, 1964), and modular maneuvering ship models (based on the work of the Japanese Mathematical Model Group, hence called the MMG model, Yoshimura, 2005). In WSM models, the mathematical model is constructed from hull coefficients obtained from experimental tests or numerical simulations. Planar motion mechanism (PMM) tests have typically been applied to obtain the coefficients. During a simulation, these coefficients are considered to be tabulated values, which means that regression models are suitable for real-time simulations. Commercial simulators used for training purposes are often based on regression models. In such simulators, the coefficients can be "tuned" based on free-running model tests or full-scale measurements, to improve the accuracy of the simulator.

A modular model with the solver-in-the-loop is an alternative model, where the different physical phenomena are calculated separately. This can be favorable in the design phase, since it is straight forward to modify the ship hull and perform new maneuvering simulations. Moreover, in research, the modular approach has some advantages, since it is possible to investigate the dominating physical phenomena for different kinds of maneuvers.

The combination of seakeeping and maneuvering can be done in several ways. In the last decades there are two dominant approaches: one is based on convolution integrals to account for memory effects (Bailey et al., 1998; Fossen, 2005), and the other is based on a two-time scale assumption (Skejic and Faltinsen, 2008). The two-time scale approach assumes that the maneuvering behavior of the ship experiences a more slowly varying time scale than the linear wave-induced motions. Hence, only the mean second-order wave loads are accounted for in the maneuvering equations (Chillcce and Moctar, 2018; Cura-Hochbaum and Uharek, 2016; Seo and Kim, 2011; Yasukawa and Nakayama, 2009; Yu et al., 2021; Zhang and Zou, 2016). The maneuvering models in Cura-Hochbaum and Uharek (2016) and Chillcce and Moctar (2018) are regression models, while the others are modular maneuvering models. The models above generally show high accuracy. However, the two-time scale assumption can be questionable for long waves, particularly for following sea. This is because when the wave encounter frequency is low, the linear wave-induced motions can experience the same time-scale as the maneuvering motion.

In addition to the maneuvering and seakeeping theories, that account only for hydrodynamics (wave loads), much has to be incorporated in a simulator maneuvering model. Maneuvering models should account for the following physical phenomena:

- A very basic maneuvering model should account for:
  - Hydrodynamics forces: maneuvering and seakeeping theories.
  - Control inputs: rudder, propeller, and thruster forces.
- A more advanced maneuvering model should also account for:
  - Environmental forces: wind and currents forces.
  - 2^{nd} order slowly varying wave drift forces.
- A specialized maneuvering model should also account for one or more of the following effects:
  - Shallow, restricted, and confined water effects.
  - Ship-ship, ship-bank, and ship-tug interaction effects.
  - Broaching, Hull fouling, or other effects.

In Appendix A, a detailed description of the components of a "basic" maneuvering model (unified model approach similar to Eq. 3.2) is attached as an example of simulator maneuvering model components.

5.1.1 Background theory

This section provides a short description of the background theory of the two simulators included in the Simulations method 3.1.

Simulator A

Sim A is a navigation simulator that provides ship motion time-domain simulations in 6-DOF. It is a modular model that solves both the seakeeping and maneuvering problems simultaneously, including the effects of waves, winds, and ocean currents. It considers water depth, shallow water effects, canals and banks, ship interactions, and different propulsion configurations. It also takes into account mooring forces and anchor forces. This simulator is available in a range of configuration options, from a desktop version to a full mission bridge simulator version. Sim A trials were run on a desktop setting for this research.

This simulator is based on Ottosson and Bystrom (1991) for the basic calm water maneuvering simulation where the radiation hydrodynamic coefficients are assumed to be constant based on the mean encounter frequency during maneuvering. The wave-induced motions are incorporated as follows. The added resistance in waves is computed according to Gerritsma and Beukelman (1972). Strip theory is used for calculating the hydrodynamic added mass and damping loads according to Kaplan and Raff (1972). The horizontal slow drift excitation loads in irregular beam sea waves are calculated using the method of Faltinsen and Løken (1979).

In this simulator, the theories used for calculations are the backbone of the numerical modeling. The option for empirical adjustments is available for the manipulation of force and moment coefficients, for reproducing a desired ship behavior. This option is relevant because the model can be "tweaked" to mimic full-scale trials or model tests. Additional resistance and second-order wave forces are optional, and they were turned off according to their default setting. Explicit values of second-order wave forces can be added to provide further adjustments to drift and turning in waves.

Simulator B

The mathematical model of Sim B is implemented by Rabliås and Kristiansen (2022). It is a 4-DOF modular model based on Skejic and Faltinsen (2008). The calm water hull lifting loads are calculated with the slender body theory, while the zero-frequency added mass loads are calculated with the 3D panel code WAMIT. Experimental values of calm water resistance and propeller thrust are obtained from Shigunov et al. (2018) and El Moctar et al. (2012). A conventional rudder model is applied for the calm water rudder loads, and the 2D+t approach presented in Rabliås and Kristiansen (2021) is applied for the transverse viscous loads.

The wave loads are implemented following the two-time scale assumption, which means that the linear wave-induced motions are assumed to have a different time scale than the more slowly varying maneuvering motions. Hence, only the slowly varying second-order wave loads are accounted for. The slowly varying drift loads in irregular waves are estimated with a modified version of the "time-domain" method first presented by Hsu and Blenkarn (1972). This method considers the irregular waves as a series of regular waves with different wave periods and wave heights. The drift loads are then estimated for each wave encounter, as if it were a regular wave. The foundation of this method is the numerical method used to estimate the drift loads in regular waves. Sim B estimates the drift force in the x-direction with a combination of the pressure integration method and asymptotic method for short wavelengths in (Faltinsen et al., 1980), which accounts for forward speed. The sway and yaw drift are calculated with the 3D panel code WADAM, where only the encounter frequency is taken into account.

The effect of the wave on the propeller and rudder inflow is also considered. The x-component of the inflow is modified according to Taskar et al. (2016), where the incident wave and the linear wave-induced surge and pitch velocities are taken into account. The incident wave and the linear wave-induce sway, roll, and yaw velocities are taken into account for the y-component of the inflow. More information about the numerical model can be found in Rabliås and Kristiansen (2021, 2022).

5.2 Accuracy requirement level (ARL)

Considering the accuracy concern that was identified in Section 4.2, a standard named the "accuracy requirement level (ARL)" is proposed in this section to fulfil the following two objectives:

- For simulators: to define simulator capabilities in terms of functional fidelity. More precisely, ARLs are properties of each floating object in a simulator.
- For simulator applications: to classify the level of physical modeling accuracy required by the various applications.

What difference does it make whether a simulator appreciates the impact of increasing wave height on ship speed? How can one tell if this maneuvering model is good enough and if this simulator is fit-for-purpose? Looking at the various applications covered in Section 4.1.2, it is clear that the objective of the applications is to dictate the level of accuracy required. For example, a ballast handling simulator course should have a different accuracy requirement compared to a safety-critical operation training or a pilot recruitment final cut assessment.

To summarize the root of the accuracy concern, as it resonates with the status-quo, the standard for Maritime Simulator System (DNVGL-ST-0033, 2017) does not recognize applications other than training, additionally, it does not require objective assessment of ship dynamics, as is the case with the flight simulation standard (CS-FSTD, 2018). There is a need for definitions of accuracy requirements of the different applications. Therefore, a simple classification of the accuracy requirement levels (ARLs) is proposed and presented in Figure 5.1, with the definitions of the levels as follows:

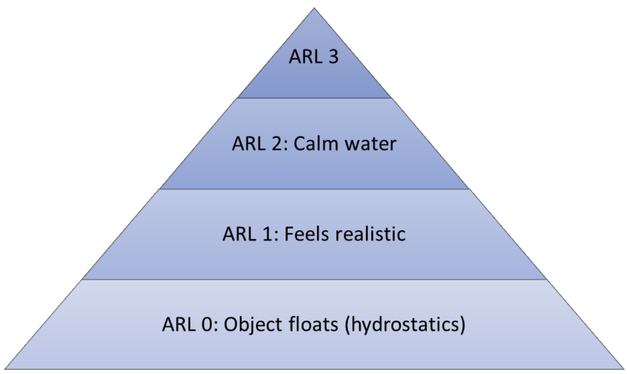

FIGURE 5.1: Accuracy requirement levels

- ARL 0: object floats in water. In this accuracy level, only the hydrostatics are involved. Hydrodynamics are not required. Objects are floating and according to their purpose, are visible on the surface, such as buoys or icebergs.

- ARL 1: maneuvering feels realistic. Most navigation simulators fall in this category. After the model of a ship is created, it is evaluated by a navigator experienced with similar ships (subjective testing). Once the subjective evaluation result is deemed positive, the model is issued for use. Such models are generally considered (among their users) very accurate and are used for education, training, and beyond.
- ARL 2: calm water accurate. This level, in addition to the subjective testing of an experienced navigator, requires "objective testing" of the model. Quantitative measures of the model's maneuvering performance in calm water need to be compared against a benchmark and must fall within given predefined tolerances (10% error margin from the benchmark, for example). The maneuvering performance should be documented according to the IMO maneuverability standards. Maneuvering benchmarks should be collected from full-scale sea trials or free-running model tests.
- ARL 3: accurate in operational conditions. In addition to satisfying all previous levels, this level requires the model to appreciate the operational environmental loads, such as waves, ocean currents, and winds, accurately. Operational conditions can include different water depths, such as the shallow water condition. Benchmark data is difficult to obtain for a combination of environmental effects. However, experimental and sensor technologies are evolving, for example, 3D wave radars are now feasible. Despite challenges, the possibilities are immense on this frontier. A shortlist of operational conditions needs to be defined. Quantitative measures of the model's maneuvering performance, in the selected operational conditions, need to be compared against a benchmark and must fall within given tolerances. In addition, the ship model should appreciate the environmental loading (whether it is wave, wind, or current loads) and its effects on maneuverability.

These levels are relevant and useful. They are relevant because the accuracy of real-time hydrodynamic models (especially under environmental loads) is not to be taken for granted. On the contrary, high uncertainties are involved. The levels are said to be useful because they are simple and serve as communication tools that describe the amount of effort behind creating a ship model and they can also communicate the capabilities of a model.

Therefore, it is relevant to keep the question in mind when using a simulator "is this maneuvering model good enough for the given application?". In Table 5.1, there are examples of application classifications in terms of the accuracy requirement levels (ARLs) according to the applications mindmap in Figure 4.1.

In most cases, ARL 1 is enough for applications that fall in the "education and training" category as well as research applications in the fields of human factors and learning.

ARL 2 applications can be summarized as "research and innovation" projects in the fields of human-computer interaction (HCI), computer or control engineering, safety engineering, and ocean or naval engineering. Development and testing of either software or hardware, including the human-in-the-loop and the human-centered design simulator phases, also require ARL 2, at a minimum. Operator training for specific operations such as the training for the man overboard emergency maneuver or training for low emissions maneuvering also require ARL 2.

TABLE 5.1: Classification of the accuracy requirement levels (ARLs)

ARL Classification of simulator applications (an example)	
ARL 1	"Education and training"; and "research and innovation" applications in the fields of human factors and learning
ARL 2	"Research and innovation" projects in the fields of HCI; computer/control engineering; safety engineering; and ocean or naval engineering; "development and testing" applications of low TRL; and "Operator training" applications
ARL 3	High TRL "development and testing" applications; and safety critical "operator training" applications.

The development and testing of new controllers or autonomous maneuvering technologies should require ARL 3, at least for the products that matured to a high technology readiness level (TRL). The assessment of pilot applicants based on their performance in simulator-based "exams" requires attention to operational accuracy because winds and currents in fjords and straits can be very tricky to model. Safety-critical training such as ship-to-ship operations, extreme weather operations, and the pilotage of huge ships to harbor requires higher fidelity than a "normal" nautical school simulator. The ARL classification provided in this section in Table 5.1 is just an example and is not based on research.

Simulator applications falling under the category "development and testing" include the development of remote control systems and autonomous (or semi-autonomous) systems. For high TRL systems that are supposed to perform in the real-world, it is not only simulators that require ARL 3, but also the actual systems (that are being developed and tested in simulators) require maneuvering models with high functional fidelity. The functional challenges of autonomous vessels identified in Literature review A, in Ch. 3, *ship dynamics* and *environmental loads* are well-manifested in the maneuvering models. For systems that are supposed to guide the ship by predicting its maneuvering behavior, such as collision avoidance or path planning systems, the importance of the functional fidelity grows exponentially, especially when no operator is on board.

5.3 Maneuverability

The first objective of this chapter is connected to the evaluation of the accuracy of maneuvering models used in simulators. A prerequisite of such evaluation is the understanding of maneuverability. According to the standards for ship maneuverability of the Maritime Safety Committee of the International Maritime Organization (IMO) (MSC.137(76), 2002), the aim of the standards is to evaluate the maneuvering performance of ships and to assist in their design, construction, repair, and operation. The standards are based on the idea that ship maneuverability can be evaluated from characteristics of conventional trial maneuvers (standard maneuvers). This idea links maneuverability to maneuvering trials, such as turning circles and zigzag tests. Therefore, the standard (MSC.137(76), 2002) is used as the basic guideline for the understanding of ship maneuverability.

Main features of the maneuverability standards

- The standards recognize the maneuvering capability of ships to be an important contribution to the safety of navigation.
- Ships should demonstrate compliance with these standards.
- The maneuvers should be performed without the use of aids that are not readily available in normal operation.

Standard maneuvers and compliance criteria

- Turning circle maneuver: to be performed on both sides with the maximum allowed rudder angle at the test speed. A fixed rudder angle of 35° is applied in this case with the DTC containership. The maneuver starts with a steady approach with a zero yaw rate. Turning circles include multiple characteristics, such as advance, transfer, tactical diameter, turning radius, and drift angle, as shown in Figure 5.2.

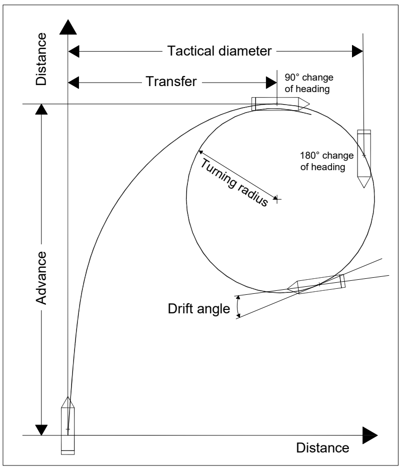

FIGURE 5.2: Turning circle maneuver characteristics

- Zigzag test: it is the maneuver where a known amount of helm is applied alternately to either side as a known heading deviation from the original heading is reached. In this case, a helm of 20° is applied and is alternated to the other side once the heading reaches a deviation of 20°. Such a test is referred to as a 20/20 zigzag. Zigzag tests include multiple characteristics, such as first overshoot angle, second overshoot angle, and reach, as shown in Figure 5.3. The figure is showing an illustration of a 10/10 zigzag maneuver.
- Full astern stopping test: it determines the track reach of a ship from the time the "full astern" order is given until the ship almost stops.

The acceptance criteria of ship maneuverability according to IMO is as follows:

- The turning ability is satisfied if the characteristics of the 35° turning circle maneuver satisfy the following:
  - The advance is less than 4.5 times ship length.

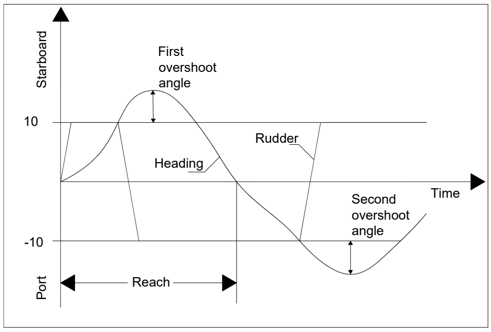

FIGURE 5.3: Zigzag maneuver characteristics.

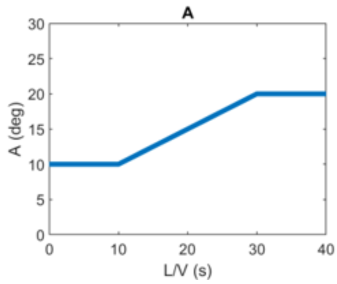

FIGURE 5.4: Threshold A

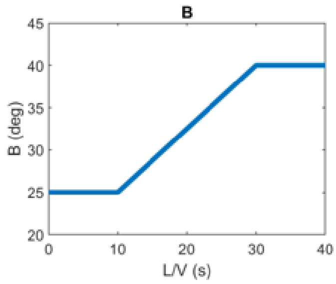

FIGURE 5.5: Threshold B

  - The tactical diameter is less than 5 times ship length.

- The initial turning ability is satisfied if, after applying a 10° rudder angle,
  - the ship would not have travelled more than 2.5 times the ship length by the time the heading has changed 10° from the original heading.

- The yaw-checking and course-keeping abilities are satisfied if the characteristics of the zigzag tests satisfy all the following:
  - For the 10/10 zigzags, the 1^{st} overshoot angle must be less than Threshold A.
  - For the 10/10 zigzags, the 2^{nd} overshoot angle must be less than Threshold B.
  - For the 20/20 zigzags, the 1^{st} overshoot angle must be less than 25°.

  The A and B thresholds are demonstrated as functions of the ship-length-to-speed ratio, they are shown in Figures 5.4 & 5.5.

- The stopping ability is satisfied if the track reach of the crash stop test is less than 15 ship lengths, or 20 ship lengths for very large ships.

Among the standard maneuvers presented above, only 20/20 zigzags and 35° turning circle tests are performed in this study. The primary reason this study is limited to these two test types is the availability of a benchmark. A benchmark is needed for the evaluation of numerical simulators. The benchmark that was available for this study consisted of only 20/20 zigzags and 35° turning circles, therefore, the selection of simulation trials matched the benchmark availability.

Limitations of the Maneuverability Standards

- The standards were developed for big ships, above 100 meters in length, with traditional propulsion and steering configurations. Except for chemical tankers and gas carriers, the standards should be applied regardless of the length. It is stated in the standards that they should be regularly reviewed and updated by IMO, as appropriate, to take into account new technologies, findings of new research, and experience with the present standards.
- The standards consider maneuvering performance in calm water. They do not consider adverse weather conditions.
- The standards apply to the following conditions: deep, unrestricted waters, calm environment, full load (summer load line draught), even keel condition, and steady approach at the test speed.

5.4 Objective testing

Simulations with the two simulators, in calm water and irregular waves, are now compared to the experimental results. Turning circles with a 35° rudder angle and 20/20 zigzag maneuvers are simulated with the DTC hull. The irregular wave conditions used in the simulations are presented in Table 2.6. For the wave conditions highlighted in green (last five rows), the simulations are compared to experimental results.

The timeseries of selected conditions are presented for illustration purposes, while some trial characteristics are chosen to compare trends for a range of conditions. For the turning circles, these characteristics are: the advance, transfer, tactical diameter, and average speed. The first three are standard characteristics that are widely used, while the last one is defined as the average speed for the first 1000 seconds of the maneuver. For the zigzag maneuvers, the first overshoot angle, the second overshoot angle, reach, and average speed are considered. The first three are standard responses, while the last one is defined as the average velocity for the first 350 seconds of the maneuver.

The experimental results for irregular waves are from the experiments in Rabliås and Kristiansen (2022). An irregular sea state has a stochastic behavior, which means that different realizations of the same wave spectrum will not give identical results. The experimental tests were performed for different realizations of the same sea state. To illustrate the stochastic behavior of irregular waves, results from all these realizations are included in the figures, presenting the comparisons of the simulations and experiments, whereas the numerical simulations are performed for only one realization in each condition. This must be taken into account when the results are compared. The numerical results would also be different if they were performed with a different random seed. Investigations with both Sim A and Sim B (not shown here) indicate that the results vary when the simulations are performed in different realizations of the wave spectrum. However, the stochastic variation in both cases was slightly less compared to the experiments. For the calm water maneuvers, the experimental results are presented from both experiments in Rabliås and Kristiansen (2019, 2022) from two different test campaigns.

5.4.1 Turning circles

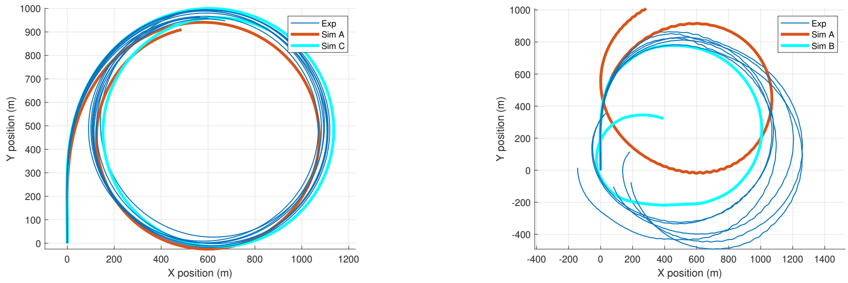

FIGURE 5.6: Trajectories of turning cirlces with 35° rudder angle. Left: Calm water. Right: Irregular waves, in initial head waves, with $H_s = 8.57$ m and $T_p = 11.97$ s (Wave ID 85040)

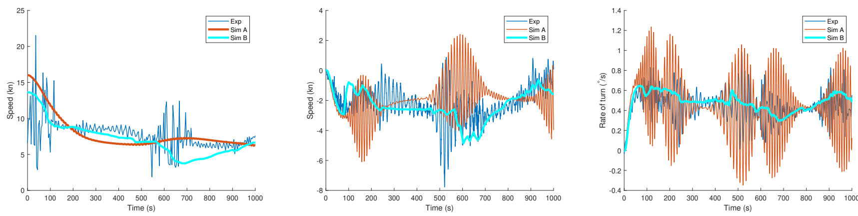

FIGURE 5.7: Velocities from a turning circle with 35° rudder angle, in irregular waves, in initial head waves, with $H_s = 8.57$ m and $T_p = 11.97$ s (WAVE ID 85040). Left: Surge velocity. Middle: Sway velocity. Right: Yaw rate

The trajectories of turning circles with a 35° rudder angle, with the DTC hull, are presented in Figure 5.6. To the left, turning circles in calm water are presented, while turning circles in the severe irregular wave condition, with $H_s = 8.57$ m and $T_p = 11.97$ s (Wave ID 85040), are presented to the right. The initial velocity for the turning circle in calm water corresponds to the Froude number Fn=0.14, while Fn=0.12 for Wave ID 85040. Several repetitions are presented for the experiments, which explains the variation. For the turning circle in calm water, the predicted trajectory is in good agreement with the experiments, for both simulators. However, for Sim A, the steady turning circle in calm water is slightly underpredicted (smaller diameter).

There is more deviation in the turning circle results in irregular waves. The drifting distance is better predicted with Sim B. However, both simulators underpredict the drifting distance compared to experiments. Moreover, for this condition ($H_s = 8.57$ m and $T_p = 11.97$ s), the circle is significantly deformed compared to calm water, this is in particular true for Sim B.

The surge velocity, sway velocity, and yaw rate, for the turning circle in irregular waves, with $H_s = 8.57$ m and $T_p = 11.97$ s (Wave ID 85040), are presented in Figure 5.7. Both simulators fairly predict the initial speed drop in the surge velocity. The linear wave-induced velocities are not included in Sim B. This is due to the two-time scale assumption. However, Sim B compares more adequately to the experiments in the estimation of the slowly varying surge, sway, and yaw velocities.

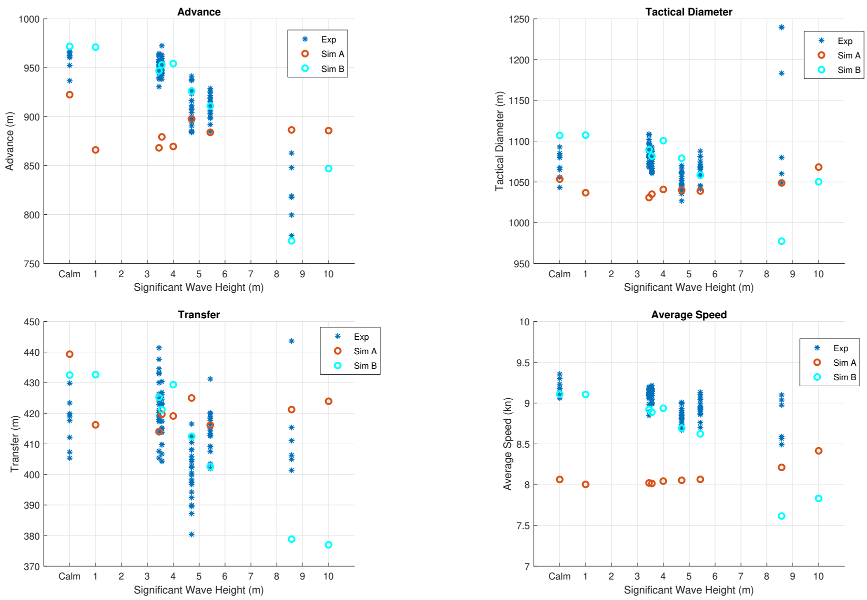

FIGURE 5.8: Results from turning circles with 35° rudder angle, of the DTC hull, in calm water and irregular waves, in initial head waves. Top: Advance and tactical diameter. Bottom: Transfer and average speed

Considering the results in irregular waves, it is important to keep in mind that an irregular sea state has a stochastic behavior, which means that repetitions in the same sea state can give significantly different results. This is particularly true for adverse sea states, where extreme events can be dominant. Comparing single repetitions should be handled with care. Wave ID 85040, with $H_s = 8.57$ m and $T_p = 11.97$ s, is an adverse sea state, and heavy ship motions and non-linear phenomena (slamming in the bow, propeller and rudder in and out of water, etc) were observed during the experiments. This also affects the maneuvering behavior of the ship. Since maneuvering models often are based on linear seakeeping theory, it is expected that there are some deviations from experiments for these kind of harsh conditions.

In Figures 5.8 and 5.9, results from the turning circle characteristics of the DTC hull, with a 35° rudder angle, are presented for calm water and a range of irregular sea states. Advance, tactical diameter, transfer, and average speed are presented for the experiments and two simulators. The results are presented as a function of significant wave height, H_s. The corresponding peak periods can be found in Table 2.6. For the conditions where experimental results are available, the measured significant wave height is applied. The experiments were performed with a constant propeller RPS corresponding to the Froude number Fn=0.14 in calm water, which means that the initial velocity is slightly different for different wave conditions.

For the experimental results, several repetitions are presented for each sea state. This illustrates the stochastic variation that can be expected for maneuvering in irregular waves. For calm water, the results from the two experimental campaigns are presented. This is the main reason of the scatter of the calm water results. However, this illustrates that the experimental results, even in calm water, are vulnerable

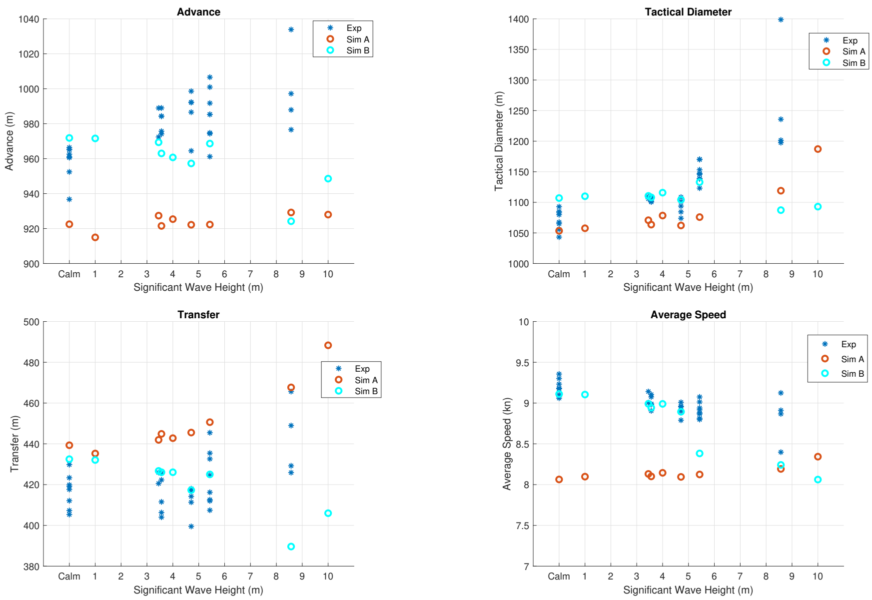

FIGURE 5.9: Results from turning circles with 35° rudder angle, of the DTC hull, in calm water and irregular waves, in initial following waves. Top: Advance and tactical diameter. Bottom: Transfer and average speed

to some uncertainty. Possible contributors to the experimental uncertainty can be model-setup, measurement system, and the neutral rudder angle. Moreover, before the second test campaign, the model was refurbished and repainted. This was done to fix minor dents and scratches in the model, which came from several test campaigns over the years. However, this could also explain some of the deviations between the two test campaigns.

First, we considered the turning circles in initial head sea, presented in Figure 5.8. For advance, the experimental results showed a decreasing trend with increasing significant wave height, H_s. Sim B followed the same trend as the experimental results, and the predicted advance was in fair comparison to the experiments. Sim A slightly underpredicted the advance, and the wave dependency was not as obvious as for the experiments and Sim B.

For tactical diameter and transfer, the wave-dependency was not as obvious as for advance, and both simulators compared satisfactorily with the experiments. However, for the average speed, Sim B captured the wave dependency better, and it was generally in much better agreement with the experiments compared to Sim A. This is because the slowly varying second-order wave loads were not accounted for in Sim A setup.

Also for the turning circles in the initial following waves, presented in Figure 5.9, Sim B was more consistent with the experimental results, compared to Sim A. The experimental results showed an increasing trend, with increasing H_s, for advance and tactical diameter, and a slightly decreasing trend for the average speed. The increasing trend for the advance is opposite of that for the initial head waves, which indicates that the ship experienced an added thrust in the following waves, unlike the added resistance in the head waves.

5.4.2 Zigzags 20/20

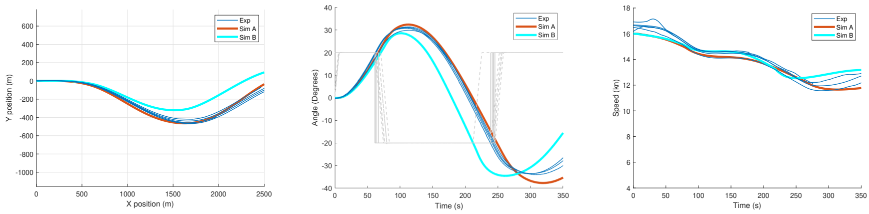

FIGURE 5.10: Results from a 20/20 zigzag maneuver in calm water. Left: Trajectory. Middle: Heading. Right: Speed

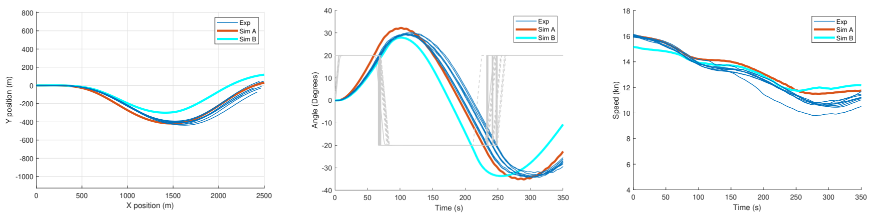

FIGURE 5.11: Results from a 20/20 zigzag maneuver in irregular waves, in initial head waves, with $H_s = 5.43$ m and $T_p = 11.97$ s (wave ID 85020). Left: Trajectory. Middle: Heading. Right: Speed

The trajectory, heading, and velocity for the 20/20 zigzag maneuvers in calm water and irregular waves are presented in Figures 5.10 and 5.11. For calm water (Figure 5.10), Sim A compared more adequately with experiments than Sim B. Sim B reacted faster than the experiments and Sim A. Both simulators predicted the speed drop well. However, Sim A slightly underpredicted the increase in velocity at time, t=300 s, while Sim B slightly overpredicted the velocity.

In Figure 5.11, the trajectory, heading, and velocity, are presented for 20/20 zigzag maneuvers in irregular waves, with $H_s = 5.43$ m and $T_p = 11.97$ s (Wave ID 85020), in initial head waves. The same trends were observed for calm water. Both simulators predicted the speed drop well, but the ship in Sim B turned a little bit faster than in experiments.

In Figures 5.12 and 5.13, the 1^{st} overshoot angle, 2^{nd} overshoot angle, reach, and average speed are presented for 20/20 zigzag maneuvers in initial head waves and initial following waves for a range of irregular wave conditions; calm water results are also included. For the initial head waves (Figure 5.12), the experimental results show a decrease in the 1^{st} overshoot angle in waves compared to calm water, while the 2^{nd} overshoot angle was slightly higher in waves compared to calm water.

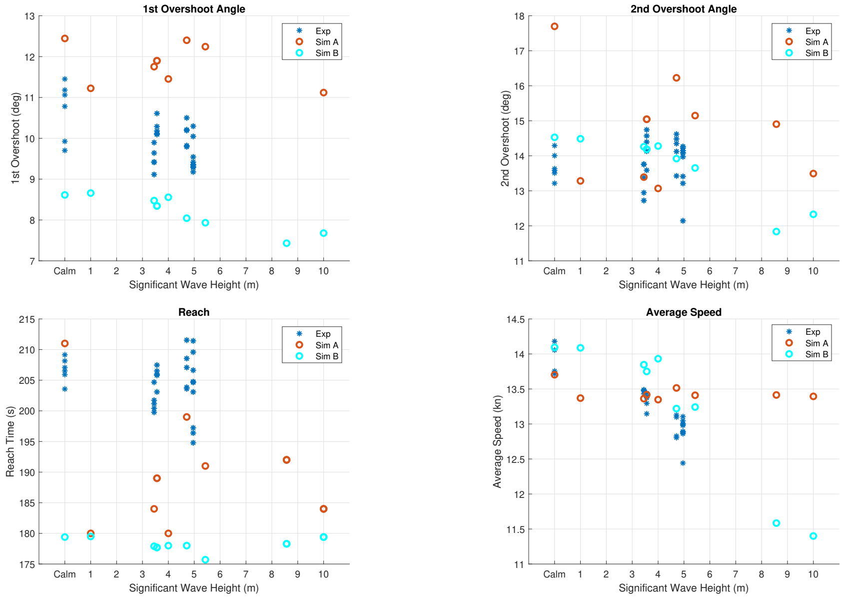

FIGURE 5.12: Results from 20/20 zigzag maneuvers, of the DTC hull, in calm water and irregular waves, in initial head waves. Top: 1^{st} and 2^{nd} overshoot angles. Bottom: Reach and average speed

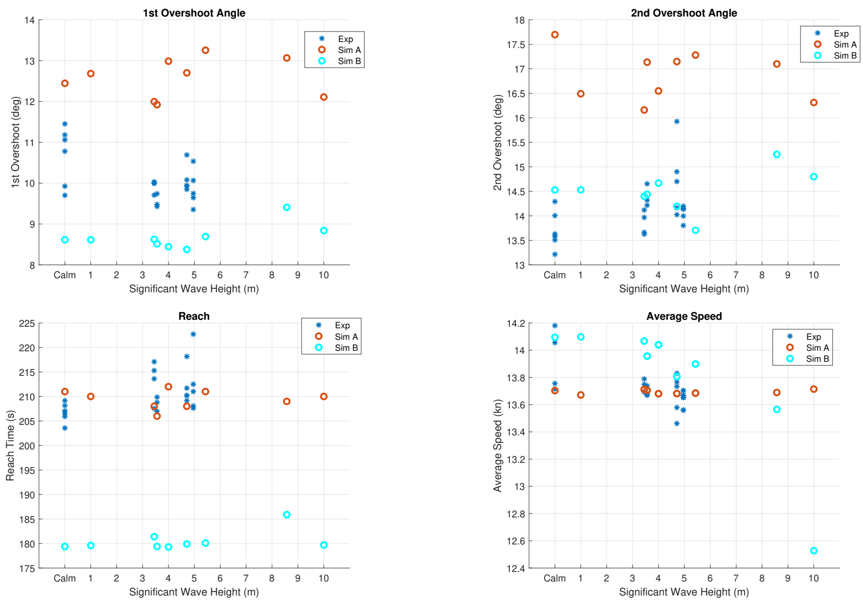

FIGURE 5.13: Results from 20/20 zigzag maneuvers, of the DTC hull, in calm water and irregular waves, in initial following waves. Top: 1^{st} and 2^{nd} overshoot angles. Bottom: Reach and average speed

The same trend was present for the experimental results in the initial following waves. For the reach, it was difficult to deduce any trends for the experimental results in the head sea, while in the following sea the reach was higher in waves compared to calm water. For the average velocity, the experimental results showed a decrease with increasing H_s, in head waves, while the wave effect was limited in following waves.

The two simulators showed similar accuracy for the first overshoot angles and average velocity. Sim B compared better to experiments in the second overshoot angle predictions, while Sim A compared better to experiments in the reach predictions. However, for some responses, Sim A had a relatively large scatter in the results for different wave conditions. Very similar conditions can have a significant difference in the measured response, which indicates that Sim A can be very sensitive to changes in the wave conditions. This behavior was not recognized in the experimental results.

Even though Sim A was setup to only account for first-order wave loads and Sim B was methodologically developed to only account for the slowly varying second-order wave loads, the two simulators show similar accuracy for the investigated zigzag maneuvers. This indicates that the effects of waves can be of less importance in zigzags maneuvers compared to turning circles.

5.5 Discussion

The functional fidelity concern

This awareness of what the simulators can do and what they cannot is key in judging whether their use is fit-for-purpose for the various applications. Data shows that simulators are used for applications far beyond those originally intended. The functional fidelity of simulators must be documented with both objective and subjective testing. The functional fidelity is more of a concern regarding real-world scenarios and operational conditions. There are plenty of physical phenomena that are not covered by a basic maneuvering model, by default. Physical phenomena such as broaching, shallow water maneuvering, or bank effects. In addition, maneuverability is a high-sensitivity outcome based on many variables. Take the example of development of a turning DSS of a containership. This DSS is supposed to provide rudder angle advice to the operator. The DSS is supposed to predict the ship's maneuvering behavior and select the rudder angle that achieves the desired turn.

A useful containership turning DSS should consider shallow water effect, since port waterways are mainly shallow. It should also include environmental effects, especially, wind loads because wind projection area in a container ship is large. Such models should account for loading conditions; the distribution of containers on deck affects the mass distribution and the wind projection area, affecting the maneuverability of the vessel. This also affects the ship draught and disturbs the even keel condition, altering the maneuverability of the ship. The need of such DSS helping navigation operators in selecting the suitable rudder angle for their upcoming turn(s) is on the rise (Dimmen et al., 2020). The grounding of the container ship Ever Given in March 2021 in the Suez Canal and the grounding of the container ship Ever Forward in March 2022 in the Chesapeake Bay are signals on the need of such DSS.

They are also signals on: the need of maneuverability standards in operational conditions, evolution of maneuvering models, and the introduction of "objective testing" as a method to evaluate the overall performance of such models in operational conditions.

IMO maneuverability standard

A limitation in the method is perhaps, using only zigzags and turning circle maneuvers for the evaluation of the accuracy of numerical simulators (in calm water and in waves). According to the maneuverability standard of the IMO (MSC.137(76), 2002), the maneuverability of a ship can be studied using standard maneuvering trials. Standard maneuvering trials consist of i) 10/10 zigzags, ii) 20/20 zigzags, iii) turning circles with max rudder, and iv) full astern stopping tests. The standard is thus followed, but not all variations of the tests were performed. Only zigzags and turning circle tests were used to document maneuverability in waves matching the availability of the benchmark.

The irony, however, is that the standard only applies to calm water environments. The author believes that there is a need for a revised maneuverability standard that considers different kinds of operational conditions, including new standard maneuvers designed for documenting maneuverability in operational conditions.

Objective testing

For turning circles, the experimental results showed a clear trend for advance and average speed, with increasing significant wave height, while there was no obvious trend for the transfer and tactical diameter. For 20/20 zigzag maneuvers, the clearest trend was for the average speed, which decreased with increasing significant wave height. There was also a reduction of the first overshoot angle in waves, compared to calm water. For the second overshoot angle and reach, there were no obvious trends. However, even if some trends were present, the stochastic variation within each sea state could have been as large as the difference between the different sea states, especially for the sea state with $H_s = 8.57$ m and $T_p = 11.97$ s, which represents adverse weather. This has some practical consequences when experiments and/or different numerical models are compared. Conclusions can not be drawn based on a single realization in one sea state. Either trend must be investigated for a range of conditions, or several realizations in the same sea state must be performed to calculate statistics.

Both Sim A and Sim B generally performed in an acceptable manner, compared to experiments. In calm water, Sim B more adequately compared to the turning circle experiments, while Sim A more adequately compared to the zigzag maneuvers. It is noteworthy that Sim A was setup to appreciate the first-order wave effects only (added resistance and drift loads in sway and way were turned off), and Sim B was setup to appreciate the second-order wave effects only (first-order wave loads are not explicitly present in the equations of motion).

Experiment results in waves showed a maneuverability trend of decreasing speed with increasing wave height. This can be seen in average speed figures, most evidently in Figure 5.12. Ship speed drops during (for example: zigzag) maneuvers in initial head waves. As wave height increases, this drop in speed increases. This can be observed across the results of multiple maneuvers with different wave heights. This trend was not captured by the two simulators. One simulator that accounts for the slowly varying second-order wave loads appreciated this trend. The other simulator, that accounts only for first order wave loads, did not appreciate the trend, probably due to turned off drift loads. The contribution of each wave load component in the overall maneuverability results is a subject for further investigations.

The question is, how important is this for the different kinds of applications of simulators? The objective testing results, in Section 5.4, show that simulators, in their default configurations, behave differently. The new knowledge learned from the results is elaborated as follows:

- Both simulators have excellent performance. This can be seen in Figures 5.6 and 5.10.
- Differences in the simulators exist. In calm water, both simulators showed excellent performance. The recommendation is, however, to choose Sim A for applications in calm water conditions.
- In waves, the recommendation is to choose Sim B, because it appreciates the trend of average speed drop as wave height increases, shown in Figures 5.8 and 5.12.
- Results, in contrast with the benchmark, also help in developing simulators, because they show their strengths and weaknesses, and indicate areas that can be modified.

Without objective testing, the two simulators would seem good enough and particular differences in their performance would not be easily identified.

The use of the ARL classification

What difference does it make whether a simulator appreciates the impact of increasing wave height on ship speed? How can one tell if this maneuvering model is good enough and if this simulator is fit-for-purpose?

Looking at the various applications covered in the introduction section, it is clear that the objectives of the application are to dictate the level of accuracy required. For example, a ballast handling simulator course has different accuracy requirements compared to a safety-critical operation training or a pilot recruitment assessment.

There is a need for definitions of accuracy requirements of the different applications. Therefore, we proposed a simple classification of accuracy requirement levels (ARLs), shown in Figure 5.1, which thereafter is linked to the various applications. ARLs are properties of simulators, and, more precisely, they are properties of each floating object in simulators.

Considering the turning circle results in Figure 5.8, the simulators satisfy the ARL 2 requirement for the advance, tactical diameter, transfer and average speed. However, by looking at the zigzag results in Figure 5.12, the overshoot angles for both simulators do not satisfy the ARL 2 accuracy requirement (if the tolerance is to be set to 10% error margin from the benchmark, for example). Therefore, according to our proposed ARL definition, both simulators are classified as ARL 1 "feels realistic" and can be used for education, training, research, and innovation applications. For a slightly more relaxed tolerance, both simulators could qualify as ARL 2 "calm water accurate" simulators.

The classification of the applications shown in Table 5.1 is a rough example of how the ARL system can be used. This research has not elaborated on the standards and acceptance criteria of the levels. The absolute limit of 10% tolerance as an acceptance criterion is quite strict. Moreover, it is possible that a model is approved as ARL 3 for some conditions, while it is only ARL 2 for other conditions. An alternative to this "black-white" criterion could be a more continuous grading system. However, the system will then lose some of its simplicity. This is a topic for further research. Therefore, the reader is encouraged to take this as a demonstration of the use of the ARLs rather than an evaluation of the simulators involved in this study. Both show great results in calm water conditions, and Sim B, in general, appreciates the effects of increased wave height on ship speed.

The bottomline is that the functional fidelity of the simulators is not to be taken for granted. Objective testing should be documented. Such testing can be used together with a classification standard such as the ARL to classify the performance capabilities of a simulator. This procedure is recommended especially for applications that require high accuracy (ARL 3) or for applications where important operational decisions are based on the outcome of the simulator trials, such as the final cut recruitment assessments.

The limitations of the maneuverability standard

It is stated in the standards that they should be regularly reviewed and updated by IMO, as appropriate, to take into account new technologies, findings of new research, and experience with the present standards. The author believes that there is a need for a revised maneuverability standard that considers different kinds of operational conditions.

The limitations of simulators

Ship simulators have a front-end and a back-end. The front-end is the interface between the users and the software. The back-end, is where all the hidden configuration settings exist. There are many settings that can be manipulated, however, they are not accessible for the users.

The effect of every single component in the back-end on the end result is important, and is interesting for research and development of the simulator itself. However, the end result itself is what the users learn and experience in simulator trials, and that is what this study is concerned with, "the performance of simulators".

The limitations of experiments

The availability of proper benchmark data is of high importance to simulator classification. The issue of the availability of data, ownership, and access need to be addressed. The already existing free-running model test data can be very valuable, should it be used for this purpose.

Free-running model tests can be designed for different conditions such as calm water and wave conditions even for shallow water. Shallow water basin facilities exist, and they are getting more focus lately after the Ever Given grounding incident in the Suez Canal (March 2021). However, it becomes more challenging for basin facilities to provide combined effects. Therefore, for ARL 3 (operational conditions) simulator classifications, the importance of full-scale data increases.

This limitation can be seen as an opportunity. Experiments, either full scale or model tests, are very challenging to conduct. However, there lies the opportunity of observing maneuverability of ships while they operate, without the need of running dedicated experiments for the data collection. Operating ships can continuously log the required "ship" data (including control inputs, position, heading, and other motions), and "environmental" data (including wave conditions, wind conditions, current conditions, water depth). This data could be used as a benchmark data for "operational conditions" fulfilling the "objective testing" requirements for ARL 3.

5.6 Takeaways

The key points of this chapter are summarized in the following list:

I The functional fidelity of a simulator is not to be taken for granted when "objective testing" is not documented. Results show that one simulator does not appreciate wave effects on ship speed.

II The maneuverability standard of the IMO is used as a guideline to understand and document maneuvering characteristics of the DTC. The maneuverability standard must evolve to consider operational conditions.

III A simple ARL standard is proposed to:

- (a) Classify simulator capabilities
- (b) Classify application requirements

IV The "objective testing" example showed that:

- (a) It is possible to document ship maneuverability in operational conditions, considering trial type, magnitudes, directions, and ship speeds.
- (b) When two simulators are compared, the differences in the performance become apparent, strengths thus can be identified and selection preferences can be established.
- (c) Depending on the pre-defined tolerances, both simulators could qualify as ARL 2 simulators (accurate in calm water). The recommendation established from the objective testing is to choose Sim A for calm water applications and Sim B for applications in waves (according to their current configuration).

Chapter 6

Discussions

6.1 Maritime autonomy

What is autonomy? Is it ships that decide and act on their own, or is it our management capabilities of remote assets that is meant by "autonomy"? In case the former is meant, then perhaps machines would be able to reach the "full autonomous" LOA, however, uncertainties from all directions, such as unknown unknowns, environmental effects, political, or economical instabilities would exist surrounding the asset, requiring human operators to be "in the loop".

In case the latter is meant, then the focus toward the future of automation in the maritime industry should focus on operators and their capabilities of managing remote assets; this includes monitoring, supervision, and intervention capabilities. This also includes other concerns such as security, cybersecurity, and feasibility.

In both cases, the human operator is required to be "in the loop". Therefore, regardless of the direction the future would bring, the capabilities of human operators should be a focal point in the pursuit of autonomy in maritime operations.

6.2 Operator side

The pursuit of autonomy in the maritime industry is not merely a technological challenge. Literature shows that operators experience various "human factors" when the automation level increases in their workplace. These factors include responsibility, automation surprises, management by exception, and communication (in Section 3.1.3) that accompany automation and affect the operators. Such factors touch upon the performance of operators, their workload, attention and cognitive demands, and their intervention capabilities, and should be considered a focal point in the pursuit of autonomy in maritime operations.

6.3 Technology side

When ship bridges are manned, the human operator is responsible to be constantly on the lookout to double-check ship position and "get a fix". However, when ship bridges are unmanned, then fixing one's own position becomes a challenge. GNC systems are designed to use multiple data sources for estimating position, and the remote operator would be responsible for the quality of the estimate. Technology is required to help remote operators perform better; become more capable in monitoring, supervision, and intervention.

Hydrodynamic models are part of GNC models, they support the GNC system objective listed in Section 3.1.2 and are used in model-based navigation. They are used for ship trajectory predictions and are becoming more involved in GNC systems. Literature shows that the two main sources of uncertainty in GNC systems are "vessel dynamics" and "environmental loads". Maneuvering models describing ship motion including the effects of waves, winds, and currents is a research area still far from being considered fully explored. This is alarming because GNC systems are becoming more dependent on maneuvering models for positioning and trajectory predictions.

6.4 Remote control

Given that human operators are required to be "in-the-loop" in any future direction, then, autonomy should advance maritime operations by advancing the capabilities of remote operators. Remote control would be a suggested way forward with the focus on the operators' capabilities in managing remote assets and on the challenges, from both the technology and human side indicated by Literature Review - A in Section 2.3.1.

The field of remote control is a multidisciplinary field. In order to research such a multidisciplinary field, ship simulators should be used because they could resemble appropriate labs. However, there is a need for learning more about ship simulators, their applications, opportunities, and challenges to determine their suitability in research and industry applications.

6.5 Simulators

An overview of the simulator applications is provided in Section 4.1.2. The three data collection methods revealed a wide range of applications. The extent of application ranges from research to development, from concept to testing, from student training to operator training, and from risk analysis to recruiting assessments. The extent of applications is on the one hand, indicating great potential, but on the other hand, raising a concern about the accuracy of ship motion in simulators.

The subject matter expert interviews revealed that the advantages and opportunities associated with simulator use are vast, progressive, and promising. They are inline with IMO HCD philosophy. They are able to demonstrate trials with human-in-the-loop and hardware-in-the-loop, handle multidisciplinary objectives, and test extreme scenarios that are otherwise "impossible" in full-scale experiments. Providing both industry and academia with essential tools for facing current global challenges, such as energy efficiency, safety, and security. Such results suggest that the quantity and quality of simulator applications are on the rise.

The interviews also revealed challenges associated with simulator use. The coded challenges, however, are mostly practical, related to availability, data management, and software issues. Such challenges can be overcome with time. The asymmetry of the opportunities versus the challenges is indicative of a high possibility for future growth of simulator applications. Together with the extensive current simulator applications reviewed in Chapter 4 the concern for the accuracy of ship dynamics, indicated in Chapter 3, is magnified.

The methods of Chapter 4 show that simulators are useful and have a huge potential, but still, the previous question "Do simulators actually resemble appropriate labs?" is not answered yet. In addition to the following questions. How accurate are ship dynamics in simulators? How suitable are simulators for their wide range of applications? Chapter 5 is at least aiming to address the status of the simulator suitability as they are at the moment.

6.6 Maneuvering models

A deeper investigation involving simulator dynamics is essential. First, the DNVGL maritime simulator standard was reviewed and a gap in the requirements was recognized. The standard does not explicitly require "objective testing", as is the case with the airplane simulator standard. This identified gap in the maritime simulator standards confirms the accuracy concern.

Second, "objective testing" of simulator models was carried out. The benchmark was a group of basin free-running model tests. Without the benchmark data, the "objective testing" would have been inaccessible, therefore, simulations followed the setup of the model tests in the selection of the ship model and trial types. Going a few steps backwards to ask some questions.

- What is "objective testing"? It is a quantitative assessment based on comparison with validation data.
- Assessment of what? In the case of ship dynamics, then the assessment should address maneuverability (maneuvering behavior) of the ship.
- What is maneuverability and how should it be documented? The IMO standard of maneuverability is used to answer this question. Maneuverability, maneuvering capability, or maneuvering behavior mean the same thing, they are broken down into the following:
  - turning ability
  - initial turning ability
  - yaw-checking and course keeping abilities
  - stopping ability

  The standard provides acceptance criteria that includes some KPIs, those KPIs are maneuvering trial characteristics that are used in the documentation of maneuverability together with additional characteristics and timeseries. The "objective testing" only considers zigzags and turning circles, reflecting on turning ability, yaw-checking, and course keeping abilities.
- Why the DTC hull was selected? It was selected following the model tests. Second, it was chosen because maneuvering is a more interesting problem for big ships with a conventional single rudder-propeller configuration. Such ships are designed for optimized transit efficiency, while maneuverability is compromised. Note that the DTC has a tactical diameter larger than 1 km in calm water meaning that its turning radius is above 500 m (Figure 5.8).

Once the maneuvering characteristics are defined, the results of simulator trials can be compared against those of free-running model tests. Predefined tolerances are required to give meaning to the comparison. Is this simulator accurate enough? This thesis presents a performance of an "objective testing" example however, it does not include research work to define tolerances; this topic is to be included in future work.

A limitation of the use of the IMO standards as a guideline for "objective testing" for a ship maneuvering in waves is that the standard is made for calm water conditions. The author believes that the standard should evolve to include "maneuverability in operational conditions". New standard maneuvers should be included to capture effects of environment loads on ships. The author suggests new trial types as follows:

- Straight line test: The test starts with a steady approach at the test speed with a zero yaw rate, the initial heading is northwards and the heading autopilot is activated to maintain it, for the total length of the test (for instance, 10 minutes). In low-load environmental forces the autopilot manages the maneuver in a straight line, however, in adverse weather the beam loads would move the ship in a drifting course as shown in Figure 6.1. This test is made to investigate the effects of waves (winds, and currents) on transit sailing and on energy efficiency.
- Standing still test: The test starts at zero speed and a neutral rudder, the propeller level is set to zero as well. The ship remains idle for the test length (10 minutes for example). This test is made to investigate the drift that starts from zero-speed as shown in Figure 6.1. This test is ideal for calibration of the environmental load models.

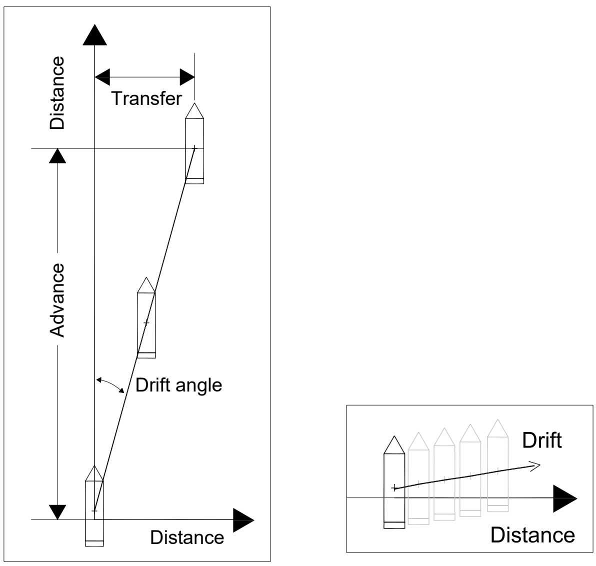

FIGURE 6.1: Suggested new trial types: Straight line test (on the left) and standing still test (on the right)

It is noteworthy to stress that maneuverability is a high-uncertainty process involving many variables, therefore, the "objective testing" and the maneuverability results should be handled with care considering the following points:

- An irregular sea state has a stochastic behavior, which means that different realizations of the same wave spectrum will not give identical results. Encouraging repetition of trials for enabling statistical analysis.

- The absolute results of trials characteristics provide some information, however, the trends of such results as wave height (or wind speed for example) increases provides more essential information. Encouraging researchers to perform simulator trials (and benchmarking model tests) for a number of different sea state conditions enabling trend observations.

6.7 Suitability of maneuvering models in simulators (application based)

Basic maneuvering models such as the ones presented in Eq. 3.2 and 3.3 do not include various physical phenomena that affect the overall maneuverability. Physical phenomena such as ship-to-ship interaction, bank effects, shallow water effects, broaching and fouling are not by default included. However, the models are modular, meaning that additional effects can be added based on the assumption of superposition. For example, the maneuvering model of Sim A is a modular model that includes effects of waves, winds and ocean currents, water depth, shallow water effects, canals and banks, ship interactions, and different propulsion configurations. It is crucial to know what physical effects are considered in a model, and it is also crucial to test the overall performance of the model in operational conditions in comparison with an appropriate benchmark.

Different simulator applications require different functional fidelity. For example, student training courses do not require same fidelity as critical operation training. This difference suggests the need of a classification standard that connects application requirements (in terms of functional fidelity) and simulator capabilities (in terms of maneuvering performance). Hence, an ARL classification standard is proposed in Section 5.2.

Given the need, the availability of such a standard is believed to serve both simulators and applications in addressing the suitability. From the simulators side, ARLs would:

- Serve to communicate about the functional fidelity of a particular simulator (or to be more precise, of a particular ship model). Usually, users of simulators consider ship hydrodynamics accurate and seldom question its fidelity. This classification would bring the functional fidelity of simulators to the surface and enable users/researchers to select simulators and judge whether a particular simulator is "good enough" for their application or not.
- ARLs would reflect the amount of work used for "objective testing" of a particular simulator. They would directly convey the accuracy (supported by data) of a simulator.

From the applications side, ARLs would serve as a classification standard, as presented in the example in Table 3.1. Together, "objective testing" and ARLs can help the classification of simulator capabilities and ensure fit-for-purpose simulator applications. Hence, enabling simulators resemble appropriate labs. This answers RQ3.

RQ3: How can the accuracy of maneuvering models and their suitability in simulators for various applications be addressed?

The extent of simulator applications together with their opportunities and advantages answers RQ2.

RQ2: How do maritime simulators contribute in shaping the future of maritime operations?

The reason for converging RQ2 on simulators is the hypothesis that simulators can be appropriate labs for researching focal points in maritime autonomy challenges. Based on the findings of Literature Review A, in Section 2.3.1, according to the reviewed fields, the challenges were split into technological challenges and human factors answering RQ1.

RQ1: What are the main functional challenges in autonomous vessels?

6.8 Research limitations

This research may suffer from the following limitations:

- The approach used in Method 1.1 (Literature Review - A, in Section 2.3.1) to address challenges related to autonomous vessels can be seen as a too general of a starting point. This method may suffer from selection bias because the reduction of the term *autonomous vessels* to *hydrodynamics, GNC, and human factors* reflects author's own biases interconnected with the research's preliminary scope. The functional challenges found for RQ1 are limited to the reviewed fields. Additional functional challenges could be found if other fields were reviewed such as cybersecurity for example.
- Literature review B, in Section 2.3.2, is looking at the past twelve years only; this could be a limitation. Second, a literature review, is not a suitable method for finding state-of-the-art simulator applications beyond the research domain. That is the main reason this method was complemented by two other methods: Method 2.2, Interviews, and Method 2.3, Case Study.
- All of the interviewees except one are from Europe. The more diverse the group of interviewees, the more diverse the knowledge captured and the less bias captured, which can influence the results. The pool of interviewees was not as diverse as the author hoped when sending interview invitations.
- The case study shows that knowledge does not only exist in research articles. Fruitful content is obtained about NCA's use of simulators. Other fruitful knowledge may exist, about the use of simulators by other ocean economy businesses. Such knowledge is not captured at all in this thesis.
- The use of zigzags and turning circles only is based on the dependence on both the IMO standards for ship maneuverability and availability of benchmark data. The author believes other tests (beyond the standard maneuvers) can provide useful insight on maneuverability in operational conditions.
- The IMO standards for ship maneuverability were used as a guideline for "objective testing" for maneuvering in waves, given that the standard is made for calm water conditions.
- Only waves in "objective testing" were used, while operational conditions involve other environmental effects such as winds and currents.
- Research regarding ship dynamics (maneuvering) of a sailing ship that are subject to environmental forces is a field of research that generally suffers from

low ecological validity. Ecological validity refers to how closely the lab setting approximates how the ship would naturally respond to hydrodynamic forces and environmental effects. The experimental translation might be very different from what happens in real life, but that does not mean that the variables of interest are not adequately manipulated, measured, or that lab results would not apply to other, more natural instances. However, field research is necessary to improve our understanding of the topic and thus our prediction models. Having low ecological validity means that our understanding of the subject is not complete. In this research, we shed light on the importance of further research in the field of ship dynamics in operational conditions from multiple perspectives (application range, state of art limitations, objective evaluations).

Chapter 7

Conclusions

7.1 Contribution

The major contribution of this study to science is:

- Providing an overview of simulator applications using multiple data collection methods.
- Finding the "objective testing" gap in the maritime simulator standards in contrast with the airplane simulator standards.
- Providing insight into the maneuverability of the DTC containership in calm water and in waves.
- Providing an example of "objective testing" for the accuracy of ship dynamics in simulators.
- Proposing the ARL classification standard that addresses the functional fidelity concern.
- Combining the ARL classification standard and "objective testing" to alleviate the accuracy concern (a methodological contribution).

The main contribution to the industry is:

- Demonstrating that accuracy of ship dynamics in a simulator is a concern.
- Introducing ARLs for simulators and their applications. ARLs can help users match the functional fidelity with the application to ensure suitability, and of course satisfy simulator application objectives.

The main indirect contribution to society is:

- Simulators are subjected to scrutiny to ensure appropriate use.
- The appropriate use of maritime simulators is paving the way for (safer) maritime operations given the limitations of ship physical modelling.
- The appropriate use of maritime simulators contributes to safety in the sea.

7.2 Conclusions

Autonomy is a continuous process gradually changing the way we move, work, and live. Maritime autonomy, similarly, is a gradual change towards the use of more digital tools in our day-to-day operations. As operations in the maritime industries become more challenging, technological support becomes more useful, and more required. Full autonomy, as described in the various LOAs starting with Sheridan and Verplank (1978) to Rødseth and Nordahl (2017), refers to a state where ships are able to make decisions and perform actions on their own. This study reveals that human presence "in-the-loop" is mandatory regardless of the capability of the machine. Actually, the author thinks that full autonomy should refer to a state where remote operators can fluently manage their remote assets whether floating on the surface or diving underwater. Remote control technology is required to enable safe and feasible future operations. Simulators can be used as labs for research, development and testing of several remote-control assisting technologies. The key points of the maritime autonomy chapter are summarized in the following list:

I The progress of automation along the scale of LOAs results in higher capabilities of the autonomous ship to decide and act on her own, nevertheless, it still requires human monitoring, supervision, and intervention capabilities.

II Ironically, as automation increases, the demand for superhuman skills (in non-normal times), such as workload, attention and cognitive demands, and intervention capabilities, increases as well.

III Hydrodynamic models are an integral part of GNC systems, and their role increases in importance as the vehicle systems increase in the level of automation.

IV *Ship dynamics* and *environmental loads* are the main functional challenges for autonomous vessels from the technology side.

V The capability of the state-of-art maneuvering models in predicting ship motion (in operational conditions) is far from being considered fully understood, and is crucial in the development of autonomous ships.

VI The capability of operating ships remotely is necessary, regardless of the level of autonomy. The remote operation can be in the form of control, monitoring, or supervision. The infrastructure and technology enabling remote operators to better perform their tasks are crucial in the development of autonomous ships.

VII Ship simulators enable research in both maneuvering models and remote ship operations. Therefore, they are necessary to the development of autonomous ships. This point needs further investigation.

VIII It is of importance to know how capable and fit are ship simulators as labs for the research and development of maritime operations.

Maritime simulators are currently used for a wide range of applications. The extent of their usage resonates with their potential, however it is growing beyond the intentions of their original use. This growth in application is raising a concern of functional fidelity. The maritime simulator standard is reviewed in contrast with the airplane simulator standard, the former does not explicitly require "objective testing" as is the case with the latter. The key points of the maritime simulators chapter are summarized in the following list:

I The need and potential of maritime simulators are significant. The wide range of simulator applications confirms the need, and the list of the advantages of simulators confirms the potential.

II The scope of simulator applications is growing beyond both the intentions of manufacturers and the certification requirements.

III The functional fidelity is a concern. According to the standards, in the airline industry, simulators are subject to "objective testing", however, in the maritime industry, they are not.

IV Questions have been raised regarding how accurate the hydrodynamic models used in simulators are. A method for evaluating their accuracy is needed.

"Objective testing" of two simulators is performed and compared against free-running model tests. The testing confirms that ship maneuvering models is still a research area far from being considered fully explored. The operational conditions included in the test were limited to five waves conditions. Results show that simulators do not appreciate wave effects identically. One compares more adequately to model tests when considering effects of waves on ship speed. Given that maneuvering models in simulators perform differently, a method for addressing the accuracy concern is required. This study is proposing "ARL" classification standard. Together, the ARL and "objective testing" enable users/researchers to alleviate the accuracy concern. The key points of the maneuvering models chapter are summarized in the following list:

I The functional fidelity of a simulator is not to be taken for granted when "objective testing" is not documented. Results show that one simulator does not appreciate the wave effects on ship speed.

II The maneuverability standard of the IMO is used as a guideline to understand and documents the maneuvering characteristics of the DTC. The maneuverability standard must evolve to consider operational conditions.

III A simple ARL standard is proposed to:

   (a) Classify simulator capabilities

   (b) Classify application requirements

IV The "objective testing" example showed that:

   (a) It is possible to document ship maneuverability in operational conditions, considering trial type, magnitudes, directions, and ship speeds.

   (b) When two simulators are compared, the differences in the performance become apparent, the strengths thus can be identified and selection preferences can be established.

   (c) Depending on the pre-defined tolerances, both simulators could qualify as ARL 2 simulators (accurate in calm water). The recommendation established from the objective testing is to choose Simulator A for for calm water applications and Simulator B for applications in waves.

7.3 Future work

This research is anticipating the following future works:

- Developing "objective testing" procedures under wind, currents and combination of environmental conditions.

- Updating the maneuverability standard and proposing new test types for maneuverability in operational conditions.
- Developing testing methods for the high ARL applications / high TRL technologies such as advanced GNC systems for autonomous operations.
- Developing and testing the "objective testing" standard for maritime simulators.
- Developing the acceptance criteria and predefined tolerances for the ARL classification standard.
- Addressing the benchmarking data availability issue, including the opportunity to acquire operational data (while ships operate), avoiding the need for dedicated experiments.
- Further developing the simulator-fit maneuvering models (for both surface vessels and diving robots) that account for operational conditions.

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Appendix A

Maritime Simulator Background

Maritime Simulator Background

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22 February 2021

1 OSC Simulator

1.1 General Introduction

OSC simulator is a tool made for demanding offshore operations. This tool is provided by the firm named Offshore Simulator Centre (www.osc.no).

This simulator tool uses a series of tools in the back-end. The hydrodynamics-relevant tools in the back-end are ShipX and FhSim. The vessel response calculations in this tool are based on potential flow theory and the classical strip theory (Salvesen, Tuck, and Faltinsen, 1970). Overview of the assumptions involved in the potential flow theory and the strip theory are found in the background section 2.1 (outside this document).

ShipX is a tool by Sintef (www.sintef.no/en/software/shipx). ShipX is a hydrodynamic workbench that comprises multiple plug-ins therein that include calculation capabilities such as but not limited to, ship speed and powering, station keeping, maneuvering, and vessel responses. The main plug-in of ShipX used by OSC tool is the Veres plug-in (VEssel RESponse package) which is used for sea-keeping calculations, including ship motions and global loads, also capable of short term and long term statistics calculations and operability analyses. The main output of ShipX is basically the added mass and damping matrices for the given ship hull geometry. These matrices are calculated for different ship speeds ranging from zero speed to maximum speed. They are also calculated for different relative wave directions. They are also calculated for different wave heights and wave periods. The results of ShipX are offline results. Offline in this context means that the response results are calculated beforehand and saved to be used later, usually this offline calculation is time consuming. FhSim converts them into online results throughout the simulation by finding the appropriate added mass and damping matrices by interpolating offline results given the actual ship state (ship speed, heading, relative wave direction, wave height and wave period) at every time step. In other words, FhSim is a lookup table and ShipX results are the database.

FhSim is also a tool by Sintef (www.fhsim.no). FhSim tool is the core of the OSC simulator. FhSim functionality is beyond a lookup table, it is a software platform for mathematical modeling focusing on marine application. In addition to the calculations of hydrodynamic forces, FhSim framework is an object-oriented co-simulation tool that calculates current, wind, propulsion and rudder forces in real time.

Pierre Major at OSC et al. have published their methods for fast virtual prototyping in a conference proceeding that includes insight about the software architecture of the tool and details about the hydrodynamic model Major et al., 2020.

1.2 Mathematical Model

Given the linear strip theory assumptions, small motion amplitudes, small wave steepness and applicability of steady-state conditions, the ship response is considered harmonically oscillating with the same frequency as the wave-encounter frequency. The frequency of encounter, ω_e, is defined in Equation 1.

$$w_e = w_0 + \frac{w_0^2 U}{g} cos\beta \tag{1}$$

where

- ω_0 is the wave frequency $[Hz]$,
- g is the gravitational acceleration $[m/s^2]$,
- U is the ship's forward speed $[m/s]$ and
- β is the heading angle $[rad]$.

Ship response will thus oscillate harmonically at the encounter frequency ω_e. Given the assumptions that the ship responses are linear and harmonic, the six degrees of freedom equation of motion in vector-form can be written as in Equation 2.

$$(M_{RB} + M_A)\ddot{\eta} + (C_{RB} + C_A)\dot{\eta} + B\dot{\eta} + G\eta = F(t) \tag{2}$$

where

- η is the ship motion vector,
- M_{RB} is the rigid body mass matrix,
- M_A is the hydrodynamic added mass matrix,
- C_{RB} is the rigid body mass Coriolis-centripetal matrix,
- C_A is the hydrodynamic added mass Coriolis-centripetal matrix,
- B is the damping matrix,
- G is the stiffness matrix and
- $F(t)$ is the total external force matrix, including excitation forces, wind forces and control input forces from rudders and propellers.

For every degree of freedom, the motion transfer functions are given by a harmonic relation that consists of motion amplitude, phase angle, and encounter frequency as in Equation 3.

$$\eta_k(t) = \eta_{ka} cos(\omega_e t + \phi_k); \qquad k = 1, 2, ..., 6 \tag{3}$$

In VERES, if the vessel is lateral-symmetric, then surge, heave and pitch are not coupled with sway, roll and yaw. In addition to that, motion limits are set to following waves (waves coming from the stern side of the ship) to avoid unrealistic large motions in surge, sway and yaw as frequency of encounter approaches to zero.

1.3 Hydrodynamic coefficients

VERES calculates the added mass and damping coefficients based on the classical STF Strip Theory and the Potential Theory. The Potential Theory results in expressions for wave surface elevation, water particle velocities and accelerations. Whereas, the pressure in the fluid is obtained from the Bernoulli equation. Linearized pressure terms are integrated over the hull surface resulting in hydrodynamic force and moment amplitudes that can be expressed in terms of a real part (added mass effects) and an imaginary part (damping effects) such as in Equation 4.

$$T_{jk} = \omega_e^2 A_{jk} - i\omega_e B_{jk} \tag{4}$$

where

- T_{jk} is a component in the force / moment matrix,
- ω_e refers to the encounter frequency,
- A_{jk} and B_{jk} are the added mass and damping coefficients respectively.

1.4 Restoring coefficients

Restoring coefficients are also known as hydrostatic force coefficients. They are independent of wave frequency and ship's forward speed. They follow directly from hydrostatic analysis. They are dependant on geometry, mass distribution, water density and gravitational acceleration. VERES estimates restoring coefficients in heave, roll, pitch and coupled heave-roll degrees of freedom.

1.5 Viscous roll damping

Damping analysis is carried out in a 2-dimensional setting. Both linear and nonlinear damping components are incorporated. VERES considers the following components of viscous roll damping:

- Frictional damping caused by skin friction stresses on the hull:
  The flow in full scale is usually assumed to be turbulent. Kato's formulas are used (Kato, 1957).

- Eddy damping caused by pressure variations on the hull:
  Flow separation at the bilge of the cross section causes this damping component. Ikeda et. al. formulations based on results from forced roll tests are used (Ikeda, Himeno, and Tanaka, 1977).

- Lift damping:
  Lift forces of a ship moving with forward speed contribute to roll damping. Himeno's formulations are used (Himeno, 1981).

- Bilge keel damping:
  Bilge keels contribute in increasing roll damping due to two factors, the drag forces caused on them and the pressure difference they introduce around ship hull. Formulations by Ikeda are used (Ikeda et al., 1979).

1.6 Added resistance in waves

As a ship advances in water, resistance builds up because of the wave reflections and the motion-induced wave generation. VERES computes added resistance based on two alternative principles, energy conservation and pressure integration. The former is conservative in predictions in head to beam seas. While the later is of limited applicability in following waves.

1.7 Current forces

With the assumption that ocean currents are constant and irrotational, the method of incorporating current forces in the model is implemented by replacing the ship's speed-over-ground vector from the equation of motion with the speed-in-water vector (relative speed). This is implemented by transforming the absolute current from inertial frame to body-frame and taking the difference between the ship speed and the transformed current, v_c, as in Equation 5.

$$v_r = v - v_c \tag{5}$$

Where

- v_r is the relative speed vector in the body-frame,
- v is the ship's speed-over-ground vector in the body-frame and,
- v_c is the current speed vector transformed (to body-frame).

The equation of motion, Equation 2, then becomes:

$$(M_{RB} + M_A)\dot{v}_r + (C_{RB} + C_A)v_r + Bv_r + G\eta = F(t) \tag{6}$$

Equation 6 is built on the assumption that ocean currents consist of a constant single layer within ship draft. Currents in this model produce in-plane translation forces applied at the center of gravity of the ship, therefore, currents do not induce yaw moments in this model.

1.8 Wind forces

For incorporating wind forces on a moving ship two methods are used, Blendermann, 1986 and Isherwood, 1973. These methods provide estimation for the force coefficients that can be computed as in Equation 7.

$$F_{wind} = \frac{1}{2}\rho_a V_{rw}^2 \begin{bmatrix} C_X(\gamma_{rw})A_{Fw} \\ C_Y(\gamma_{rw})A_{Lw} \\ C_Z(\gamma_{rw})A_{Fw} \\ C_K(\gamma_{rw})A_{Lw}H_{Lw} \\ C_M(\gamma_{rw})A_{Fw}H_{Fw} \\ C_N(\gamma_{rw})A_{Lw}L_{oa} \end{bmatrix} \tag{7}$$

where

- ρ_a is the density of air $[Kg/m^3]$,
- V_{rw} is the relative velocity of wind $[m/s]$,
- C_i are the wind force/moment coefficients [-],
- γ_{rw} is the relative wind direction $[rad]$,
- A_{Fw} is the frontal projected area $[m^2]$,
- A_{Lw} is the lateral projected area $[m^2]$,
- H_{Fw} is the centroid of the frontal area $[m]$,
- H_{Lw} is the centroid of the lateral area $[m]$ and
- L_{oa} is the ship's overall length $[m]$.

1.9 Propeller forces

Control input forces for a containership equipped with traditional single rudder-propeller configuration are simply the rudder forces and the propeller forces. Usually such ships are also equipped with a bow thruster, then the bow thruster forces are to be of importance at zero-speed maneuvers, however, as ship picks up forward speed, the impact of bow thruster decreases, therefore, in maneuvering at operation speeds bow thrusters can be neglected.

The estimation of the propeller forces is achieved using the four-quadrant method by Robert Roddy et al. Roddy, Hess, and Faller, 2007. This method operates in the full four-quadrant range of the propeller shaft speed and the ship speed, meaning that it works for both forward and backward ship speeds and for both clockwise and counter-clockwise shaft rotations. This method models the propeller using the open water data, advance, thrust and torque coefficients, and utilizes a Neural Network to achieve curve fitting and estimation of torque and thrust forces.

The thrust delivered by each propeller is given by Equation 8, the hydrodynamic pitch angle is calculated in Equation 9 and the estimated thrust coefficient is given in Equation 10.

$$T = t_r \cdot p_{ts} \cdot \frac{1}{2}\rho\frac{\pi}{4}D^2 \cdot C_T(PD,\beta) \cdot ((V_e \cdot w_f)^2 + (n\pi 0.7D)^2) \tag{8}$$

$$\beta = \arctan(\frac{V_e}{n\pi 0.7D}) \tag{9}$$

$$C_T(PD,\beta) = \sum_{i=0}^{N} a_i(PD) \cdot \cos(i \cdot \beta) + b_i(PD) \cdot \sin(i \cdot \beta) \tag{10}$$

Where

- T is the thrust of the propeller [N],
- t_r is the thrust reduction [-],
- p_{ts} is the propeller's thrust scaling [-],
- ρ is the density of water [kg/m^3],
- D is the propeller diameter [m],
- V_e is the mean entrance speed of water in the propeller [m/s],
- w_f is the wake fraction [-],
- n is the propeller revolution speed [rad/s],
- PD is the pitch of the propeller, angle of attack [deg],
- $C_T(PD,\beta)$ is the thrust coefficient [-],
- a_i, b_i is the trigonometric polynomial coefficients [-] and
- β is the hydrodynamic pitch angle [rad].

1.10 Rudder forces

The rudder hydrodynamic forces are computed using hydrofoil lift and drag formulations derived from what is usually called two-dimensional (2D) foil theory in steady conditions. Steady, in this context means irrotational flow of an inviscid fluid flowing only parallel to the horizontal plane. Rudder induced forces and moments acting on a hull are expressed in the body-fixed frame as in Equations 11

$$
\begin{aligned}
F_{1_{rudder}} &\approx -D \\
F_{2_{rudder}} &\approx L \\
F_{4_{rudder}} &\approx -r_r \cdot L \\
F_{6_{rudder}} &\approx -LCG \cdot L
\end{aligned} \tag{11}
$$

Where

- F_i subscripts 1,2,4,6 refer to surge, sway, roll and yaw respectively,
- D is the rudder drag force,
- L is the rudder lift force,
- r_r is the rudder roll arm,
- LCG is the distance between ship center of gravity (COG) and rudder center of pressure (COP).

The lift and drag are dependant on angle of attack and fluid field velocity over the rudder. The lift and drag forces on a hydrofoil or a rudder are approximated using Equation 12. Because the rudder is located right after the propeller's output, the flow velocity over the rudder is different than the ship's forward speed. The 2D momentum theory leads to an expression for the fluid field velocity over the rudder that can be found in Pérez, 2005 textbook as Equation 5.22 in his book named *Ship Motion Control*, and can be used in the following lift and drag equations, Equations 12.

$$
\begin{aligned}
L &= \frac{1}{2}\rho V_f^2 A_f^2 C_L(\alpha_e) \\
D &= \frac{1}{2}\rho V_f^2 A_f^2 \left(C_{D0} + \frac{C_L(\alpha_e)^2}{0.9\pi a} \right)
\end{aligned} \tag{12}
$$

Where

- ρ is the water density,
- V_f is the fluid field velocity over the rudder,
- A_f is the rudder or foil area,
- $C_L(\alpha_e)$ is the lift force coefficient that is a function of the effective angle of attack and
- C_{D0} is the minimum section drag (e.g. for a NACA 15 profile $C_{D0} = 0.0065$).

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Appendix B

List of papers

B.1 Zghyer, R., Ostnes, R., & Halse, K. H. (2019). Is full-autonomy the way to go towards maximizing the ocean potentials?. TransNav: International Journal on Marine Navigation and Safety of Sea Transportation, 13(1).

B.2 Zghyer, R., & Ostnes, R. (2019). Opportunities and challenges in using ship-bridge simulators in maritime research. Proceedings of Ergoship. P. 119-131.

B.3 Zghyer, R., Rabliås, Ø., Ostnes, R., Halse, K. H., & Kristiansen, T. (2022). On the various ship simulator applications and their accuracy requirements: Comparison of two numerical simulators with experiments. (MASHCON 2022)

B.4 Zghyer, R., Ostnes, R., Halse, K. H., Hareide, O. S., & Johnsen, E. (2022). Applications of maritime simulators in industry and research. (NECESSE 2022)

TRANSNAV
http://www.transnav.eu
the International Journal on Marine Navigation and Safety of Sea Transportation
Volume 13 Number 1 March 2019
DOI: 10.12716/1001.13.01.02

Is Full-autonomy the Way to Go Towards Maximizing the Ocean Potentials?

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ABSTRACT: Growth prospects for ocean economy are promising because ocean industries are addressing challenges such as food security, energy security and climate change. However, safety and efficiency are the general challenges of ocean operations. Increased automation is believed to solve these problems. This paper discusses the impact of automation on safety and efficiency. A literature review of 'Human factors' mainly from the aviation and maritime industries is presented to untangle the human-machine relationship characteristics when increased automation is introduced to operators. A literature review of Hydrodynamics, Guidance, Navigation and Control (GNC) technologies is presented to introduce the state-of-art and associated limitations. It is concluded that, if the industry's drive is safety and efficiency, then full-autonomy is, at present, not the way to go. Remote control, instead, could facilitate a feasible future, while focused research and development are in need.

1 INTRODUCTION

1.1 *Motivation*

Oceans are resourceful. Ocean operations are vastly increasing the last decades, and so is the interest in unmanned surface vehicles (USV) and autonomous ships. The ocean's extreme weather and far distances can result in high-risk-high-cost work conditions.

The world's economy is mainly defined by three areas: energy, transportation and communication (Rifkin, 2012). Ocean industries push the boundaries of these three areas to the limits. Unmanning of maritime assets by excessive automation and remote control could reduce or eliminate the risk imposed on crew; however, infrastructure cost will increase. A huge safety potential is accompanied with more benefits; by removing crew from the assets, crew related costs are, in theory, removed, costs such as cooling, heating and ventilation. Accommodation spaces are, in theory, no longer required, less power consumption is projected and the chain of promises goes on.

The drivers for unmanning maritime assets are developing into motivations for building and operating autonomous vessels. One example is, Yara Birkeland, a 120 TEU open-top zero emissions autonomous containership, planned launch is expected before 2020, the ship is under construction with Kongsberg technology. Another example is the car ferry Falco that was built using Rolls-Royce technology, launched late 2018.

As operators are moved from the far end of the operation to shore control centers, their experiences are changed, their feelings and senses while on duty from one hand, their toolboxes and control authority on the distant ship from the other hand. The current remote-control technologies and their limitations are subject to discussion. In this paper, the challenges of unmanning maritime assets and the transfer towards full-autonomy will be discussed.

1.2 *Introduction*

This literature review is part of a PhD study with the objective of "evaluation of technology using simulators". Main research area is safety and efficiency of semi-autonomous vessels and the research scope includes Hydrodynamics; simulation and testing; and semi-autonomous maneuvering in close proximity to structures. The simulator facilities at NTNU include a variety of simulators used for teaching and research. The use of simulators enables operators-in-the-loop testing, connecting technology to humans. The author is studying the man-machine semi-autonomous maneuvering problem from both the technology side and the human side. The technology side is broken down to four scientific fields: *Hydrodynamics*; *Guidance*; *Navigation*; and *Control*. Those four fields reflect the state-of-art in ship motion prediction and enhancement of automation level in ship maneuvering. Whereas the field of *Human Factors* (relevant to remote operators) is the field representing the human side of the problem. These five fields are reviewed briefly in this paper. The terms may have multiple definitions, therefore, in this review, the main fields are defined as follows:

- **Hydrodynamics** field in this review refers to methods that describe the motions and responses of a ship moving in water using maneuvering and seakeeping theories such as unified models (Skejic and Faltinsen, 2008).
- Guidance, navigation and control (GNC) is a well-established technical term used in engineering and control (cybernetics) fields in topics related to traveling vehicles; cars, ships, or planes.
  - Guidance module is the brain of the robotic controller that is responsible for trajectory planning, collision avoidance and conforming to protocol (such as COLREG) (Fossen, 2011).
  - Navigation module is responsible for estimating own state, that is, identify own position and motion information using sensors and GNSS signals, as well as estimating *external* situation, including environment perception (wind, waves, water depth, etc.) and obstacle state estimation, that is, identify obstacle position and motion information (Farell, 2008).
  - Control is the translation of guidance (desired trajectory) into actuator instructions that result in an actual trajectory as close as possible to the desired one and provides stability to the vehicle (Pérez, 2005).
- **Human factors** refers to reflections from human operators as more automation is introduced to their operations. Sections below include reviews of each of the fields separately.

2 LITERATURE REVIEW

After the fields of interest were defined, 59 relevant articles were reviewed in those fields of interest. Challenges and conflicts are presented. The literature is found in two ways: Education and search. Education literature is based on relevant courses and their relevant references. While Search literature is based on digital databases search of the following keywords: *Hydrodynamics; seakeeping; maneuvering; ship simulation; semi-autonomous vessels; unmanned surface vehicles; guidance; navigation; control; and human factors.* Search results were filtered based on relevance to the already defined subjects of interest.

2.1 *Topic 1: Hydrodynamics*

Dynamics is broken down by the studies of kinematics and kinetics, the former deals with geometrical aspects of motion and the latter deals with forces causing the motion. This review is concerned with ship dynamics, therefore this section starts with the maneuvering and the seakeeping theories as foundation for ship dynamics models. The former is the study of ship moving in constant speed in calm waters with the assumption that ship motion is frequency independent, that is, no wave excitation takes place. The latter is the study of ship motion at zero or constant speed in waves using frequency dependent hydrodynamic coefficients.

An overview of methods for describing maneuvering and seakeeping are grouped into experimental methods, unified methods, two-time scale methods and direct calculations by Computational Fluid Dynamics (CFD) tools (Quadvlieg *et al.*, 2014). The research is focused on real-time simulations and on including dynamics-in-the-loop for marine control systems, therefore the interest lies in fast mathematical methods such as the unified methods and the two-time scale methods. CFD tools are high computationally demanding and not suitable for real-time simulations. Both examples presented below, *the unified model* and *the two-time scale method*, are suitable for real-time simulations.

The unified model is a vectorial model that describes both the maneuvering and seakeeping ship motions and dates back to 1991 (Fossen, 1991) and is considered by the international community as a "standard model" for marine control systems design. The "standard model" is an upgrade of an earlier model (the "classical model") that represents the ship motion in a component form instead of vector form and is mostly used in hydrodynamic modeling where isolated effects are studied.

The 6 degrees-of-freedom (6-DOF) model is represented as (Fossen, 2011):

$$\boldsymbol{M}\dot{\boldsymbol{v}} + \boldsymbol{C}(\boldsymbol{v})\boldsymbol{v} + \boldsymbol{D}(\boldsymbol{v})\boldsymbol{v} + \boldsymbol{g}(\boldsymbol{\eta}) + \boldsymbol{g}_0 = \boldsymbol{\tau} + \boldsymbol{\tau}_{wind} + \boldsymbol{\tau}_{wave} \quad (1)$$

where $\eta = [x, y, z, \phi, \theta, \psi]^T$ and $v = [u, v, w, p, q, r]^T$ are vectors of position / Euler angles and velocities respectively. $\boldsymbol{\tau}$ vectors are vectors of environment and control forces and moments. The model matrices $\boldsymbol{M}, \boldsymbol{C}(\boldsymbol{v})\, and\, \boldsymbol{D}(\boldsymbol{v})$ are inertia, Coriolis and damping matrices respectively. While $\boldsymbol{g}(\boldsymbol{\eta})$ is a vector representing gravitational and buoyancy forces and $\boldsymbol{g}_0$ is a representation of ballast restoring forces and moments. The model is formulated in the time domain using the *Cummins equation* that considers the impulse response function over the past history of the excitation force, known as *fluid memory effects* (Cummins, 1962).

The two-time scale method was proposed by Skejic and Faltinsen in 2008. It is also a vectorial unified model that describes both the maneuvering and seakeeping ship motions. The time domain of the simulation is divided into two time scales, a slowly and a rapidly varying one associated with the maneuvering and the seakeeping respectively. This method estimates the mean second-order wave loads (that result in lateral drift caused by incident waves and wind) “as accurate as possible and at the same time to be able to simulate real-time maneuvers with acceptable CPU time.” (Skejic and Faltinsen, 2008, p. 374). The model is represented in a 4-DOF (surge, sway, roll and yaw) form as follows:

$$
\begin{bmatrix} M & 0 & 0 & 0 \\ 0 & M & 0 & 0 \\ 0 & 0 & I_{44}-Mz_g^2 & -I_{46} \\ 0 & 0 & -I_{64} & I_{66} \end{bmatrix}
\begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{p} \\ \dot{r} \end{bmatrix}
+
\begin{bmatrix} 0 & -Mr & 0 & 0 \\ 0 & 0 & 0 & Mu \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}
\begin{bmatrix} u \\ v \\ p \\ r \end{bmatrix}
=
$$
$$
=
\begin{bmatrix} X_{\dot{u}} & 0 & 0 & 0 \\ 0 & Y_{\dot{v}} & Y_{\dot{p}} & Y_{\dot{r}} \\ 0 & K_{\dot{v}} & K_{\dot{p}} & K_{\dot{r}} \\ 0 & N_{\dot{v}} & N_{\dot{p}} & N_{\dot{r}} \end{bmatrix}
\begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{p} \\ \dot{r} \end{bmatrix}
+
\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & Y_v & Y_p & Y_r \\ 0 & K_v & K_p & K_r \\ 0 & N_v & N_p & N_r \end{bmatrix}
\begin{bmatrix} u \\ v \\ p \\ r \end{bmatrix}
+
\begin{bmatrix} 0 & -C_{TN}Y_{\dot{v}}r & -Y_{\dot{p}}r & -Y_{\dot{r}}r \\ 0 & 0 & 0 & X_{\dot{u}}u \\ 0 & 0 & 0 & 0 \\ 0 & -X_{\dot{u}}u & 0 & 0 \end{bmatrix}
\begin{bmatrix} u \\ v \\ p \\ r \end{bmatrix}
$$
$$
-
\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}
\begin{bmatrix} \int_0^t u\,dt \\ \int_0^t (v + z_g p + u\psi)\,dt \\ \phi \\ \psi \end{bmatrix}
+
\begin{bmatrix} X_R \\ Y_R \\ 0 \\ N_R \end{bmatrix}
+
\begin{bmatrix} -R(u)+(1-t)T(u) \\ 0 \\ 0 \\ 0 \end{bmatrix}
+
\begin{bmatrix} 0 \\ Y_{CF} \\ K_{CF} \\ N_{CF} \end{bmatrix}
+
\begin{bmatrix} \overline{R_X} \\ \overline{R_Y} \\ \overline{M_X} + z_g \overline{R_Y} \\ \overline{M_Z} \end{bmatrix}
\tag{2}
$$

The main advantage of the two-time scale model is that it captures the second-order lateral drift phenomenon. It has better performance in incident waves, where the mean second-order wave loads heavily influence the maneuvering behavior. As it considers theories covering the whole range of important wavelengths.

For both methods, the *potential theory* is the main tool for calculating the hydrodynamic coefficients and thus forces. This theory assumes water flow across the rigid body as constant, irrotational, and incompressible. Chapter 5 of Fossen (2011) covers hydrodynamic concepts and numerical approaches. The most common numerical approaches for calculating the hydrodynamic coefficients are;

- Strip Theory; a 2-D theory that considers the flow variation in the longitudinal-section is much smaller than that of the cross-section plane of the ship.
- Panel Methods; 3-D integration method that divides the surface of the ship and the surrounding water into discrete panels, assigned a distribution of sources and sinks that fulfil the Laplace equation.

A comparison of the unified model and the two-time scale method is of interest for this research, because the hydrodynamic differences affecting ship control require further research (Liu *et al.*, 2016). Several examples of unified numerical models have been developed in the last three decades and here is a summary of the latest progress. The method proposed by Skejic and Faltinsen in 2008 was verified and validated for calm water. This method is further developed in a study on ship-to-ship hydrodynamic interaction effects between two ships going ahead in regular waves, it highlights critical maneuvering situations and it still requires experimental validation (Skejic and Berg, 2010). In 2013, the two-time scale model was applied to irregular seas and validated for a container ship (Skejic and Faltinsen, 2013). Hermundstad and Hoff (2009) implemented a time domain unified model on submarines and compared with experimental results. It was argued that the used unified model did not describe the diving maneuvers correctly because the depth dependency of the coefficients was not incorporated. A practical method for ship motion simulation using the two-time scale method is presented by Yasukawa and Nakayama (2009) that derives 6-DOF equations of motion for the high frequency problem and 4-DOF equations of motions for the low frequency problem. Wave induced motions for turning maneuver are predicted for a container ship of geometry S-175 and the predictions resulted in rough agreement with free model tests. Yasukawa, Amri Adnan and Nishi (2010) compared, numerical estimates of hydrodynamic forces and wave-induced motions taking into account lateral drift, with experiments showing that drift effects are not negligible and that the method is able to capture them. Seo and Kim (2011) extended the WISH (computer program for nonlinear Wave Induced load and Ship motion analysis) by coupling the maneuvering and the seakeeping models, and verified it by comparing with published experiment data in calm weather and regular waves. The simulations showed fair agreement of overall tendency in maneuvering trajectories.

Beside lateral drift, the broaching phenomenon is another challenge for hydrodynamic models, it concerns loss of stability while sailing in following seas where the kinetic energy of the ship along the forward axis transfers to roll motion and leads to strong heel, loss of heading, even capsize (Wu, Spyrou and McCue, 2010). Generally, maneuvering in waves is a challenge for both experimental and numerical modelling. For simulating ship motion in waves, forces and hydrodynamic coefficients need to be calculated dependent on wave frequency, ship heading and angle of attack angle between wave direction and ship course (Kim *et al.*, 2014).

2.2 *Topic 2: Guidance*

The guidance system receives information about the world, both internal information concerning the ship maneuvering and engine status, and external concerning the surroundings, environmental loading and nearby target ships and other objects and translates this information into instructions to controllers. Guidance is responsible for path planning, including collision avoidance. Fossen (2011) defines motion objectives categories. The guidance system together with the control system should fulfill the motion objectives according to one of the following categories:

1. Setpoint regulation: heading angle is constant with no consideration of time.
2. Path following: heading angle is variable, following a path, no consideration of time.
3. Trajectory tracking: heading angle is variable, following a trajectory in both space and time.
4. *Maneuvering*: considers the overall feasibility of the path, often with more importance to space than time. To incorporate COLREG, the guidance system shall consider both space and time parameters because velocities of maneuvers are critical.

The guidance system tasks are grouped into two: global and local path planning. The global path planning approach is the deliberate part of the guidance system. It is an optimized plan of the path from starting point of the trip to the end point, it includes known information about traffic, weather forecast, ship properties, land/islands, shallow waters and buoys. This is a multi-objective optimization problem and usually done offline and requires large computational requirements, in which, optimization methods and heuristic search algorithms are the two main methods. While local path (re)planning approach is the reflexive part of the guidance system, it takes charge of planning local deviations from the global plan, in case the navigation system detected an approaching object. A characteristic requirement of local path re-planning is the low computational requirements, where real-time methods such as line-of-sight (LOS) and potential fields are common.

Polvara *et al.* (2018) presented a review of global and local planning methods including a section for advanced computing-based methods. The author stated that almost all of the methods reviewed did not consider uncertainties due to environment loads and vehicle dynamics. A recent review of trajectory planning and tracking review (for autonomous driving systems) concluded that even most advanced guidance and control algorithms, with today's available sensor technology, work well under regulated environments assuming knowledge of surroundings and weather conditions. It also states that the inclusion of vehicle dynamics and environmental loads increases the effectiveness of such controllers (Dixit *et al.*, 2018). Lately, Wiig *et al.* proposed an integral line-of-sight law in the presence of constant ocean currents (2018).

LaValle in his tutorials points out that "the basic problem of computing a collision-free path for a robot among known obstacles is well understood and reasonably solved; however, deficiencies in the problem formulation itself and the demand of engineering challenges in the design of autonomous systems raise important questions and topics for future research" (LaValle, 2011, p. 108)

Polvara et al in their recent review stated the following: "It has been concluded that almost all the existing methods do not address sea or weather conditions, or do not involve the dynamics of the vessel while defining the path. Therefore, this research area is still far from being considered fully explored." (Polvara *et al.*, 2018, p. 241).

2.3 *Topic 3: Navigation*

The navigation system collects data from various sources such as sensors, cameras and satellites, and transfers the data into information of two kinds, state estimation and environment perception. State estimation is information about the ship's motion, mainly location and velocities. Environment perception is weather information, wind, waves, currents, and information about the surrounding as well, including state of target ships and objects. The scope of this system vastly increases as *level of automation* increases; the number of datasets, their resolution, frequency, quality and size are vastly increasing in remotely controlled vessels comparing to conventional ones. Moreover, since making sense of the collected data is considered part of the navigation system, its scope should then include advanced computing methods in order to deliver a fit-for-purpose output. Methods such as machine learning, sensor fusion, computer vision, prediction, and anomaly detection are now used within the navigation system for making sense of the collected data.

On board sensors are susceptible to disturbances that come from the environment, ship motion and other noise sources. The disturbances cause uncertainties in the perception model. This leads to control errors that accumulate over time, and result in undesired control behavior. Therefore, data from multiple sources are correlated against each other to calculate position and velocity estimates as accurate as possible. Data sources involved in a navigation system are:

1 Inertial measurement unit (IMU) is an onboard three-dimensional navigation system that comprises of three mutually-orthogonal accelerometers and three gyroscopes to give the position, velocity and altitude of own ship. IMU is often used with (and aided by) satellite positioning to provide drift-free positioning.
2 Automatic Identification System (AIS) is a very-high frequency communication system used by ships to transmit their identity, position, velocity, destination and other information and in return they receive information of nearby ships. Even though AIS is mandatory for commercial vessels, not all boats have it onboard!
3 GNSS is a global positioning solution system. It transmits radio signals from satellites orbiting the planet to the ship. There are a number of GNSS solution providers including GPS, GLONASS, Beidou and Galileo.
4 Radar, an acronym for radio detection and ranging, uses radio waves to detect ships and obstacles within a long range but its capability of detecting small moving targets is limited. Radar wavelength passes through fog and rain and it provides nearly all-weather data imagery.
5 Lidar, an acronym for light detection and ranging, is a high resolution and accuracy object detection sensor for near-range.
6 Sonar, an acronym for sound navigation ranging, detects submerged objects such as reefs, sunken ships and submarines. The sonar transmits ultrasonic pulses, receives the reflected echoes and displays a picture of the detected objects.
7 Other types of sensors and tools are used for navigation purposes such as cameras, infrared sensors, compass systems, navigation lights and ship whistles.

Most common method for fusing the navigation data as of today is the Kalman filter. The Kalman filter, invented by Kalman in 1960, is a real-time Bayesian estimation algorithm that uses all available measurements over time, and uses knowledge of deterministic and statistical properties of the system parameters in order to provide optimal minimum-error state estimations (Groves, 2013).

Examples of recent perception technologies in navigation systems are:

1 Non-linear observers: Advanced alternatives to the well-established Kalman filter, with proven stability properties and lower computational demands (Fossen and Strand, 1999; Aschemann, Wirtensohn and Reuter, 2016; Bryne, 2017).
2 Extended Kalman filter (EKF) for position and velocity estimation using GPS and compass measurements (Caccia *et al.*, 2008; Bibuli *et al.*, 2009; Tran *et al.*, 2014).
3 Unscented Kalman filter (UKF) for state estimation without previous knowledge of noise characteristics (Peng, Han and Huang, 2009; Vasconcelos, Silvestre and Oliveira, 2011).
4 Inverted Kalman filer (IKF) bounds model uncertainties that come from environment variability (Motwani *et al.*, 2013).
5 The eXogenous Kalman filter (XKF) for providing covariance estimates for the estimated states generated by non-linear observes (Johansen and Fossen, 2017).
6 Wave information perception using camera (Liu and Wang, 2013). Stereo vision system that generate probabilistic hazard maps and provide estimates for speed and heading of target objects (Huntsberger *et al.*, 2011).

2.4 *Topic 4: Control*

The control system is responsible to translate the information collected from the guidance system and communicate it with the actuators as commands. Actuators such as propellers, thrusters, and rudder receive commands from the control system and execute actions producing forces and moments that affect the state of the ship, approaching the desired state. The control system is responsible to make sure that the generated actuator commands are practical for the underactuated ship given the actuator limitations and ship dynamics.

Control literature is rich with control design approaches that extend from the classical proportional-integral-derivative (PID) controllers to the more advanced artificial-intelligence (AI) based controllers. Practical ship control often applies a combination of different control methods. PID control approaches are the most favored, they are, however, suitable for single-input-single-output cases such as heading control (Minorsky, 1922). This approach could suffer severe actuator damage caused by high waves. Simultaneous control of velocity and heading solves this problem. Multivariable control was realized by multi-loop PID control (Lefeber, Pettersen and Nijmeijer, 2003) and fuzzy adaptive control techniques (Le *et al.*, 2003).

Multivariable control has been widely approached by optimal control techniques such as H-infinity and Linear quadratic optimal techniques. Nonetheless, Linear Quadratic Regulator (LQR) controller suffers from the assumption that all states are measurable and known, which is not the case. Linear Quadratic Gaussian (LQG) controller together with a Kalman filter estimates in real-time the unknown states, however, suffers from instability. Instability outside predefined domain and discontinuities are major drawbacks of adaptive linear control methods (Liu *et al.*, 2016). Non-linear methods, such as Fuzzy logic control, Neural networks and Lyapunov-based methods argue that they can potentially overcome stability related issues while maintain smooth time-parametrized trajectories (Aguiar and Hespanha, 2003).

2.5 *Topic 5: Human Factors*

In this section the definition of levels of automation (or autonomy; since both terms are used interchangeably) is presented and followed by explanations of the human factors faced by operators introduced to increased automation in their operations.

2.5.1 *Levels of automation (LOA)*

Levels of automation were developed in the 1978. They were used to describe systems and aid the communication in the design phase of automated systems (Sheridan and Verplank, 1978). Multiple versions of LOAs have been issued since then. In the ship industry, LOA proposals exist from multiple sources such as Bureau Veritas, Lloyd's Register, the Norwegian Forum for Autonomous Ships (NFAS), Rolls-Royce, and others. Table 1 shows the LOAs as proposed by NFAS. General agreement exists in the different definitions as they range from human-operated ship (lowest level) to fully autonomous ship (highest level).

Explicitly, all the different variations of LOA classifications, agree that, on the highest level of automation, the machine decides and acts, and requires no communication with the human.

2.5.2 *Increased automation*

Automation is intended to increase safety and efficiency, however, in complex tasks (dynamic environments involving many variables) it changes the nature of the human-role in the task, it affects areas such as workload and cognitive demands. Moreover, the resultant impact of (increased) automation turns out to be more complex than anticipated. The changes are qualitative in context rather than quantitative and uniform (Woods *et al.*, 1996). Main human factors involved in the operator-technology interface are summarized as follows, including responsibility, surprises of automation, management by exception and communication:

1 **Responsibility:** Decisions that the human operator is used to take and implement will be routinely delegated to machines. However, can responsibility be delegated as well? Responsibility perception and calibration of trust between humans and machines are important to safe autonomous operations (Muir, 1987).
Jordan was one of the first to stress out that "we can never assign them (i.e., the machines) any responsibility for getting the task done; responsibility can be assigned to man only" (Jordan, 1963, p. 164). As suggested by Billings, human operators bear ultimate responsibility for operational goals, they must be in command, well involved and well informed about ongoing autonomous activities (Billings, 1991).

Table 1. LOAs as proposed by NFAS (Rødseth and Nordahl, 2017).

Level	LOA name	Description
1	Decision support	This corresponds to today's and tomorrow's advanced ship types with relatively advanced anti-collision radars (ARPA), electronic chart systems and common automation systems like autopilot or track pilots. The crew is still in direct command of ship operations and continuously supervises all operations. This level normally corresponds to "no autonomy".
2	Automatic	The ship has more advanced automation systems that can complete certain demanding operations without human interaction, e.g. dynamic positioning or automatic berthing. The operation follows a pre-programmed sequence and will request human intervention if any unexpected events occur or when the operation completes. The shore control centre (SCC) or the bridge crew is always available to intervene and initiate remote or direct control when needed.
3	Constrained autonomous	The ship can operate fully automatic in most situations and has a predefined selection of options for solving commonly encountered problems, e.g. collision avoidance. It has defined limits to the options it can use to solve problems, e.g. maximum deviation from planned track or arrival time. It will call on human operators to intervene if the problems cannot be solved within these constraints. The SCC or bridge personnel continuously supervises the operations and will take immediate control when requested to by the system. Otherwise, the system will be expected to operate safely by itself.
4	Fully autonomous	The ship handles all situations by itself. This implies that one will not have an SCC or any bridge personnel at all. This may be a realistic alternative for operations over short distances and in very controlled environments. However, and in a shorter time perspective, this is an unlikely scenario as it implies very high complexity in ship systems and correspondingly high risks for malfunctions and loss of system.

2 **"Automation surprises":** It could be difficult for the operators to follow up with the autonomous vehicle and understand the grounds for its decisions. When the actions of the "machine" are not similar to what the human operator would do if placed in the same situation then the human would lose track and fail to predict next steps. A simulator experiment to evaluate pilots' mode awareness was carried out that confirmed that "automation surprises" are experienced even by operators with extensive amount of line experience on similar highly autonomous aircrafts. It was shown that in non-normal situations, more problems related to "automation surprises" occurred (Sarter and Woods, 1994). A previous study by Wiener, who conducted a survey of B-757 pilots, resulted that 55% of respondents were still being surprised by the automation after more than one year of line experience on the aircraft (Wiener, 1989). Norman referred to the phenomenon of human operator losing track of machine's behavior as 'breakdown in mode awareness' which has been linked strongly to the following factors: automation surprises, increased error possibilities, new cognitive demands, and failure to intervene appropriately. Increased automation would also cause surprise to the ship designers and owners who experience unexpected consequences because their automated system fails to behave as was intended (Norman, 1988).

3 **Management by exception:** A remote operator, whether monitoring or supervising, is in a double bind dilemma with the machine. A dilemma between trust and takeover. Dekker and Woods explained this phenomenon in their work titled "To intervene or not to intervene: the dilemma of management by exception" (Dekker and Woods, 1999). Supervisory control places the operator in a decision-making situation. A trade-off between intervening too early, before enough evidence is collected about the situation, and intervening too late, after it escalades into an irreversible crisis. The operators, for every moment in time, must assess the criticality of the situation and decide whether to intervene or not. Late decisions are catastrophic. Early decisions are not justified. Decision aids and prediction tools are required, but how much should they be trusted? (Sheridan, 2000).

Human-machine interaction is changing in nature. Increased automation reduces workload in normal-times and increase them dramatically in non-normal times. In non-normal times the 'automation surprises' factor is higher, the 'mode awareness' factor is lower, the attentional demands and the cognitive demands are highly increased. Given the dilemma, this setting is critical in non-normal times as it leads to less situational awareness (SA) and less intervention capabilities. Thus, safety is a big concern if things went wrong in non-normal times. Sarter et al define the term Mode awareness as "the ability of a human operator to track and anticipate the behavior of automated system" (Sarter, Woods and Billings, 1997, p. 6). Situational awareness, according to Endsley, is "the perception of the elements in the environment within a volume of space and time, the comprehension of their meaning, and the projection of their status in the near future" (Endsley, 1995, p. 36).

4 **Communication:** For example, the grounding of the Royal Majesty is referred to as a loss of situational awareness problem; a communication problem because of increased automation. Among other factors, the GPS has failed, positioning information were incorrect, autopilot used the faulty information, the ship drifted and that was not apparent to the crew. They believed that the sailing was flawless but in fact, it lead to a grounding (Lützhöft and Dekker, 2002). Researchers emphasized on the value of communication and collaboration with the machine for safer autonomous navigation. Effective communication and coordination

between humans and machines is believed to be key for successful operations (Sarter, Woods and Billings, 1997).

3 RESULTS

This review covers topics concerning the future of autonomous vessels from three perspectives. First from the side of the technology advancements that make such a future possible. Second from the human operator side and the challenges faced while teams are operating highly autonomous systems, remotely. Third from the levels-of-automation side, multiple versions of LOA definitions for the maritime industry that classify human-machine relationship as automation increases. Trying to answer the article's question.

One may argue that the supporting technologies are already available, as there are booming examples of domain-specific advancement, but this review identifies a shortage in the studies that show how well these building blocks work out together, and under uncertainties. Analysis and breakdown of this identified shortage follows:

There is interaction and signal flow among the GNC and hydrodynamics fields, as shown in Figure 1. One publication proposing a novel path planning method would have built-in assumptions regarding (and pre-selections of) ship dynamic models, navigation methods, and control design approaches. For example, Liu, Bucknall and Zhang (2017) proposed a guidance "*fast marching*" method for a USV, and presented their results of full-scale experiments. They used a preselection of navigation methods (Kalman filter), control methods (PID autopilot), and vehicle dynamics model (3-D model) as in (Motwani *et al.*, 2013).

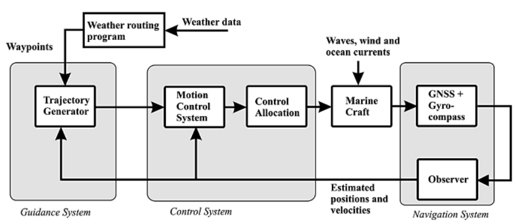

Figure 1. GNC module interaction and signal flow (Fossen, 2011, p. 233)

Given the interrelation, applications of semi-autonomous vessels, both real (full-scale) and virtual (simulators), require a package of GNC and hydrodynamics technologies interacting together. It is widely agreed that the performance of methods is largely altered by uncertainties coming from environmental loads and ship dynamics (LaValle, 2011; Liu *et al.*, 2016; Polvara *et al.*, 2018).

"Automation could increase sources of error". Precautionary perspective is necessary in research and development. Porathe *et al.* (2018) includes a fictive story that predicts a possible future scenario in one of the Norwegian fjords and provides a forecast of the risk picture in the maritime industry.

Human operators face challenges with highly automated systems. In the future, as autonomous ships become reality, advancing through the LOA scale, until eventually, full-autonomous vessels are realized in a safe and efficient manner, remote control will be essential. Safe and efficient remote operations are as important as, or even more important than, no-human-interaction type of control (according to LOA definitions of full autonomy). There is a literature shortage in this multidisciplinary field of "ship remote control". It should cover remote control-centered topics of ship design, GNC systems design, human-machine interaction, navigation functions, interface, and remote control center design.

4 DISCUSSIONS

4.1 *Disagreements*

Viewpoints such as "A ship must follow and adhere to the international regulations for preventing collisions at sea (COLREGS)" are common in GNC technology research. However, these viewpoints oversimplify the problem. They inherently assume that traffic in the sea is well regulated and all players follow the rules. In reality, operators and crew do violate procedures, for different reasons, as shown by a research that collected 1262 questionnaires from tankers and bulk carriers crew (Oltedal, 2011).

Some collision avoidance methods enable manual input of waypoints by a supervisor operator for replanning the path and avoiding approaching obstacle. As Campbell et al describe them: "This is not the most efficient method for avoidance and is subject to operator error" (Campbell, Naeem and Irwin, 2012). This view is common. It promote two points. First, that human operators are subject to more errors than machines. Second, researchers are oriented to develop technologies with high automation level and low human interaction, to avoid human errors. This view conflicts with the status quo of technology, because also machines are subject to error, and it conflicts with human factors research, that having less human interaction with highly automated system introduces the dilemma of management by exception and it can be avoided by having human input and authority over the machines even for highly autonomous systems.

In a recent survey on communication technologies (Zolich *et al.*, 2018) a relation of LOAs with communication requirements was presented. It says, basically, that the higher the LOA is, the lower the amount of data the ship would require to communicate with land. This view conflict with the human operator's requirements for safe and efficient monitoring, supervision and control of the autonomous remote asset.

The definition of full-autonomy, in all the variations of LOA scales, emphasizes on "no human interaction; machine ignores human; no human input". These definitions favor automation over safety and efficiency of the asset because full-autonomous ships need to be remotely controlled, on demand, upon the decision of the supervisor in charge. In such a dynamic multi-objective shipping task, the option of remote control is necessary; the reason for this desire of remote control could be any of the following examples:

- Business and market fluctuation
- Environment regulations and emission related rules
- Cyber-attacks, piracy and hijacking
- Environment loads and extreme weather
- Incidents at ports such as fires or chain-reaction accidents
- Customer relations; cargo health; maintenance issues and etc.

4.2 *Main challenges*

Main challenges from the different perspectives are summed up in this section as follows.

Motion coupling: control advancements consider a simplified ship model, similar to that of a 3-D unicycle model. The effect of motion coupling to stability requires further analysis.

Ship motion in waves: Describing ship motion in harsh weather is a challenge; there is no standard way of doing it. Hydrodynamic research considers that ship motion in calm water is assumed to converge to an underlying true trajectory. The maneuvering committee of the 27th ITTC address this issue as a challenge for both experimental work and numerical modelling (Quadvlieg *et al.*, 2014, sec. 6.4).

Co-simulation of digital models: The development of GNC algorithms has boomed lately. It is challenging to know how they will work together under the influence of stochastic environmental loading and uncertainties. In addition, how will the human (remote) operator experience those advancements?

Remote operator input: How well does these technologies workout together? Research towards enhancing the performance of man-machine systems in dynamic control tasks is crucial in design and operation of future maritime operations. Effects of LOA towards situation awareness and mental workload are researched (Kaber and Endsley, 2004). However, it is challenging to judge automation based on the LOA scale because the whole scale is course; massive variations could be possible within one LOA level. Variations in terms of interface, controllers, inputs, outputs and engagement level are expected for each level.

4.3 *Full Autonomy*

The main challenges of the previous section maps man-machine challenges that are valid for the maritime industry as of today. Worldwide research and development projects will certainly tackle them and innovations will pave the way, gradually, to realizations of higher levels of ship autonomy. The progress will be gradual, evolutionary rather than revolutionary, because of the political, legal and financial inertia involved in such industry.

Systematic bias: Assume that "we are dealing with a transition towards fully autonomous systems" with the main objectives "safety and efficiency". The way the developers perceive the future is key in determining the safety and efficiency of that future. The definitions of LOAs form a huge anchoring bias that weakens the focus on the objectives and strengthens the following views:

1 The ultimate goal is full autonomy
2 Full autonomy is that systems run by themselves with no human interaction
3 Human input is a negative contribution to system objectives

And those views are expanding systematically within and across industries and can be seen popular in technical scientific disciplines and among the youth in societies of most industrial countries. Broek *et al* (2017) mentioned the need of a man-machine "collaboration framework" even for fully autonomous systems.

Towards full-autonomy: As it brings value to other industries, the values of advanced technology must be harvested in the shipping industry as well. We strive for fewer accidents, less social and environmental impact by the utilization of tools such as data analytics, decision support aids, and advanced autopilots. Surprisingly, the GNC literature shows that technology is being developed towards a future with no human interaction. However, I think that the values of full-autonomy cannot be harvested unless the technology becomes developed towards a future with full human interaction.

5 CONCLUSIONS

If the industry's drive is safety and efficiency, then full-autonomy is, at present, not the way to go. Remote control, instead, could facilitate a feasible future, while focused research and development are in need. From the technology side, the literature shows that uncertainties coming from environmental loads and ship dynamics largely affect the performance of GNC technologies in a semi-autonomous vessel. Thus, accurate modeling and prediction of semi-autonomous maneuvering is fragile under uncertainties. From the human side, the literature shows that as automation is increased and interaction is decreased the operators face the *management by exception* dilemma. Operators undertaking safe and efficient ship remote control, even for highly autonomous ships, require high interaction and high authority over the system. Automation is promising because of the possible reduction of cost and risk involved in maritime operations, nevertheless; it could bring in new sources of error, while human operators face serious challenges dealing with highly automated systems. There is a rush of technology-related research but there is a lack of holistic research focusing on "ship remote control". Research that tests the GNC technologies under uncertainties with human-operator in-the-loop is needed. Digital advancements enable virtual experiment environments with human interaction such as simulators. Those safe environments could be the only tools available, for now, to enable us research whether it is full-autonomy the right way to go for exploiting the ocean potentials.

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Opportunities and Challenges in Using Ship-Bridge Simulators in Maritime Research

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Abstract - **Ocean industry prospects are addressing core challenges such as food, security, energy and climate change. The ocean holds the promise of great potential for economic growth. Appropriate tools are required for answering the questions of the emerging ocean operations. Questions related to technology development, training, safety and efficiency rise on daily basis. Ship-bridge simulators are ideal arenas for research and innovation. Simulators are used in maritime contexts, mainly in education and training. However not much is published regarding the use of simulators in maritime research. This paper presents a literature review of the use of simulators in maritime research in the recent years. Additionally, it highlights the opportunities and challenges of using simulators in the maritime industry according to interviews held with academics and professionals in the field, in Norway and abroad.**

Keywords

Ship simulators, research, opportunities and challenges, training, the future of shipping.

INTRODUCTION

What is a simulation? What is a simulator?

Replication, duplication and projection of reality are three faces of simulation. Role-play, maps, and computers are possible tools for running simulations. Computer simulations are powerful tools to study complex systems and have wide variety of applications in engineering, science, medicine, economics and social sciences. A computer simulation, in its narrowest sense, is a computer program that follows step-by-step instructions to approximate the state of the system being described by the instructions. The algorithm takes as input the initial values (the values of all of its variables at time t equals to zero). Then it calculates the system's state (the variables of interest) at the first time step.

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From the values of the state at the first time step it calculates the state at the second time step, and so on the computer simulation progresses the calculations with time. The results of the computer simulation can be visualized and compared to results obtained from a scientific instrument that measures the system's state.

According to Winsberg (2003): "Successful simulation studies do more than compute numbers. They make use of a variety of techniques to draw inferences from these numbers. Simulations make creative use of calculational techniques that can only be motivated extra-mathematically and extra-theoretically. As such, unlike simple computations that can be carried out on a computer, the results of simulations are not automatically reliable. Much effort and expertise goes into deciding which simulation results are reliable and which are not."

Simulations are generally used for estimation of system states (prediction of data that we do not have) or generating understanding of data that we do already have. In the case of ship motion, the simulation accounts for hydrodynamics seakeeping and maneuvering theories in finding the progress of motions in the desired degrees of freedom. Mathematical equations based on those theories are at the core of the simulation. It also accounts for environmental loads as stochastic processes that keep on changing with time. The loads from winds, waves and currents are fed, at every time step, into the mathematical equations and influence the resultant force. The force that affects the direction and magnitude of the motion of the ship. Still, the motion of the ship can be controlled by, for example, rudder and thruster human inputs. Such control inputs can also be incorporated, otherwise be set as predefined states, depending on the goals and objectives of the simulation.

A computer simulation is normally run on a desktop computer and the results are processed and visualized, mainly in graphs, after the calculation is over. Whereas, a simulator is a real time computer simulation that looks and feels like reality, it is "a piece of equipment that is designed to represent real conditions, for example in an aircraft or spacecraft: people learning to fly often practice on a flight simulator." (Cambridge University Press, 2018).

Simulator is interactive, with human in the loop, such as in a flight simulator, sailing simulator or a driving simulator. It is "a device that enables the operator to reproduce or represent under test conditions phenomena likely to occur in actual performance" (Merriam-Webster, 2016).

Industry trends regarding the use of simulators

Use of simulators, either for entertainment or for training, is increasing. Nowadays there are off-the-shelf bicycle simulators and golf simulators for customers that want to practice at home. Apart from personal-use simulators, the use of simulators in the industry is expanding. The healthcare industry is using medical simulators to teach therapeutic and diagnostic procedures. The automotive industry is using truck simulators to provide beginners adequate training. CARLA is an open source simulator for autonomous driving research to support development, training and validation of autonomous urban driving systems (Dosovitskiy *et al*, 2017). The racing industry is using racing simulators to train professional racers maintain their skill and sharpness. The chemical industry is using operator-training simulators to create a safe and realistic virtual environment to train engineers for safer operations in process plants. In the space industry, shuttle grounds operations simulator is used to debug and verify the functionality of space application software of the international space station. Ending the examples with the maritime industry, ship-bridge simulators, remotely operated underwater vehicles (ROV) simulators and crane simulators are used together for advanced offshore operations planning.

Trends regarding use of simulators in training and education

Ship-bridge simulator-based training practice is well established in maritime education. The International Convention on Standards of Training, Certification and Watchkeeping of Seafarers (STCW) of the International Maritime Organization (IMO) regulates the standards of training. The main purpose of the Convention is to promote safety of life and property at sea and the protection of the marine environment to ensure that future professional mariners can operate properly and safely in their work practice, this convention emphasizes on the use of simulators for both training and assessment.

The set of simulator-based training courses offered by IMO, for both the novice and the experienced participants includes:

- *Ship simulator and bridge teamwork course;*
- *Liquefied petroleum gas (LPG) tanker cargo & ballast handling simulator course;*
- *Liquefied natural gas (LNG) tanker cargo & ballast handling simulator course;*
- *Chemical tanker cargo & ballast handling simulator course;*
- *Oil tanker cargo and ballast handling simulator course;*
- *Automatic Identification System (AIS) course; and*
- *Train the simulator trainer and assessor course.*

In June 2015, after a series of EU projects from 2009, the IMO approved a "Guideline on Software Quality Assurance and Human-Centred Design (HCD) for e-Navigation". The objective of e-Navigation concept is to harmonize the collection, integration, exchange, presentation and analysis of marine information by electronic means to enhance the operations and their safety. IMO considers that e-Navigation should be user driven rather than technology driven. HCD methods require heavy involvements of seafarers and operators in the design and development process of navigation aid tools. From 2015, the IMO recommends that HCD should be used in development of new navigation equipment (IMO, 2015).

Maritime simulators are classified into four classes based on their capabilities. Class A (full mission); Class B (multi-task); Class C (limited task); and Class S (special task) is used when the performance is defined on a case by case basis (Det Norske Veritas, 2011). Different types of maritime simulators exist, related to the operation they replicate, for example:

- Bridge operation simulator;
- Machinery operation simulator;
- Radio communication simulation;
- Cargo handling simulator;
- Dynamic positioning (DP) simulator;
- Safety and security simulator;
- Vessel traffic services (VTS) simulator;
- Survival craft and rescue boat operations simulator;
- Offshore crane operation simulator; and
- Remotely operated vehicles (ROV) operation simulator.

This article is about the use of ship-bridge simulators in research, this includes simulator Classes A & B, and bridge operation and dynamic positioning simulator types. Other names are also used to describe them such as full-mission simulators and ship handling simulators. In this article, the simulators of interest are ship-bridge simulators. From now on the term "simulators" is used to refer to ship-bridge simulators. As described by Porathe (2016) "A ship-bridge simulator is a piece of laboratory hardware and software that simulates a ship's behavior from the vintage point of its bridge.

Often consists of a mock-up bridge (a more or less realistic bridge interior with consoles, screens, instruments and windows to the outer world) but often also a visualization, i.e. the egocentric 3D view of the surrounding world with ships, islands and ports projected on screens outside the windows".

While lately, the demand in using simulators is increasing and the purposes of using simulators are branching into specific niches. Simulators are not only used for training, they are also being lately used in research. This paper tries to answer the following questions:

1. What are simulators currently used for in research?
2. What are the opportunities of using simulators in research?
3. What are the challenges of using simulators in research?

METHODOLOGY

In order to answer the three questions above, two main methods have been used. First is a literature review for relevant research that uses simulators, second is interviews with professionals and researchers in the field. Details about the two methods follow.

Method I – The literature review is made to contribute mainly in answering the first question: "What are simulators used for in research?" A literature search in the search engine "Oria" of the Norwegian University of Science and Technology (NTNU) that provides search of the university's both printed and electronic collections of internationally renowned scientific databases (and publishers) such as INSPEC (Journal of Navigation), Scopus (Elsevier, Springer, IEEE), ProQuest, Transnav and WMU. Search criteria of the literature review are as follows:

Table 1: Literature review search criteria

Keywords:	Ship simulator; bridge simulator; mission simulator
Publication date:	Last 10 years
Material type:	Articles and journals
Other filters:	The publications that do not involve use of simulator are filtered out
Number:	50 publications

Method II – Interviews were held to bring a variety of perspectives from both researchers and professionals in the field. A google search was made for both academic and commercial simulator centers all over the world. Thirty-five centers were found. A shortlist of contacts for interview invitations was created that includes the following three groups:

- Group i. Six internal researchers (employed by NTNU) that have performed experiments in simulators.
- Group ii. Sixteen external researches (employed by other institutions around the world) that were first authors of publications found in the literature review.
- Group iii. Twelve managers at research centers.

The shortlisted people were invited to interviews. Ten positive responses were received and actually nine interviews were performed: four from the first group; one from the second group; and four from the third group. The interview questions were the same for all of the interviewed persons. A little bit of customization was included in the introduction of the interviews to fit with every person's background and current works. The interview questions are:

- Question i. Tell us about yourself and the field of your interest.
- Question ii. What opportunities do you think simulators provide for research (/ or for the industry)?
- Question iii. What challenges you faced during using simulators for your research (/or for your work)?

The general semi-structured open-ended questions helped in outlining the interview conversation. They were half-an-hour interviews that started with an introduction about the authors of this article and their motivation for writing it. This paper utilized inductive coding method for analyzing data from interviews.

LITERATURE REVIEW

Fifty publication were found based on the search criteria. The publications are classified into three categories. The first category is "Simulator Facility" and this concerns publications that focus on the simulator facility itself, they provide proposals of software and hardware developments, including algorithms and models. The second category is "Experimental Practice" and this concerns publications that provide knowledge about the practice of performing experiment in the simulator, this includes instructor roles, hierarchies and social structures. The third category is "Training and Evaluation" and this concerns publications that report on methods for performance monitoring of navigators, including evaluations of teamwork and training for specific operations. The Venn diagram of the classification is shown in Figure 1.

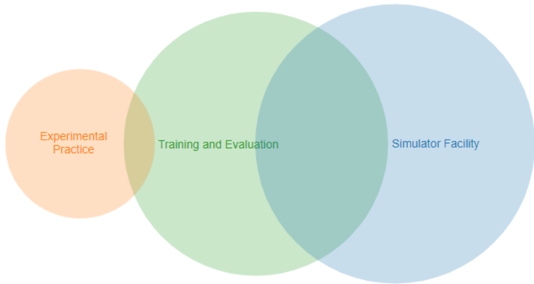

Figure 1: Venn diagram of the literature classification. Created by the online tool https://www.meta-chart.com/venn

The publications of the *Simulator Facility* category are split into five sub-classifications as presented in Table 2. The table provides a sample of publication names and lists the remaining references for each sub-classification. Table 2 is found in the Appendix.

The *Evaluation of technology* sub-classification includes publications that investigates technologies such as visual system; advanced decision support systems; direct gesture interaction methods; and accuracy of hydrodynamic methods.

The *Software for autonomous capability* sub-classification includes publications that propose algorithms and models for autonomous maneuvering; intelligent target ships maneuvering; communication and intention exchange; and safety quantification. One publication presents the capability of generating real-time objects in a simulator based on Automatic Identification System (AIS) data (Last, Kroker, & Linsen, 2017).

The *Software for fuel and emissions* sub-classification includes publications that investigate the relationship between maneuvering and fuel efficiency or emissions. Such research do not only provide knowledge, also provides models that can be incorporated in a simulator to extend its usage.

The *Software for human evaluation* sub-classification is a subset of the *Training and Evaluation* category. It includes methods and algorithms for quantifying human interactions; performance; non-technical skills and mental workload.

The *Software for specific operation* sub-classification includes publications that presents software additions to simulators to enable simulations of specific operations such as icebreaker escort; restricted waters maneuvering; ship-to-ship lightering and shallow waters maneuvering with attention to ship squat.

The publications of the *Experimental Practice* category are split into two sub-classifications as presented in Table 3. Table 3 is found in the Appendix.

The *Safety training* sub-classification includes publications presenting simulator experimental practices for ship Bridge Resource Management training; simulating marine collisions leading to a safer operating future, and benefits for safety training and investigation.

The *Pedagogical approach* sub-classification includes publications that provide analysis and assessment of the training activity. They focus on the learning component and the actions of instructors.

The publications of the *Training and Evaluation* category are split into three sub-classifications as presented in Table 4. Table 4 is found in the Appendix.

The *Evaluation of training technology* sub-classification includes publications that examine the effect of technology advancements on human performance.

The *Performance evaluation* sub-classification includes publications that study the human performance. Most of them study the human performance quantitatively using physiological measurements. Quantification efforts of the following are apparent: workload; human interactions; mental stress and strain; and teamwork.

The *Technology on Training* sub-classification includes innovative methods for training for specific operations. Training such as emergency unberthing without tug assistance and training for energy-efficient maneuvering. Additionally, it includes methods for quantifying training evaluation, such as the proposal of an evaluation index for berthing operations.

The literature shows two main paths and one emerging path of simulator research. The first main path evolves around the capability of the simulator facility. On the one hand, investigating the current capabilities, such as the accuracy of hydrodynamic models. On the other hand, developing models that enable new capabilities such as simulating ship-to-ship lightering operations. The second main path evolves around the use of simulators for training and evaluation. This path investigates and utilizes technology for training. In addition, this path focuses on quantification, providing methods for performance evaluation in a quantitative manner. Finally, the emerging path is investigating "how to make the most of simulator training by understanding the practice?" this path mainly concerns the simulator instructors. Next section is the presentation of the second method, the interviews.

INTERVIEWS

Nine interviews were held. Conversations about usage, opportunities and challenges of simulators were coded and analyzed. The interview findings are listed in Table 5. The next section, Discussions, includes two parts, the analysis of the interviews, and the discussions based on the two methods. Table 5 is found in the Appendix.

The interviewees have different backgrounds, seven of them have engineering background and two have social science background. The main usage of simulators according to the interviews is related to education and training. However, interesting applications are emerging such as sensor fusion of physiological data and testing technology and algorithms towards autonomous operations.

The opportunities are summarized in three main points. First, simulators are facilitators of research and innovation. Second, simulators stimulate change in industry workflows. Third, simulators open new frontiers towards transforming the industry.

All the researchers have agreed on the research infrastructure challenges. Such as the availability of simulators and availability of some expert helping hand to aid them throughout their experiments. While the managers mentioned issues related to cost of handling and maintaining simulator facilities. Analysis, interpretations and discussions follow in the next section.

DISCUSSIONS

In the light of data from both the literature review and the interviews, the three areas (usage, opportunities and challenges) are discussed in this section. The literature review data provided relevant and up-to-date knowledge regarding research using simulators. The authors have very different backgrounds, in fact, the majority of researchers are not from nautical science disciplines. However, in interviews, researchers emphasized the challenge of needing some expert help to aid them throughout the experiments. Since the nautical science education in not taking precedence over the research in ship-bridge simulators, then a gap and a need in maritime research activity is identified. Filling such a gap will shape the future of shipping. Especially that simulators are embracing multi-disciplinarity and bringing human and technology in the loop. Domain education and expertise are worth to be brought in the loop as well.

Usage

It is promising to see this spectrum of research disciplines running simulator experiments in the last ten years. However, the use of simulators in research is limited to researchers with access to simulators. This privilege is not available to many researchers around the world. Taking into consideration the trend of increased demands and increased usage of simulators in the past years. Keeping in mind that the opportunity list is very seducing for both the academy and the industry to pursue simulator research for shaping a safer and a more efficient future for the maritime industry. Given these inputs, I think it is probable that the demand on simulator facilities will rise significantly in the next ten years and thus the usage of simulators in research will. The accessibility is a limiting factor in the growth of simulator research, however, technology advancements could provide solutions, such as virtual reality (VR) simulator technology.

The usage of simulators today, other than simulator-based education and training, is summarized as research towards education and towards developing technologies. It is interesting to harvest the fruits of the technology research part. Then, it is expected, quite soon, to see simulator usage embedded in industry processes such as ship design, port design, controllers design and the like. Such processes complement and support human-centred design frameworks that are essential methods for designing safety-critical systems and are recommended by the IMO. The next section is an analysis and discussion of the opportunities.

Opportunities

This section summarizes the opportunities of broadening the use of simulators. Simulators offer important proof of concept capability to innovations in ship-bridge design, port design and research ideas. Simulators are a haven for human factors and sociocultural diversity research. Nevertheless, the research and development of autonomous vessels will depend largely on simulator experiments. Starting with a brief about simulator advantages to lay the foundation for the opportunities.

Advantages

The advantages of simulators are massive, and here are several of them. First, simulators bring human-in-the-loop. The human user in the simulator is a central element of the performed operation. For the case of ship-bridge simulators, the human is the one observing, perceiving and interacting with the navigation equipment to achieve the desired maneuvers. Second, in the same manner, simulators bring the hardware in the loop as well. Real and up to date hardware is required to be installed in the simulator for delivering the expected experience of realism. This requirement is valid for all interaction hardware, such as rudder and thruster controllers, seat, cabin / bridge furniture, radar screen and so on.

Third, simulators provide full control of the situation. A simulator is a safe lab to practice risky operations in harsh conditions. Fourth is feasibility. Running a demanding operation in a simulator is certainly dramatically more feasible than actually executing the operation itself. Instead of simulating the complete actual operation, concentrated chunks can be simulated to investigate or train the users for particular skill, thus saving time and resources. Fifth is Flexibility. The simulators offer flexibility in setting winds, waves and currents loads. In addition, it also offers flexibility in setting scenarios, the traffic, time, day and night, and so on. However, the flexibility is limited to designed flexibility. For instance, if the researcher requires enhancing the level of autonomy for the target ships, this cannot be done without further programming and software development.

Sixth, simulators run in real time, some of them have a capability in running faster than real time, and this property opens prediction and augmentation opportunities. Seventh simulator operations are reproducible. This is key property for research. The researcher is able to reproduce the conditions and perform the experiment over and over again.

And finally, simulators open new frontiers. They can simulate operations in very harsh and very rare weather conditions. They even can simulate cases not possible in real life. Such as planning iceberg management or optimization of seismic survey ship scan routes. A simulator center in Canada has developed a dynamic positioning (DP) controller for the arctic waters that accounts for wind, waves, currents and snow forces. A simulator center in Norway identified that seismic ship operators navigate differently and is investigating the optimal route for seismic survey navigation.

Proof of concept

Simulator runs come handy in the ability to validate or refute concepts regarding ship and port design. Not only valuable for proof of concept, but also for further developments and training. According to an interviewee, simulator runs can be used to train people, algorithms and procedures. Simulator experiments are crucial in the development of the following disciplines. First, research ideas can be validated in a simulator. For example, a researcher with own hypothesis: “separated traffic schemes will enhance safety in the sea” can structure simulator experiments to investigate the very existence of a relationship between the variables of interest. Second, algorithms can be trained in simulators and by simulators. Artificial intelligence algorithms require learning datasets. Datasets that teach the algorithm how things work in certain conditions. Simulators can provide valuable learning datasets for such algorithms. Then, the performance of the trained algorithm can be put under investigation in another simulator experiment.

Third is hardware. That is a two-folded opportunity. From the one hand, simulator experiments are used to verify and validate the performance of a piece of hardware, whether it delivers the actions as expected. From the other hand, an interviewee mentioned that learning curves of novice and experienced users could be investigated to evaluate the easiness and user-friendliness of the piece. Fourth, simulators are fit for purpose for evaluating new port designs. Pilots can run trials into and out of the port in a simulator with different ship sizes and test geometrical port features. Fifth, the use of simulators early on in the process of ship design. From maneuvering capabilities to bridge technologies, all can be investigated with operator in the loop in the simulator. Finally, simulators are the place to risk-free test interaction methods. Interface items such as controllers, visuals and bridge layout are subject to testing in a simulator for evaluating the impact of the changes on the performance of seafarer subjects.

Human factors

Simulators bring the opportunity to investigate group dynamics and interactions in a maritime operation setting. According to an interviewee, sociocultural variables could be considered and investigated in research such as gender differences, cultural differences, experience, and age differences. I think that “teamwork in critical operations” is a field that will benefit a lot from simulator capabilities. Simulator experiments also make observing the experts possible. An important data source for designers to learn how do experts really use and interact with the machine.

Development of methods

According to an interviewee, simulator involvement in the process of ship design for example is disrupting the industry practices and workflows. In line with HCD philosophy, the simulator becomes a regular meeting point among the designer, the owner, and the operator. I see that simulators can bring integrated operator’s experience and owner’s desires and constraints into the design process early on. This provides transparent exposure and understanding among project partners. Creating a paradigm shift in industry practices.

Another perspective for looking at this point is that simulator experiments reveal knowledge that was not known before, this knowledge is used as a convincing tool to persuade the industry rethink their methods and practices.

Autonomous vessels

While investigating the safety and efficiency of different levels of autonomy, I think that simulators are the best havens for running numbers of scenarios and cases with all kinds of traffic mixtures involving autonomous vessels, remotely controlled ships, and conventionally-controlled commercial vessels including leisure boats and small fishing boats. The accumulated digital nautical miles provide experience and knowledge preparing the industry to take assured steps forwards. Simulators can also be the lab for testing guidance, navigation and control (GNC) algorithms.

Virtual ocean

As the numbers of simulators increase and their demand increases as well. I see that there is an opportunity of connecting simulator centers together and creating a digital model of the world's oceans, including coastlines and ports. Calling it the *Virtual connected ocean,* a shared ocean space for all kinds of ocean economy related research. Simulator centers can access the shared space and perform operations for research, training and technology development.

Anywise, when linking the current usages with the opportunities, then the imagination and the processing power are the limits of what a simulator can do. In other words, I believe that the scope of simulator usage is expected to grow significantly in the future. The next section is an analysis and discussion of the challenges.

Challenges

Simulators are technology driven. They advance together with technology advancements in computer processing power, graphics and visual systems and real-time hydrodynamic models. Despite of the state of the art, technologies do have their pitfalls occasionally. The challenges based on the experiences of the interviewed experts are summarized in this section. Part of the challenges is practical and is related to the setup, equipment, participants, and etc. The other part is philosophical, and is attached to the fact that a simulator is a simulator and reality is something else. Ironically, the philosophical challenges are closely related to the advantages of simulators.

Availability

The main challenge is availability. Simulators are physical rooms and there are some requirements need to be met before an experiment is ready to be held. According to interviewees, the challenge of the availability of the following was mentioned. First, the availability of simulators facilities. Researchers need to wait elongated periods sometimes in order to have a time slot for their simulator experiments. Second, the availability of experienced participants. It is not simple to book experienced seafarers for simulator experiments. They are not always available.

Third, the availability of technical support. An expert technician is required to help the researcher manage the data flows and logging. Additionally, to implement modifications on simulation configuration including scenario location, target ships, traffic, time, weather, equipment functionalities, and so on. Fourth and last, the availability of up-to-date interaction hardware is a challenge. Maintaining the feeling of the experience as realistic as possible, the full-scale up-to-date hardware is required to be installed, calibrated and connected in the simulator and be ready for use.

Data management

Big data volumes can be collected from a simulator experiment. Research infrastructure is required to enable researchers collect the data they seek otherwise it is very challenging to setup and achieve the desired data collection. Multiple possible data sources are there, and here are some examples. First, the ship data. This is mainly the data of the simulation software that holds quantitative information about the locations and motions of the ship(s) (i.e. location coordinates, course, heading, speeds, roll, pitch and other motions as they progress with time). Second, the navigation aids data, this include Radar images, ECDIS and AIS data. Third, the human-machine communication data, which is the record of all human control, inputs including thruster, rudder and other instructions.

Fourth, the human-human communication data. Whether it is communication among the bridge team, or communication between the bridge and others vessels, instructors or VTS. Fifth, physiological sensor data. This includes data from eye-trackers, heart-rate sensors, Electrocardiography (ECG), Electroencephalography (EEG), Electromyography (EMG), respiration sensors and temperature sensors. Note that wearing the physiological sensors on the body and keeping the wires connected is not only challenging, also heavy and motion restricting, thus the participant will be limited in motion and not feeling comfortable. Lastly, video data. Video recordings of the simulator session includes the bridges and instructor rooms brings valuable data for education and collaboration research fields.

Realistic physics and underlying assumptions

With the real-time constraint, the accuracy of the physics is not guaranteed in a simulation. The hydrodynamic models at the core of the simulator software have underlying assumptions. In some conditions where such assumptions are physically invalid, the uncertainty in the computed ship response becomes high, thus, the simulator experience becomes less realistic. Unless, specialized hydrodynamic models where created and validated. Few examples of less realistic simulator experiences:

i. The last meter in a docking operation: as the ship is approaching into a dock, the behavior of the ship in the simulator gets less realistic. This is also true with approaching to any structure, such as ship-to-ship operations or sailing in a tunnel.
ii. Co-simulation: for example, the co-simulation of an offshore crane operation, the crane is mounted on the ship. The ship is moving in waves, the crane is lifting a load; the motion of the ship is affecting the motion of the lifted load and vice versa. The motion coupling is a non-trivial problem to solve. Therefore, the simulator experience deviates from the real world.
iii. Shallow water navigation effects are not appreciated in a simulator, because one of the underlying hydrodynamic assumptions is that the ship is sailing in deep water. However, there have been development of shallow water hydrodynamic models lately to cover this gap.

Software is software

Simulators, like other software, might have periodic problems, bugs and shutdown problems every now and then. According to interviewees, one expert technician per facility is required to maintain the simulators and perform both corrective and preventive maintenance measures. System updates increase the realistic functionality and feel, however it is typical, with every update, there is something lost that requires troubleshooting and fixing. The maintenance of a simulator facility is costly.

Philosophical challenges

A simulator experiment is not a real-life operation, yet, we desire them to be identical. The philosophical challenges are rooted from the differences of real-life operation conditions and simulator exercise conditions. For instance, the duration of the operation in real-life is long. It includes the trip to the location, the operation and the trip back, in which the operators live onboard. However, in simulator exercises, the participants would have a much shorter exercise, after which they can go home to relax and then have comfortable sleep. Real-life operators work longer shifts and they sleep with the ship motions, and would develop feelings of isolation. The duration, location, motions, seriousness and the overall feelings and thoughts of the operator would be different. This difference is related to the difficult question of validity and reliability of simulator experiments.

Discrepancies in results

In the literature review, one finding is the clear lack of published articles by authors with nautical science backgrounds. The nautical sciences are a new scientific tradition, very grounded in work and experience, while technologies are advancing fast and their involvement, as nautical scientists, in research and innovation is crucial for preparing the industry towards a better a future.

In the interviews there were no disagreements found, therefore, just the main agreements are highlighted. Regarding opportunities, 8 out of 9 mentioned statements that mean “simulators are tools for technology advancements such as the development of autonomous ships”. 5 out of 9 referred to simulators as good places for human factors research. 4 out 9 referred to simulators as enablers for developing processes, such as industry practices. Regarding challenges, 6 out of 9, expressed the urge of availability of expert help during simulator exercise. Help with managing the data and configuring the simulators is described as “indispensable”. 3 out of 9 agreed that achieving the realistic feel of the operator’s experience is quite challenging in a simulator.

CONCLUSIONS

Motives supporting the use of ship-bridge simulators in research, and thereafter, in the industry could be safety, efficiency and developing current technologies. A substantial share of the research work can be done in simulators, hence, simulators can be described as the safe havens and feasible laboratories for maritime research. They open new frontiers of research and development. Not only development of products and algorithms, but also the development of mindsets. Simulators gather people and gather disciplines together. Industry practices in design, for instance ship design, could change as a result of simulator research benefits. The IMO, since 2015, is recommending human-centred design approach in industry practices. This was a tangible result of simulator research. Simulators offer researchers multidisciplinary exposure, with engineer, seafarer, hardware and software in the loop. However, a gap in research is identified where the nautical domain education and expertise are needed and are encouraged to follow up.

The main opportunity for using ship-bridge simulators in research is the integration in the development processes of new technologies and designs. Whereas, the main challenge is the need of research infrastructure that includes technical support and appropriate tools for observation, collection and management of data.

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APPENDIX

Table 2: Presentation of the *Simulator Facility* category

Classification	Sub-classification	Publications' Names (a sample) and References
Simulator Facility	Evaluation of technology	"A Few Comments on Visual System of Ship Handling Simulator Based on Arriving Port" (Mitomo, Hikida, Murai, Hayashi, & Okazaki, 2008) "An experimental simulation study of advanced decision support system for ship navigation" (Nilsson, Gärling, & Lützhöft, 2009) "Accuracy of Potential Flow Methods to Solve Real-time Ship-Tug Interaction Effects within Ship Handling Simulators" (Jayarathne, Ranmuthugala, Chai, & Fei, 2015) (Arenius, Athanassiou, & Sträter, 2010; Bjørneseth, Dunlop, & Hornecker, 2012; Hontvedt, 2015; Jose Miguel Varela & Soares, 2017; Weber, Costa, Jakobsen, MacKinnon, & Lundh, 2018)
	Software for autonomous capability	"Deep Convolutional Neural Network-Based Autonomous Marine Vehicle Maneuver" (Xu, Yang, Zhang, & Zhang, 2018) "A user test of Automatic Navigational Intention Exchange Support System using an intelligent ship-handling simulator" (Miyake, Fukuto, Niwa, & Minami, 2013) "Developing a Maritime Safety Index using Fuzzy Logics" (Olindersson, Bruhn, Scheidweiler, & Andersson, 2017) (Ari, Aksakalli, Aydoğdu, & Kum, 2013; Benedict et al., 2014; Last et al., 2017; Wang, Yang, & Chen, 2011; S. H. Yang, Chen, Wang, & Yang, 2011)
	Software for fuel and emissions	"Effects of ship manoeuvring motion on NOX formation" (Trodden & Haroutunian, 2018) "Comparison of the Efficiency of Williamson and Anderson Turn Manoeuvre" (Formela, Gil, & Sniegocki, 2015)
	Software for human evaluation	"Quantitative projections of a quality measure: Performance of a complex task" (Christensen, Kleppe, Vold, & Frette, 2014) "A proposed Evidential Reasoning (ER) Methodology for Quantitative Assessment of Non-Technical Skills (NTS) Amongst Merchant Navy Deck Officers in a Ship's Bridge Simulator Environment" (Saeed, Bury, Bonsall, & Riahi, 2018) (Cohen, Brinkman, & Neerincx, 2015; Orlandi & Brooks, 2018)
	Software for specific operations	"A coupled kinematics model for icebreaker escort operations in ice-covered waters" (Zhang, Goerlandt, Kujala, & Qi, 2018) "Interactive 3D desktop ship simulator for testing and training offloading manoeuvres" (J. M. Varela & Guedes Soares, 2015) "Development of a Decision Support System in Ship-To-Ship Lightering" (Husjord, 2016) (De Souza, Tannuri, Oshiro, & Morishita, 2009; Șerban, 2015)

Table 3: Presentation of the *Experimental Practice* category

Classification	Sub-classification	Publications' Names (a sample) and References
Experimental Practice	Safety training	"A Comprehensive Experimental Practice for Ship Bridge Resource Management Training Based on Ship Handling Simulator" (Y. F. Yang & Feng, 2014) "Study on Dynamic Simulation System for Vessel's Collision Process and Its Application" (S. Yang & Chen, 2011) "Safety First: How simulating marine collisions can lead to a safer operating future" (Morter, 2015)
	Pedagogical approach	"The human factor and simulator training for offshore anchor handling operators" (Håvold, Nistad, Skiri, & Odegård, 2015) "On the Bridge to Learn: Analysing the Social Organization of Nautical Instruction in a Ship Simulator" (Hontvedt & Arnseth, 2013) "From briefing, through scenario, to debriefing: the maritime instructor's work during simulator-based training" (Sellberg, 2018)

		(Sellberg & Lundin, 2017, 2018)

Table 4: Presentation of the *Training and Evaluation* category

Classification	Sub-classification	Publications' Names (a sample) and References
Training and Evaluation	Evaluation of training technology	"An experimental simulation study of advanced decision support system for ship navigation" (Nilsson et al., 2009) "The human factor and simulator training for offshore anchor handling operators" (Håvold et al., 2015) "The AIS-Assisted Collision Avoidance" (Hsu, Witt, Hooper, & Mcdermott, 2009)
	Performance evaluation	"Systemic assessment of the effect of mental stress and strain on performance in a maritime ship-handling simulator" (Arenius et al., 2010) "Quantitative projections of a quality measure: Performance of a complex task" (Christensen et al., 2014) "Measuring mental workload and physiological reactions in marine pilots: Building bridges towards redlines of performance" (Orlandi & Brooks, 2018) (Kitamura et al., 2013; Murai & Hayashi, 2010; Murai et al., 2010)
	Technology on training	"Emergency Unberthing without Tug Assistance" (Kunieda, Yabuki, & Okazaki, 2015) "Energy-efficient operational training in a ship bridge simulator" (Jensen et al., 2018) "Fundamental Study of Evaluation at Berthing Training for Pilot Trainees Using a Ship Maneuvering Simulator" (Inoue, Okazaki, Murai, & Hayashi, 2013)

Table 5: Interview codes

Q1: Usage	**Q2: Opportunities**	**Q3: Challenges**
Education and training • Performing demanding tasks / operations • Individual and group training • Training novice and professionals • Leadership and joint situation awareness • Tools for enhancing safety and efficiency Research in education • Finding learning curves of student • Researching the learning in simulators • Instructor role in simulators Research in technology • Collecting physiological data • Testing new interaction designs • Data driven models for digital prototyping • Human in the loop research • Hardware in the loop research • Testing technology and algorithms • Mariner's response rates • Future projections • Offshore wind industry	Research and innovation facilitator • Innovation facilitator • Multidisciplinarity • Flexible scenarios • Connect simulator centers • Shallow water / bank effects • Docking • Complete control of situation • Proof of concept for new designs • Huge savings • Research teams / genders / cultures / groups • Training of algorithms / people / procedures • Observing the experts Developing industry workflows • Development of design methods • Convincing the industry New frontiers • Harsh environments • Autonomous vessels • More tests / scenarios / participants. Cases impossible in real life	Research infrastructure challenges • Availability of simulators • Availability of participants • Availability of technical support • Availability of maritime research partner • Data management • Availability of hardware Simulator being just a simulator • Limited setup flexibility • Duration of simulation • Location of simulation • Expensive to maintain • Bugs and shutdowns • Upgrade issues Technology readiness • Technology of sensors • Validity and reliability • Physics in co-simulation • Physics and visuals requirements • Mimic circumstances as good as possible

ON THE VARIOUS SHIP SIMULATOR APPLICATIONS AND THEIR ACCURACY REQUIREMENTS: COMPARISON OF TWO NUMERICAL SIMULATORS WITH EXPERIMENTS

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SUMMARY

Ship maneuvering models are mainly used in navigation simulators for seafarers education. Recent trends show that the scope of maneuvering model applications is growing. The increased integration of maneuvering models into modern ship systems and the extent of simulator applications raises concerns about the accuracy of such models.

This study is addressing physical modeling accuracy in ship simulators. The maneuverability of a large containership in irregular waves is investigated. Simulations with two different maneuvering codes are compared with experiments. Turning circles with 35° rudder angle, and zig-zag 20/20 maneuvers are investigated in calm water and for a range of irregular sea states, in initial head sea and initial following sea. Overall, the "objective testing" shows that the performance of the two simulators in calm water is similar and compares adequately with experiments. However, their performance in waves varies, showing that waves are affecting maneuverability differently in the two simulators.

The study aims to address the accuracy of maneuvering models and the suitability of navigation simulators for various applications. Accuracy Requirement Level (ARL) classification standard is proposed to fulfil two objectives. First, ARL classification defines simulator capabilities. Second, ARLs define the accuracy required by a given application. Together, the "objective testing" and the ARLs address the suitability of simulators and help users match their applications with appropriate simulators.

1 INTRODUCTION

Ocean operations are addressing vital challenges such as food security, energy security, and climate change. Such operations face a multitude of challenges such as waves, ocean currents, winds, water depth, and distance from port. Safety and efficiency are crucial objectives of ocean operations, and technologies such as guidance, navigation and control (GNC) are evolving to enable safe and efficient operations.

One component in GNC technologies is the maneuvering model, a model that describes the dynamics of a moving ship in water. Maneuvering models are also used in ship simulators for education and training of seafarers, and for a spectrum of prediction-based digital solutions. There is a need of describing ship motions in realistic conditions. Therefore, the combined effect of maneuvering and seakeeping theories should be taken into consideration simultaneously in real-time.

Apart from the main application of maritime simulators, i.e. i) seafarer education, the applications of ship simulators are rapidly increasing. Ship simulators nowadays are being used for several applications such as ii) operator training; iii) assessment; iv) development and testing; and v) research and innovation. i) In seafarer's education, simulator courses are rooted in nautical schools study plans, covering a range of skills such as ship handling, ballast handling, bridge teamwork and the navigation of different types of tankers (MSC, 2015). ii) The second application, operator training, is basically comprised of training experienced operators for specific objectives, such as training for emergency maneuvers, for example, the man overboard turns. It can include training for upcoming safety critical maneuvers such as pilotage of a large container vessel into port through tight turns or shallow waters. iii) The third application, assessment, where the simulator data generated during a given simulator trial can be used for evaluation of the candidate (Sellberg et al., 2022), where artificial intelligence methods, perhaps, can be used to facilitate the assessment and remove human subjectivity from the results (Ernstsen, 2020). Organizations such as the Norwegian Coastal Administration are using simulator trials as examinations part of the recruitment process for candidates applying to become pilots on the Norwegian coast (Pan et al., 2021). iv) The fourth application, development and testing, where simulators are used within the development process of tools supporting remote control or autonomous maneuvering technologies. Simulators enable the development of procedures and specifications of such tools and enable human-in-the-loop testing as well as hardware-in-the-loop testing, for example, (Varela & Soares, 2015). v) Last but not least on this brief summary of applications, research and innovation, where simulators play an important role in human factors research. A trend of physiological monitoring of operators is emerging that is coupled with data science methods for analyzing the changes in the state of health of the operator during the operation including stress level and workload (Orlandi & Brooks, 2018). Simulators enable research on teamwork where cultural differences can prevail on the performance. Simulators are arenas for multidisciplinary research including, learning research, human-computer-interaction, ocean and naval engineering, safety engineering, and waterway design.

The evolution in the use of simulators is appealing, and the value they can potentially contribute with to the maritime industry is crucial, assuming ship dynamics are accurate. Some applications do not require higher accuracy of ship dynamics than the subjective approval of an experienced operator, confirming that the feeling of how the ship maneuvers is rather realistic. However, in other applications where operational decisions are drawn based on the simulator trials, the accuracy requirement should be higher. Therefore, it is of particular interest for us to investigate the accuracy of maneuvering models.

Initially, ship dynamics was split into two theories, calm water maneuvering and seakeeping, the former deals with horizontal plane motions of a ship moving and turning in water assuming calm water conditions while the latter deals with wave-induced motions for a ship at zero or constant speed and straight course. Seakeeping calculations are often done in the frequency domain by potential flow theory.

For maneuvering, there are two dominating mathematical models: Regression models, also referred to as Abkowitz models, and modular models. In regression models, the mathematical model is constructed from hull coefficients obtained from experimental tests or numerical simulations. Planar motion mechanism (PMM) tests have typically been applied to obtain the coefficients. During a simulation, these coefficients are considered to be tabulated values, which means that regression models are suitable for real-time simulations. Commercial simulators used for training purposes are often based on regression models. In such simulators, the coefficients can be 'tuned' based on free-running model tests or full-scale measurements, to improve the accuracy of the simulator.

A modular model, solver-in-the-loop, is an alternative model, where the different physical phenomena are calculated separately. This can be favorable in the design phase, since it is straight forward to do modifications on the ship hull and perform new maneuvering simulations. Moreover, in research the modular approach has some advantages, since it is possible to investigate the dominating physical phenomena for different kinds of maneuvers.

The combination of seakeeping and maneuvering can be done in several ways, in the last decades there are two dominating approaches: One is based on convolution integrals to account for memory effects (Bailey et al., 1998; Fossen, 2005), and the other is based on a two-time scale assumption (Skejic & Faltinsen, 2008). The two-time scale approach assumes that the maneuvering behavior of the ship experiences a more slowly varying time scale than the linear wave-induced motions. Hence, only the mean second-order wave loads are accounted for in the maneuvering equations. Examples of simulations models based on the two-time scale assumption are: (Chillcce & el Moctar, 2018; Cura-Hochbaum & Uharek, 2016; Seo & Kim, 2011; Yasukawa & Nakayama, 2009; Yu et al., 2021; Zhang & Zou, 2016). The maneuvering models in (Cura-Hochbaum & Uharek, 2016) and (Chillcce & el Moctar, 2018) are regression models, while the others are modular maneuvering models. The models above show in general a good accuracy. However, the two-time scale assumption can be questionable for long waves, in particular for following sea. This is because when the wave encounter frequency is low, the linear wave-induced motions can experience the same time scale as the maneuvering motion.

This study aims to provide an understanding of the maneuverability of a large container ship. Experimental results from (Rabliås & Kristiansen, 2019) and (Rabliås & Kristiansen, 2022) are presented for the Duisburg test case (DTC) hull. The focus is on zig-zag 20/20 maneuvers and turning circles with 35° rudder angle, in calm water and irregular waves, in initial head and following waves.
In addition, this study aims to discuss the accuracy of numerical maneuvering models. One is an industry-standard navigation simulator (used for research purposes), the other is the modular maneuvering model presented in (Rabliås & Kristiansen, 2021) and (Rabliås & Kristiansen, 2022). The required accuracy of maneuvering simulators is discussed relative to different simulator applications.

2 ACCURACY REQUIREMENTS

What difference does it make whether a simulator appreciates the impact of increasing wave height on ship speed? How to tell if this maneuvering model is good enough and if this simulator is fit-for-purpose? Looking at the various applications covered in the introduction section, it is clear that the objectives of each application are to dictate the level of accuracy required. For example, a ballast handling simulator course should have a different accuracy requirement compared to a safety-critical operation training or a pilot recruitment assessment.

The accuracy concern resonates in the status-quo that the standard for Maritime Simulator System (DNVGL-ST-0033, 2017) does not recognize applications other than training. Additionally, it does not require objective assessment of ship dynamics, as it is the case with the flight simulation standard (CS-FSTD, 2018).

There is a need for definitions of accuracy requirements of the different applications. Therefore, we propose a simple classification of accuracy requirement levels (ARLs), shown in Figure 1, which thereafter is linked to the various applications. ARLs are properties of simulators, and more precisely, they are properties of each floating object in simulators.

- ARL 0: Object floats in water. In this accuracy level, only the hydrostatics are involved. Hydrodynamics are not required. Objects are floating and that is their job to be visible on the surface, such as buoys or icebergs.
- ARL 1: Maneuvering feels realistic. Most navigation simulators fall in this category. After the model of a ship is created, it is evaluated by a navigator with years of experience on similar ships. Once the subjective evaluation result deemed positive, the model is issued for use. Such models are generally considered (among their users) very accurate and are used for education, training and beyond.
- ARL 2: Calm water accurate. This level, in addition for the subjective evaluation of an experienced navigator, requires the model to be within a pre-defined accuracy (90% for example) to all indicators of standard maneuvers in calm water. The standard maneuver benchmarks should be collected from full-scale sea trials or model-scale free-running tests. The standard maneuvers should include zig-zag tests and turning circle tests according to the IMO maneuverability standard.
- ARL 3: Accurate even in operational conditions. In addition to satisfying all previous levels, this level requires the model to appreciate the operational environmental loads, such as waves, ocean currents, and winds, accurately. Operational conditions can include different water depths, such as shallow water condition. Benchmark data is difficult to obtain for a combination of environmental effects. However, experimental and sensor technologies are evolving, for example, 3D wave radars are nowadays feasible. Despite challenges, the possibilities are immense on this frontier, and it is important to pose scepticism on the accuracy of state-of-the-art environment load models for applications that require high fidelity. "Objective testing" is required to show that the ship model appreciates the loads and the trends, for example, wave loads, and the trends of maneuvering characteristics as wave height increases.

ARLs are considered relevant and useful. Relevant because real-time hydrodynamic models of a turning ship in waves do not possess the quality of being accurate for granted. On the contrary, high uncertainties are involved. Therefore, it is relevant to keep the question in mind when using a simulator "is this maneuvering model good enough for the given application?". In most cases, ARL 1 is enough for applications such as simulator education and training of nautical students, and research in the fields of human factors and learning.

ARLs are said to be useful because they are simple and serve as communication tools that describe the amount of effort behind creating a ship model and they can also communicate the capabilities of a given model.

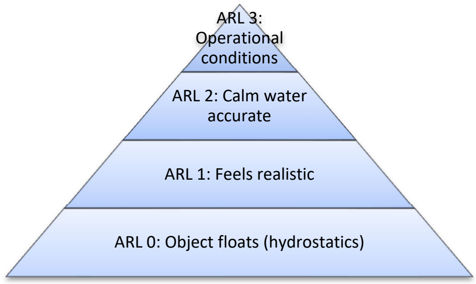

Figure 1. Accuracy Requirement Levels (ARLs) proposed definition

ARL 2 applications can be summarized as research and innovation projects in the fields of human-computer interaction (HCI); computer or control engineering; safety engineering; and ocean or naval engineering. Development and testing of either software or hardware, including the human-in-the-loop and the human-centered design simulator phases also require ARL 2, at least. Operator training for specific operations such as the training for the man overboard emergency maneuver or the training for low emissions maneuvering also require ARL 2.

Development and testing of new controllers or autonomous maneuvering technologies should require ARL 3, at least for the high technology readiness level (TRL) products. Assessment of pilot applicants based on their performance in simulator based 'exams' require attention to operational accuracy because winds and ocean currents in fjords and straits can be very tricky to model. Safety-critical training such as ship-to-ship operations, extreme weather operations, and pilotage of huge ships to harbor require higher fidelity than a 'normal' nautical school simulator.

We have now proposed a framework to classify the accuracy of maneuvering simulators. In the next sections, two numerical simulators will be compared with experiments of the DTC hull. The results and accuracy will be discussed with respect to the Accuracy Requirement Levels (ARLs) defined above.

3 DESCRIPTION OF EXPERIMENTS

A 1:63.65 model of the Duisburg Test Case (DTC) was tested, in January 2020, in the Ocean Basin at SINTEF Ocean in Trondheim. Zig-zag 20/20 tests and turning circles were tested in calm water and waves. Both regular and irregular waves were tested, with emphasize on tests in irregular waves. The test campaign in 2020 was a follow-up from the model tests described in (Rabliås & Kristiansen, 2019). Moreover, some of the results of turning circles in irregular waves with 35° rudder angle, were presented in (Rabliås & Kristiansen, 2022).

Table 1. Particulars of the DTC hull

Particulars		Ship	Model
L_{pp}	[m]	355	5.577
B	[m]	51	0.801
d	[m]	14.5	0.228
Δ	[kg]	173,468,000	673.27*
C_B	[−]	0.661	0.661
x_G^{**}	[m]	174.059	2.721*
y_G	[m]	0	0
KG	[m]	19.851	0.311*
GM	[m]	5.10	0.081*
I_{44}	[kgm^2]	7.148E+10	41.51***
I_{55}	[kgm^2]	1.322E+12	1294.2*
I_{66}	[kgm^2]	1.325E+12	1268.4
L_{bk}	[m]	14.85	0.23*

* Measured values.
** Relative to aft perpendicular.
*** Estimated from measured natural roll period and numerical added mass.

The main particulars of the model are presented in Table 1. Segmented bilge keels were mounted to the model during the tests, the length of each segment is referred to as L_{bk}.Detailed information about the hull, propeller, and rudder is given in (el Moctar et al., 2012). We refer to (Rabliås & Kristiansen, 2022, 2019) for more information about the test setup.

Five irregular waves were tested. The waves were generated from a Jonswap spectrum with γ=3.3. Traditional wave calibration was not performed, but the wave heights were documented. An overview of the tested wave conditions, with target and measured significant wave heights (H_s), is presented in Table 2. In the numerical simulations presented later, the measured significant wave heights are applied. The irregular waves indicated in green were a part of the experimental test campaign, while we have no experimental results for Wave ID 80000-80020. We note that Wave ID 80020 and 85040 can be considered as adverse weather, where non-linear phenomena are expected to have a significant effect on the maneuver.

Table 2. Irregular wave conditions

#	Wave ID	T_p $[s]$	H_s $[m]$	
			Target	Meas.
1	80000	8.0	-	1.0
2	80010	10.0	-	4.0
3	80020	15.0	-	10.0
4	85000	9.97	3.12	3.45
5	85010	11.97	3.18	3.56
6	85020	11.97	4.97	5.43
7	85030	13.96	4.33	4.71
8	85040	11.97	8.0	8.57

4 SIMULATION MODELS

Two numerical maneuvering models are involved in this study, referred to as Sim A and Sim B. Sim A is mainly used for training of seafarers. In Sim A, the maneuvering model of the DTC hull has been tuned against calm water model tests. Sim B is a novel modular maneuvering model, which is under development. Sim A is an industry-standard simulator, that is used in desktop setting for this research. Sim A was configured with the default setting of second-order wave loads turned off. Sim B however, using the two-time scale approach, does not account explicitly for the first-order wave loads, it accounts only for the slowly varying second-order wave loads. The theoretical background of the simulators is briefly described for each simulator in the following.

4.1 SIMULATOR A

Sim A is a navigation simulator that provides ship motion time-domain simulations in 6 degrees of freedom. It is a modular model that solves both the seakeeping and the maneuvering problems simultaneously, including effects of waves, winds and ocean currents. It considers water depth, shallow water effects, canals and banks, ship interactions, and different propulsion configurations. It also takes into account mooring forces, anchor forces and more. This simulator is available in a range of configuration options, from desktop version to a full mission bridge simulator version. Trials were performed on a desktop configuration for this research.

This simulator is based on Ottosson and Byström's for the basic calm water maneuvering simulation, where the radiation hydrodynamic coefficients are assumed constant based on mean encounter frequency during maneuver (Ottosson & Bystrom, 1991). The wave-induced motions are incorporated as follows: the added resistance in waves is computed according to Gerritsma and Beukelman, (Gerritsma & Beukelman, 1972). Strip theory is used for calculating the hydrodynamic added mass and damping loads according to Kaplan and Raff (Kaplan & Raff, 1972). The horizontal slow drift excitation loads in irregular beam sea waves are calculated using the method of Faltinsen and Løken (Faltinsen & Løken, 1979).

In this simulator, the theories used for calculations are the backbone of modeling and the ability of empirical adjustments is open to manipulate the coefficients of forces/moments in order to reproduce a given ship behavior, such as sea trial or free-running model test results. Second-order wave forces are optional, explicit values of second-order wave forces can be added to provide further adjustments to drift and turning in waves.

4.2 SIMULATOR B

The mathematical model of Simulator B is that implemented in (Rabliås & Kristiansen, 2022). It is a 4-DOF modular model based on (Skejic & Faltinsen, 2008).

The calm water hull lifting loads are calculated with slender body theory, while the zero-frequency added mass loads are calculated with the 3D panel code WAMIT. Experimental values of calm water resistance and propeller thrust are obtained from (Shigunov et al., 2018) and (El Moctar et al., 2012). A conventional rudder model is applied for the calm water rudder loads, and the 2D+t approach presented in (Rabliås & Kristiansen, 2021) is applied for the transverse viscous loads.

The wave loads are implemented following the two-time scale assumption, which means that the linear wave-induced motions are assumed to have a different time scale than the more slowly varying maneuvering motions. Hence, only the slowly varying second-order wave loads are accounted for. The slowly varying drift loads in irregular waves are estimated with a modified version of the "time-domain" method first presented by (Hsu & Blenkarn, 1972). This method considers the irregular waves as a series of regular waves with different wave periods and wave heights. The drift loads are then estimated for each wave encounter, as if it was a regular wave. The building brick in this method is the numerical method used to estimate the drift loads in regular waves. Simulator B estimates the drift force in the x-direction with a combination of the pressure integration method and the asymptotic method for short wavelengths in (Faltinsen et al., 1980), which accounts for forward speed. The sway and yaw drift are calculated with the 3D panel code WADAM, where only the encounter frequency is taken into account.

The effect of the wave on the propeller and rudder inflow is also considered. The x-component of the inflow is modified according to (Taskar et al. 2016), where the incident wave and the linear wave-induced surge and pitch velocities are taken into account. The incident wave and the linear wave-induce sway, roll, and yaw velocities are taken into account for the y-component of the inflow. More information about the numerical model can be found in (Rabliås & Kristiansen, 2021, 2022).

5 RESULTS

Simulations with the two simulators, in calm water and irregular waves, are now compared to experimental results. Turning circles with 35° rudder angle and zig-zag 20/20 maneuvers are simulated with the DTC hull. The irregular wave conditions used in the simulations are presented in Table 2. For the wave conditions marked in green, the simulations are compared to experimental results. Time-series of selected conditions are presented for illustration purposes, while some global responses are chosen to compare trends for a range of conditions. For the turning circles, these global responses are: The advance, transfer, tactical diameter, and average speed. The former three are standard responses that are widely used, while the latter is defined as the average speed for the first 1000 seconds of the maneuver. For the zig-zag maneuvers, the first overshoot angle, the second overshoot angle, reach, and average speed are considered. The former three are standard responses, while the latter is defined as the average velocity for the first 350 seconds of the maneuver.

An irregular sea state has a stochastic behavior, which means that different realizations of the same wave spectrum will not give identical results. The experimental tests were conducted in several realizations of the same sea state. To illustrate the stochastic behavior of irregular waves, results from all of these realizations are presented for the experiments. However, the numerical simulations are performed for only one realization in each condition. This must be taken into account when the results are compared. The numerical results would also be different if they were performed with a different random seed. Investigations with Sim B (not shown here), indicate that the results varies when the simulations are performed in different realizations of the wave spectrum. However, the stochastic variation was slightly less compared to experiments. For Sim A, we have access to only one realization of each sea state, i.e. we have not enough information to conclude about the stochastic variation. For the calm water maneuvers, experimental results are presented from both experiments in (Rabliås & Kristiansen, 2022, 2019), i.e. from two different test campaigns.

5.1 TURNING CIRCLES

Trajectories of turning circles with 35° rudder angle, with the DTC hull, are presented in Figure 2. To the left, turning circles in calm water are presented, while turning circles in the severe irregular wave condition, with H_s=8.57 m and T_p=11.97 s (Wave ID 85040), are presented to the right. The initial velocity for the turning circle in calm water corresponds to Froude number Fn=0.14, while Fn=0.12 for Wave ID 85040. Several repetitions are presented for the experiments, which illustrates the stochastic variation. For the turning circle in calm water, the predicted trajectory is in good agreement with experiments, for both simulators. However, for Simulator A, the steady turning circle is slightly underpredicted.

There is more deviation for the turning circle in irregular waves. The drifting distance is predicted better with Simulator B. However, both simulators underpredict the drifting distance compared to experiments. Moreover, for this condition, the circle is significantly deformed compared to calm water, this is particularly true for Simulator B.

The surge velocity, sway velocity, and yaw rate, for the turning circle in irregular waves, with H_s=8.57 m and T_p=11.97 s (Wave ID 85040), are presented in Figure 3. Both simulators predict the initial speed drop in surge acceptable. The linear wave-induced velocities are not included for in Simulator B. This is due to the two-time scale assumption. However, Simulator B compares more adequately to experiments in the slowly varying variations of the surge velocity, sway velocity, and yaw velocity predictions.

Considering the results in irregular waves, it is important to have in mind that an irregular sea state has a stochastic behavior, which means that repetitions in the same sea state can give significantly different results. This is particularly true for adverse sea states, where extreme events can be dominant. Comparison of single repetitions should therefore be handled with care. Wave ID 85040, with H_s=8.57 m and T_p=11.97 s, is an adverse sea state, and heavy ship motions and non-linear phenomena (slamming in the bow, propeller and rudder in and out of water, etc) were observed during the experiments. This will also affect the maneuvering behavior of the ship. Since maneuvering models often are based on linear seakeeping theory, it is expected that there are some deviations from experiments for this kind of conditions.

In Figures 4-5, results from turning circles of the DTC hull, with 35° rudder angle, are presented for calm water and a range of irregular sea states. Advance, tactical diameter, transfer, and average speed are presented for experiments and the two simulators. The results are presented as a function of significant wave height, H_s, the corresponding peak periods can be found in Table 2. For the conditions where experimental results are available, the measured significant wave height is applied. The experiments were performed with constant propeller RPS corresponding to Froude number Fn=0.14 in calm water, which means that the initial velocity is different for different wave conditions.

For the experimental results, several repetitions are presented for each sea state. This illustrates the stochastic variation that can be expected for maneuvering in irregular waves. For calm water, results from the experiments in (Rabliås & Kristiansen, 2022, 2019) are presented, i.e. from two different test campaigns. This is the main reason of the scatter of the calm water results. However, this illustrates that the experimental results, even in calm water, are vulnerable to some uncertainty. Possible contributors to the experimental uncertainty can be model-setup, measurement system, and the neutral rudder angle. Moreover, before the second test campaign, the model was refurbished and repainted. This was done to fix minor dents and scratches in the model, which come from several test campaigns over the years. This could also explain some of the deviations between the two test campaigns.

First, we consider the turning circles in initial head sea, presented in Figure 4. For advance, the experimental results show a decreasing trend with increasing significant wave height, H_s. Simulator B follows the same trend as the experimental results, and the predicted advance is in fair comparison to the experiments. Simulator A slightly underpredicts the advance, and the wave dependency is not as obvious as for the experiments and Simulator B.

For tactical diameter and transfer, the wave-dependency is not as obvious as for advance, and both simulators compare satisfactorily with experiments. However, for the average speed, Simulator B better captures the wave dependency, and is, in general, in better agreement with experiments. This could be because the slowly varying second-order wave loads were turned off in Simulator A trials. Also, for turning circles in initial following waves, presented in Figure 5, Simulator B is more consistent with the experimental results. The experimental results show an increasing trend, with increasing H_s, for advance, tactical diameter, and a slightly decreasing trend for the average speed. The increasing trend for advance is opposite of that for initial head waves, which indicates that the ship experiences an added thrust in following waves, unlike the added resistance in head waves.

5.2 ZIG-ZAG 20/20

The trajectory, heading, and velocity for zig-zag 20/20 maneuvers in calm water and irregular waves, are presented in Figures 6 and 7. For calm water (Figure 6), Simulator B reacts faster than the experiments. Both simulators predict the speed drop well. However, Simulator A slightly underpredicts the increase in velocity at t=300 s, while Simulator B slightly overpredicts the velocity.

In Figure 7, trajectory, heading, and velocity, are presented for a zig-zag 20/20 maneuver in irregular waves, with H_s=5.43 m and T_p=11.97 s (Wave ID 85020), in initial head waves both simulators predict the speed drop well, but Simulator B turns a bit faster than the experiments, same as in calm water.

In Figures 8-9, 1st overshoot angle, 2nd overshoot angle, reach, and average speed are presented for zig-zag 20/20 maneuvers in initial head waves and initial following waves for a range of irregular wave conditions, calm water results are also included. For initial head waves (Figure 8), the experimental results show a decrease in the 1st overshoot angle in waves compared to calm water, while the 2nd overshoot angle is slightly higher in waves compared to calm water.

The same trend is present for the experimental results in initial following waves. For reach, it is difficult to conclude about any trends for the experimental results in head sea, while in following sea the reach is higher in waves compared to calm water. For average velocity, the experimental results show a decrease with increasing H_s, in head waves, while the wave effect is limited in following waves.

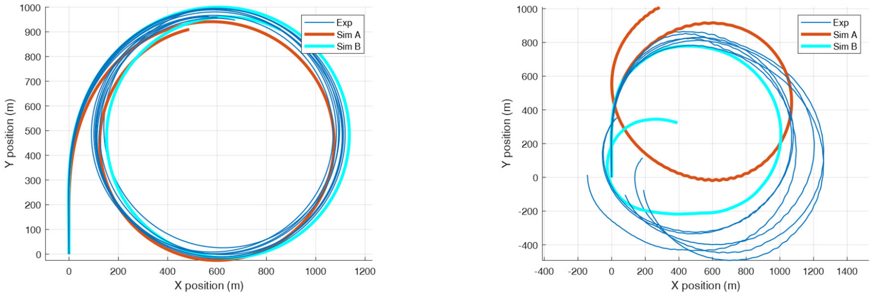

Figure 2. Trajectories of turning cirlces with 35° rudder angle. Left: Calm water. The initial velocity corresponds to Fn=0.14. Right: Irregular waves with Hs = 8.57 m and Tp = 11.97 s (Wave ID 85040) in initial head waves. The initial velocity corresponds to Fn=0.12

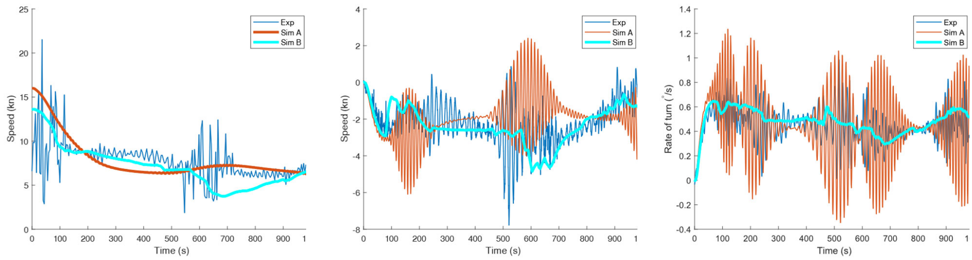

Figure 3. Velocities from a turning circle with 35° rudder angle, in irregular waves with Hs = 8.57 m and Tp = 11.97 s (WAVE ID 85040) and initial head waves. The initial velocity corresponds to Fn=0.12. Left: Surge velocity. Middle: Sway velocity. Right: Yaw rate

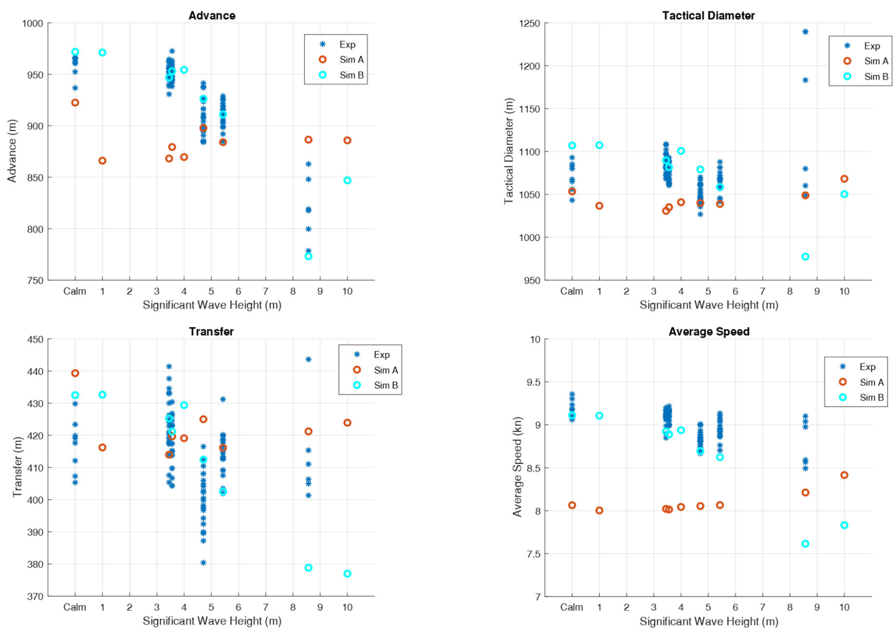

Figure 4. Results from turning circles with 35° rudder angle, of the DTC hull, in calm water and irregular waves, in initial head waves. Top: Advance and tactical diameter. Bottom: Transfer and average speed

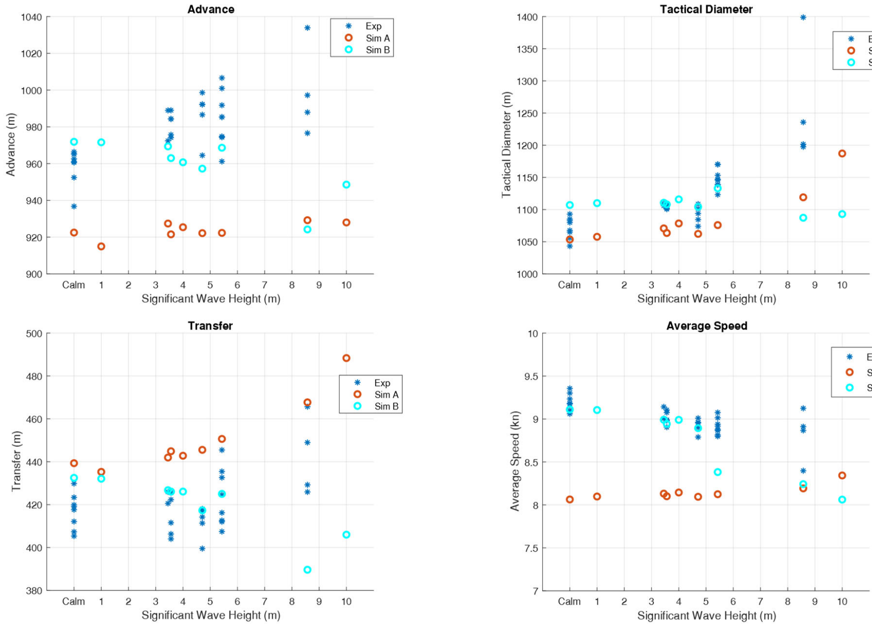

Figure 5. Results from turning circles with 35° rudder angle, of the DTC hull, in calm water and irregular waves, in initial following waves. Top: Advance and tactical diameter. Bottom: Transfer and average speed

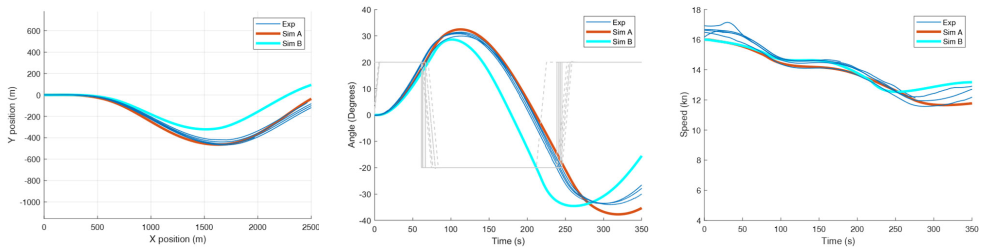

Figure 6. Results from a zig-zag 20/20 maneuver in calm water. The initial velocity corresponds to Froude number Fn=0.14. Left: Trajectory. Middle: Heading. Right: Speed

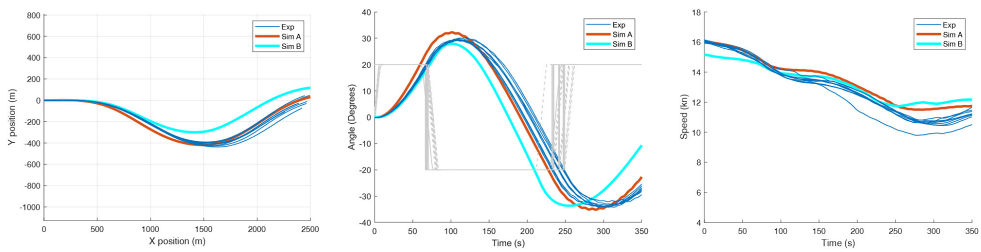

Figure 7. Results from a zig-zag 20/20 maneuver in irregular waves with Hs = 5.43 m and Tp = 11.97 s (wave ID 85020). The initial velocity corresponds to Froude number Fn=0.14. Left: Trajectory. Middle: Heading. Right: Speed

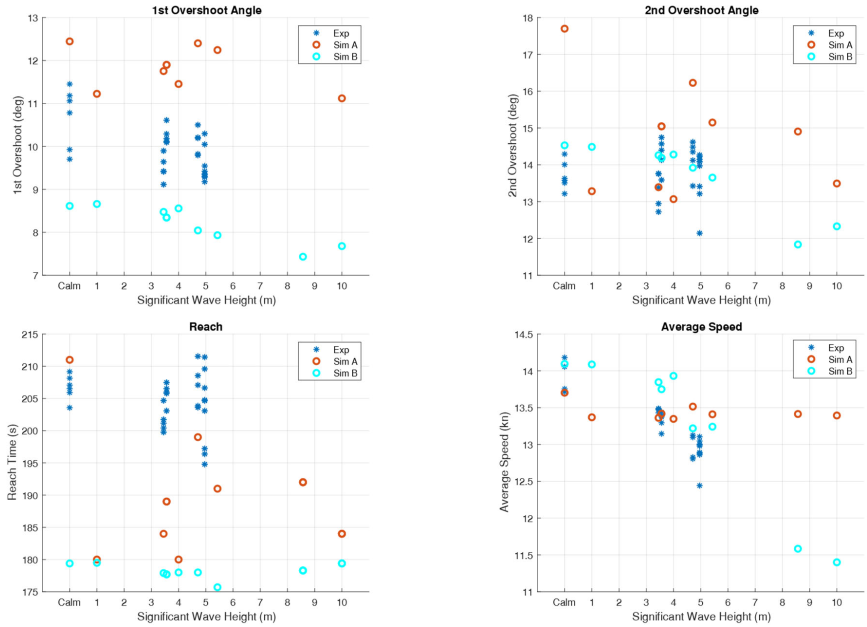

Figure 8. Results from zig-zag 20/20 maneuvers, of the DTC hull, in calm water and irregular waves, in initial head waves. Top: 1st and 2nd overshoot angle. Bottom: Reach and average speed

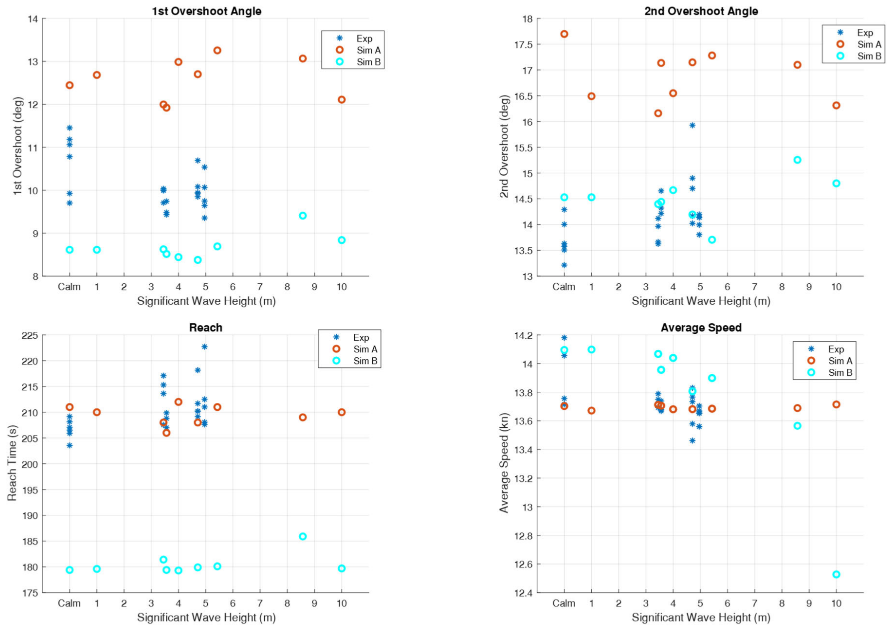

Figure 9. Results from zig-zag 20/20 maneuvers, of the DTC hull, in calm water and irregular waves, in initial following waves. Top: 1st and 2nd overshoot angle. Bottom: Reach and average speed

Even though Simulator A trials only considered first-order wave loads and Simulator B trials only accounts for the slowly varying second-order wave loads, the two simulators show similar accuracy for the investigated zig-zag maneuvers. This indicates that the effects of wave can be of less importance in zig-zag maneuvers compared to turning circles.

6 DISCUSSIONS

For turning circles, the experimental results show a clear trend for advance and average speed, with increasing significant wave height, while there is no obvious trend for transfer and tactical diameter. For zig-zag 20/20 maneuvers, the clearest trend is for the average speed, which decreases with increasing significant wave height. However, even if some trends are present, the stochastic variation within each sea state can be as large as the difference between different sea states. Especially for the sea state with H_s=8.57 m and T_p=11.97 s, which represents adverse weather. This has some practical consequences when experiments and/or different numerical models are compared. Conclusions can not be drawn based on a single realization in one sea state. Either trend must be investigated for a range of conditions, or several realizations in the same sea state must be performed to calculate statistics.

Both Simulator A and Simulator B perform in general acceptable compared to experiments. In calm water, Simulator B more adequately compares to the turning circle experiments, while Simulator A more adequately compares to the zig-zag 20/20 maneuvers. It is noteworthy that Sim A is setup to appreciate the first-order wave effects only (added resistance and drift loads in sway and yaw were turned off), and Sim B is setup to appreciate the slowly varying second-order loads only (first-order wave loads are not explicitly present in the equations of motion).

Experimental results in waves show a maneuverability trend of decreasing speed with increasing wave height. This can be seen in average speed figures, most evident in Figure 8. Ship speed drops during maneuvers in initial head waves, however this trend refers to the amount of speed drop as wave height increases, this can be observed across results of multiple maneuvers with different wave heights. This trend was not captured by all simulators. One simulator that accounts only for the slowly varying second-order wave loads appreciates this trend. The other simulator, that accounts only for first-order wave loads, did not appreciate the trend, probably due to turned off drift loads. The contribution of each wave load component in the overall maneuverability results is a subject for further research.

The question is, how important is this for the different kinds of applications?

Considering the turning circle results in Figure 4, the simulators satisfy the ARL 2 requirement for the Advance, Tactical Diameter, Transfer and Average Speed. However, by looking at the zig-zag results in Figure 8 the overshoot angles for both simulators do not satisfy the predefined margins (10% error for instance) requirement of ARL 2. Therefore, according to our proposed ARL definition, both simulators are classified as ARL 1 "feels realistic" and can be used for education, training, research and innovation applications. The 10% margin is just an example, hence the predefined tolerances are a subject for further research.

It is noteworthy that ARL 3 tolerances are dependent on application specific operational conditions. It is possible that a model is approved as ARL 3 for some applications, hence conditions, while it is only ARL 2 for other applications. An alternative to this “black-white” criterion could be a more continuous grading system. However, the system will then lose some of its simplicity. This is a topic for further research. Therefore, the reader is encouraged to take this as a demonstration of how ARLs can be used together with “objective testing” for addressing and alleviating accuracy concern.

A limitation in the method is perhaps, using only zig-zags and turning circle maneuvers for the evaluation of the accuracy of numerical simulators (in calm water and in waves). According to the maneuverability standard of the IMO (MSC.137(76), 2002), maneuverability of a ship can be studied using standard maneuvering trials. Standard maneuvering trials consist of i) zigzags, ii) turning circles, and iii) full astern stopping tests. In case of dynamic instability, the standard encourages the use of alternative tests such as spiral test or pull-out maneuvers to define the degree of instability. The standard is thus followed, and only zig-zags and turning circle tests are used to evaluate maneuverability in waves. However, the standard only applies to calm water environments. In addition, a benchmark is needed for the evaluation of numerical simulators. The benchmark that was available for this study consisted of only zig-zags and turning circles, therefore, the selection of simulations trials followed. The authors believe that there is a need of a revised maneuverability standard that considers different kinds of operational conditions.

This awareness of what physical effects the simulators can appreciate is key in judging whether the applications they are used for are fit-for-purpose.

7 CONCLUSIONS

Turning circles with 35° rudder angle, and zig-zag 20/20 maneuvers, are investigated in calm water and irregular waves. The maneuvers are investigated for a range of sea states, with incident head sea and following sea. Experimental results from model tests of the Duisburg Test Case (DTC) hull are presented for calm water and five different sea states, in incident head and following sea. The maneuvers are also simulated with two different numerical simulators, one is an industry-standard simulator (used for research purposes), and the other is a novel code that is under development.

In calm water, results from both simulators are fairly similar and compare adequately with experiments. In waves however, the results vary and both simulators appreciate wave loads differently. Only one simulator, that accounts for only the slowly varying second-order wave loads, appreciates the effect of waves on speed-drop. The other, that accounts for only first-order wave loads, does not. This discrepancy should be further investigated including the effects of first-order and second-order wave loads separately on the overall maneuverability results.

Accuracy requirement levels (ARLs) are proposed, they are used to classify the two simulators as a demonstration. This preliminary use of ARLs shows that both simulators are classified at ARL level 1 "feels realistic" though they perform well in calm water maneuverability, but do not satisfy the predefined tolerance for ARL 2. Since they are classified as ARL 1, examples of applications they are fit-for-purpose for are education and training of nautical students, and research and innovation in the human factors field or the learning field. Examples of applications that could require higher ARL levels are the development of remote control or autonomous maneuvering technologies; the simulation-based evaluation of pilot candidates as part of the recruitment process; and the training on safety-critical operations such as pilotage of huge ships to harbor. The used predefined tolerances are just an example, the topic is subject for further investigations.

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Applications of Maritime Simulators in Industry and Research

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Abstract. Ship-bridge simulators are ideal arenas for research and innovation, hence, the use of simulators in industry and in research is ramping up. Ocean industry prospects are addressing core challenges such as food, security, energy, and climate change. The ocean holds the promise of great potential for economic growth. Appropriate tools are required for answering the questions of the emerging ocean operations. Questions related to technology development, training, safety and efficiency rise on a daily basis, where ship-bridge simulators could be the labs facilitating a wide spectrum of research experiments. This paper presents the role simulators play in maritime operations and lists various applications of ship simulators according to a literature review and nine interviews with researchers and managers in simulator centres. It also presents a case study of the current and future uses of simulators by the Norwegian Coastal Administration Pilot Service. The scope of simulator applications is wide, beside training, they are used in development of autonomous controllers and in recruitment of pilots.

An accuracy concern is identified; simulators must hold an appropriate level of accuracy to fulfil the different application objectives. The standard for Maritime Simulator System, DNVGL-ST-0033, does not recognize applications other than training. In addition, it requires no objective assessment of ship dynamics, as required by the flight simulation standard (CS-FSTD).

Keywords: Ship Simulators; remote control; accuracy requirement levels

1 Introduction

Simulations and simulators have been applied in engineering for few, even several, decades. It is the maritime domain that is transforming towards a highly digitised industry, from research, training to operations, the dependence on digital systems is increasing. On top of that, the exhaust emissions regulations are getting stricter every five years according to the Marine Environment Protection Committee of the International Maritime Organization (IMO - MEPC, 2020). This tightening of the emissions regulations is challenging all the sectors involved in the shipping industry to strive for higher efficiency. Therefore, research is a key for solving such challenges and hence, simulators are methodological enablers for future potential solutions.

The strict regulations do not only challenge ship engine and fuel type. They also challenge routing, the understanding of weather systems and environmental loading along the planned route, hence the selection of the route with minimum loading yet satisfying time and emissions constraints. The regulations also challenge the manning of ships as with reduced manning the hotel loads are reduced and thus the emissions are reduced, this brings attractiveness to the concepts of remote control and higher levels of autonomy in the shipping and offshore industries. This cascades into human factors challenges of how teams can work together for an operation while dispersed, with parts of the team sitting in different places in the world, and so on.

In all mentioned challenges, simulations and simulators can play a role. However, because the nature of the challenges is broad, it is not clear who is using ship simulators and what they are using them for. This article aims to present an overview of the use of maritime simulators. The introduction covers background information on simulations, simulators and the industry trends of utilising them.

1.1 Simulations and Simulators

In short, simulations try to mimic real-life. The concern could be a real-life response such as in the case of fire drill, or it could be a real-life phenomenon, such as the elongation of a metal rod when heated. In the latter example, mathematical models are used to calculate the heat transfer and thus the thermal expansion of the rod. Using a computer simulation that can also take time into consideration, the phenomenon can be explored virtually on the computer. This opens the opportunity to investigate what happens if the heat source is changed, and similarly, if the type of metal is changed.

Computer simulations offer practical and convenient features. They enable running the 'virtual test' many times in fraction of the cost compared to physical testing. They allow for affordable 'testing' of extreme conditions, say, very hot temperatures that are hard to achieve in your lab's furnace. They also can be connected to other computer simulations building a mega simulation estimating multiple physical phenomena and their interactions.

Some computer simulations are designed to provide the user with a virtual experience. These are called simulators; they interact with human inputs and present the responses as they evolve on screens. Some maritime simulators are designed to provide a very immersive experience, with 360° curved projection-screens and, few of them have moving platforms. Recent generations of maritime simulators are quite immersive, the visuals are seamless high-definition projections, in a room with hardware that is identical to that found in real vessels (O. Hareide & Ostnes, 2016). Users of such simulators have fully furnished bridges including chairs, propeller levers, rudder control, radar, electronic chart displays, radio communication device, etc, as if they are on a real ship. For example, check the latest ship bridge simulator solutions of Kongsberg (K-Sim) or Wärtsilä (Transas).

As described by (Porathe, 2016), *"A ship-bridge simulator is a piece of laboratory hardware and software that simulates a ship's behaviour from the vintage point of its bridge. Often consists of a mock-up bridge (a more or less realistic bridge interior with consoles, screens, instruments and windows to the outer world) but often also a visualization, i.e. the egocentric 3D view of the surrounding world with ships, islands, and ports projected on screens outside the windows".*

1.2 Practices and Training

Involvement of maritime simulators in both academia and industry is becoming more visible. The following are examples on national and international collaborations involving the use of simulators for advancing maritime operations:

- SFI MOVE (*https://www.ntnu.edu/move*), a Center for Research-Based Innovation for Demanding Marine Operations is using simulation-oriented approach to solve some of the pressing challenges in the offshore industry. The centre has been running for several years. This centre is an example of academy-industry collaboration for solving real-world problems using research in simulators (*SFI MOVE*, 2016).
- EU project AutoShip (*https://www.autoship-project.eu/*), where simulators will be upgraded to better support testing, commissioning, training and operations of autonomous ships (*AutoShip*, 2019).
- SFU COAST (*https://norway-coast.no/*), A Centre of Excellence in Maritime Simulator Training and Assessment envisioning the innovative potential of the best simulator practices in maritime education (*SFU COAST*, 2020).

Ship-bridge simulator-based training practices are well established in maritime education. The International Convention on Standards of Training, Certification and Watchkeeping of Seafarers (STCW) of the IMO regulates the standards of training. The main purpose of the Convention is to promote safety of life and property at sea and the protection of the marine environment to ensure that future professional mariners can operate properly and safely in their work practice, this convention emphasises on the use of simulators for both training and assessment (STCW, 1995).

For example on the use of simulators for maritime education, the set of simulator-based training courses offered by IMO, for both the novice and the experienced participants includes, but not limited to, the following simulator courses listed in **Table 1**.

Table 1. Some of the simulator-based training courses offered by the IMO (STCW, 1995).

1.	Ship simulator and bridge teamwork	2.	Liquefied petroleum gas (LPG) tanker cargo
3.	Liquefied natural gas (LNG) tanker cargo	4.	Oil tanker cargo + Ballast Handling (BH)
5.	Chemical tanker cargo + Ballast Handling (BH)	6.	Automatic Identification System (AIS)

In June 2015, after a series of EU projects from 2009, the IMO approved a “Guideline on Software Quality Assurance and Human-Centred Design (HCD) for e-Navigation”. The objective of e-Navigation concept is to harmonise the collection, integration, exchange, presentation and analysis of marine information by electronic means to enhance the operations and their safety. IMO considers that e-Navigation should be user driven rather than technology driven. HCD methods require heavy involvement of seafarers and operators in the design and development process of navigation aid tools. From 2015, the IMO recommends that HCD should be used in development of new navigation equipment (MSC, 2015).

As the HCD guideline encourages the involvement of users in the design process, it also, indirectly, encourages the use of simulators in that process. The simulators can play the role of labs, for testing out the new product being under development, for measuring the user experience and user satisfaction while using the product, and for measuring the performance of the user in a virtual operation using the product. Thus, simulators can be used for testing and validation of design concepts enabling effective HCD processes.

According to DNVGL-ST-0033 (2017), the Maritime Simulator System Standard, ship simulators are classified into four groups. Class A (full mission), B (multi-task), C (limited task) and S (special task). In addition to the classes, different types of ship simulators exist, based on the type of functions they simulate, the types are listed in **Table 2**.

Table 2. Ship simulator types based on operation type (DNVGL-ST-0033, 2017).

1.	Bridge operations	2.	Machinery operations
3.	Radio communication	4.	Cargo handling
5.	Dynamic Positioning (DP)	6.	Safety and Security

7.	Vessel traffic services (VTS)	8.	Survival craft and rescue boat
9.	Offshore crane & Remotely operated vehicles (ROV)		

To sum up, simulators are not only used for training; they are also being lately used for research, design, and other applications. An overview of the use of simulators is presented herein, with focus on their use as a research tool. In addition, an overview of the opportunities and challenges associated with their usage is also presented. Hence, this article is a contribution towards answering the following questions:

- What are simulators used for?
- What are the opportunities and challenges of using them?

2 Methods

To answer the two questions above, three methods have been used. First, a literature review for relevant research that uses simulators, second, interviews with professionals and researchers in the field, and third, a case study with a relevant industry player. Details about the three methods follow.

2.1 Literature Review

The literature review is made to contribute mainly to answering the first question: "What are simulators used for?" from the research perspective. A literature search has been undertaken in the search engine "Oria" of the Norwegian University of Science and Technology (NTNU) that provides search of the university's both printed and electronic collections of internationally renowned scientific databases (and publishers) such as INSPEC (Journal of Navigation), Scopus (Elsevier, Springer, IEEE), ProQuest, TransNav and WMU. Searching for literature on the search engine Oria has been done without specifying certain databases. Only literature reporting use of navigation simulators are selected. The search criteria of the literature review are found in **Table 3**.

Table 3. Literature review search criteria

Keywords:	Ship simulator; bridge simulator; mission simulator
Publication date span:	12 years (2009 – 2021)
Material type:	Articles, journals, and conference proceedings
Filters:	Publications that do not involve use of simulators (removed)
Selection size:	80 publications (selected after applying the filter)

2.2 Interviews

Subject matter expert (SME) interviews are held to bring a variety of perspectives from both researchers and professionals in the field. A Google search was made for both academic and commercial simulator centres all over the world. Thirty-five centres were identified. A shortlist of contacts was created for interview invitations. Ten positive responses were received and actually nine interviews were performed. Five interviewees are researchers and four are managers at simulator centres. The interviewees have different backgrounds, seven of them are engineers and two have social science backgrounds. At the time, the interviewees were geographically located as follows: 5 were in Norway; 2 in Sweden; 1 in the Netherlands; and 1 in Canada. All the interviewees referred to maritime simulators in their interviews, most of them (seven out of nine) referred to full mission navigation training simulators (Class A) and the rest referred to offshore operation simulators (Class S). The interviews focused on, and started with, the interviewees' work and experience, shaping an interviewee-centred context throughout the conversation.

The interviews were designed as semi-structured interviews with open-ended questions. The duration of interviews was half-an-hour on average for each, which started with an introduction about the interviewers and their motivation for conducting this research. Inductive coding method is used for analysing the collected data. The interview questions are as follows:

1. Tell us about yourself and the field of your interest.
2. What opportunities do you think simulators provide for research (or for the industry)?
3. What challenges have you faced while using simulators for your research (or for your work)?

The inductive coding process was performed in two levels, the general themes, and the more specific items, nested under the themes. Responses were compared across all interviewees for each question at a time. Similarities among the answers were identified and were given labels for the general themes they address, such as "research and innovation facilitator" and "developing industry standards" labels for the second question about opportunities. There were three labels identified for each question. The labels describe the general themes and provide a rough description of the interview results. A higher level of detail was needed to convey the picture the interviewees painted, therefore, specific items where identified and coded. Every labelled theme then was described by several coded items. For example, in the second question (about opportunities), nested under the label "research and innovation facilitator" the following codes were given: "innovation facilitator"; "multidisciplinary"; and "proof of concept". The codes are, in most cases, self-explanatory, and provide additional level of detail to the description of the interview results. The coded items aid the labelled themes in describing the content of the interviews, and together they provide answer to usage, opportunities and challenges as presented in **Table 5**.

2.3 Case Study

The Norwegian Coastal Administration Pilot Service (NCA PS) is selected as a case study for an intensive investigation regarding their day-to-day operations and their approach to using simulators, and maritime technologies, for solving today's and tomorrow's challenges. The information is collected mainly in a webinar that is designed for the purpose of this study. The webinar was held on 19 January 2020 and was named "Learning from the Pilots". The agenda of the webinar included the following sessions as listed in **Table 4**.

Table 4. Learning from the Pilots webinar agenda

1.	Short introduction from the NCA
2.	Everyday life of a pilot
3.	"Sleipnir" platform to Haugesund operation
4.	Recruitment and simulation
5.	R&D strategies of the NCA
6.	Open discussion

The design of the webinar included long questions/answers (QA) sessions. In addition, participants, who were mainly students and researchers, were encouraged to ask. The active participation in the QA sessions was modest therefore the collection of data was mainly passive.

The interviews took place in April 2019. The literature search took place from February to April of the same year, and later the search was complemented in the beginning of 2022 to include relevant research that was published within and after the year 2019. Within the 2019, the main author participated in a research work that aims to develop a decision support tool that aids navigators in selecting the proper rudder angle for the coming turn (Dimmen et al., 2020). The decision support tool was tested in navigation simulators and the conclusion was that such a tool can help navigators in close quarter maneuvering. This conclusion motivated the author to pursue collaboration with the Pilot Service to learn about their use of technology, seeking confirmation (or rejection) of the previous conclusion. Apparently, the Pilot Service were also motivated to collaborate with researchers and eager to increase their use of technology to advance their operations. Therefore, as a first step in the collaboration, the webinar "Learning from the Pilots" was suggested. The webinar was not meant to answer a specific question, on the contrary, it was designed to convey as much as possible from the pilots' experience and challenges. Such information serves as a necessary background for the creation of different research sparks. In addition to that, supplementing this article by providing a detailed contribution on their use of simulators.

3 Results

The results are presented in this section. First, results from the literature review, second, from the interviews, and third, from the case study.

3.1 Literature Review

Starting with describing the demographics of the collected literature. It is observed that 63% of the reviewed literature belongs to the Natural Sciences, 25% belongs to the Social Sciences and the rest can be identified with both scientific branches. It is also observed that 54% of the literature is using Quantitative methods, 26% is using Qualitative methods, while the rest is using mixed methods. The literature is classified into five groups. Fig 1 includes the distribution of the literature into the five groups: Development; human factors; training; learning; and risk analysis.

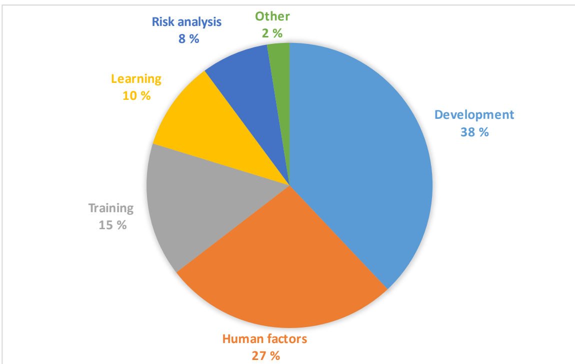

Fig. 1. Literature classification

Development

This group constitutes of 38% of the literature. This group is using the simulator as a step in the development or evaluation process. Most of this group is developing programs / algorithms that enable autonomous maneuvering, and they are using the simulator to present their development program, or to evaluate it using the human-in-the-loop concept. In the literature, the development group is not limited to products (such as programs / algorithms), it also includes development of procedures and specifications. For example, Ari et al (2013) developed a path planning algorithm that is length-optimised and feasible regarding turning radii of the given ship. They demonstrated a proof-of-concept of their algorithm using a ship simulator experiment. Varel and Sores (2015) on the other hand, developed a simulator program that is built specifically for training on ship-to-ship offloading maneuver. Their research constitutes basically of presenting the development works and final product. Hareide and Ostnes (2017) however, developed a navigation procedure that is inspired by a simulator experiment. They performed a simulator experiment with eye tracking devices. They identified efficient scan patterns and developed scan patterns for maritime navigators that maximise safety. Lastly, it is observed that virtual reality (VR) simulator development studies are emerging (Jinlong, 2019; Lauronen et al., 2020).

Human factors

This group is the second largest, constituting 27% of the literature. This group is mainly researching the human operator inside the simulator. The focus is on either the human experience, or the human performance. More than half of the literature in this group use physiological monitoring as part of their data collection methods. They measure either heart rate or brain signals to gain understanding of the workload or stress level the operator is experiencing in real-time. For example, Hontvedt (2015) introduced a study that examines the experience of professional maritime pilots in a simulator training exercise using azipod propellers to navigate in high winds. The participants reflected on their experience in debriefings. The interaction analysis performed by Hontvedt shows that simulator training has distinct advantages, however, the pilot's experienced lack of photorealism and graphical fidelity in that simulator and this could compromise the effectiveness of the training. Orlandi and Brooks (2018) also evaluated the experience of marine pilots in a berthing operation exercise. They used both qualitative data, such as the self assessment scales, the NASA TLX and the Likert scale, and quantitative data from Electrocardiography (ECG), Electroencephalography (EEG), and eye tracking. They demonstrated that they could indirectly monitor levels of mental workload as they develop over time in a demanding operation. Lastly, Nilsson et al. (2009) presented a study similar to Orlandi's, evaluating the performance of marine pilots, in two different bridges, one with more advanced instruments, and the other with less advanced technology on board. They used several data collection methods, both qualitative (questionnaires and expert opinion) and quantitative data (physiological sensors and response times). They concluded that performance is not clearly correlated with the level of technology on board, however, if mariners' experience is taken into consideration, they found a link between experienced navigators performing better in less advanced bridges and less experienced navigators performing better in more advanced bridges.

Training

15% of the literature belongs to this group. This research mainly demonstrates the potential of simulators in training of operators to achieve higher levels of safety or efficiency. Some consider training for higher energy-efficiency and lower emissions, some consider training for a specific maneuver such as the man-overboard Williamson turn, and some consider training in specific conditions such as shallow water maneuvering. For example, Benedict et al. (2014) presented their development of an innovative simulator that presents future projections of a ship's path according to current conditions. This could be classified in the development group, however, they emphasised on the value of their developed simulator in training, elaborating that it can be useful in briefing and debriefing sessions for ship handling simulator training, and that it can be used as a training tool on board ships. Jensen et al. (2018) presented a proof-of-concept of a training that is helpful in saving fuel. They stated that fuel-efficiency of ships is not merely a technical concern, they showed that awareness, knowledge, and motivation are also important parameters in fuel consumption. Lastly, Formela et al. (2015), on the other hand, used a maritime simulator to train candidates of two different man-overboard maneuvers. Their investigation concluded that the Anderson Turn is more efficient than the Williamson turn.

Learning

10% of the literature belongs to this group. A group of literature that uses the simulators in their research to focus on learning. The difference between training and learning in this context is as follows: Training describes the use of a simulator for nautical students and experienced professionals to enhance some of their relevant skills. However, learning describes the use of a simulator to understand the process of knowledge transfer (and skill transfer as well). This includes education science, the actions that contribute to learning, including the role of the instructor in briefing, debriefing, or during the exercise. For example, Hontvedt and Arnseth (2013) are researching the learning in a simulator. They are investigating the context in which students and instructors collaborate to achieve learning goals. The study shows that the collaboration and meaning making of students is an important entity to address in the design of simulator exercises. In addition, Sellberg (2018) has performed an ethnographic study to investigate the instructor role in a simulator exercise. The research shows that a continuous instructional achievement, from briefing to in-session instructions, to debriefing is highly important to facilitate learning towards a profession.

Risk analysis

A minor group that is grabbing attention in recent years, a group of literature that uses the simulators in their research to focus on safety. Statistical methods for calculating collision probabilities are common here. Some studies do reconstruction of previous accidents, such as the 'Ever Given'grounding in the Suez Canal. Others develop practices that aim for a reduction in risk, for example ship-whale strike risk. For example, Popov et al., (2021) held an investigation based on a reconstruction of the Ever-Given grounding incident in the Suez Canal in a ship simulator. Grende et al., (2019), alternatively, proposed a set of practices for reducing ship strike risk as an active whale avoidance strategy and tested its feasibility in the simulator.

Research in ship simulators is multidisciplinary. The research fields of the main authors (of the collected literature) are noted. A variety of disciplines are involved, the leading discipline herein is Ocean / Naval Engineering, followed by Teaching / Training; Safety Engineering; Computer / Control Engineering; Industrial / Civil Engineering; Psychology; Human-Computer Interaction (HCI); Social Research; Mathematics;

and others like Finance / Economics; hydrodynamics; fishery and aquatic disciplines. The distribution of the main-author-disciplines is presented in **Fig. 2**.

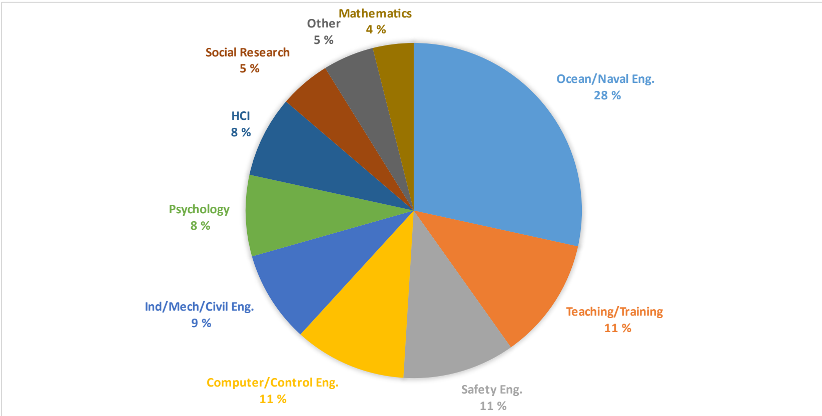

Fig. 2. Disciplines of main authors of collected literature

3.2 Interviews

The interview codes are found in Table 5. The main usage of simulators according to the interviewees is related to education and training. However, interesting applications are emerging such a sensor fusion of physiological data and the testing of technology and algorithms for enabling autonomous operations become safer than conventional ones.

The opportunities are summarised in three main points. First, simulators are facilitators of research and innovation. Second, simulators stimulate change in industry workflows. Third, simulators open new frontiers towards transforming the industry.

All researchers have agreed on the research infrastructure challenges, such as the availability of simulators and the availability of some expert helping hand to aid them throughout their experiments. While the managers mentioned issues related to cost of handling and maintaining simulator facilities. Interviewees using offshore operations (Class S) simulators were more innovation-oriented in their answers focusing on simulators' role in development of products and development of industry workflows. Elaboration on the results follows in the discussions section.

Table 5. Interview codes

Q1: Usage	Q2: Opportunities	Q3: Challenges
Education and training • Performing demanding tasks • Individual and group training • Training novice and professional • Leadership training • Joint situational awareness • Enhancing safety and efficiency	**Research and innovation facilitator** • Innovation facilitator • Multidisciplinary • Flexible scenarios • Connect simulators together • Autonomous docking • Complete control of situation • Proof of concept • Huge savings • Human factors: teams/genders/cultures • Training of algorithms/people/procedures • Observing the experts	**Research infrastructure challenges** • Availability of simulators • Availability of participants • Availability of technical support • Availability of maritime research partner • Data management • Availability of hardware
Reseach in education • Learning curves • Research "learning" • Instructor role	**Developing industry standards** • Development of design methods • Validation of new methods	**Simulator being just a simulator** • Limited setup flexibility • Duration of simulation • Location of simulation • Simulator maintenance cost • Bugs and shutdowns
Research in technology • Collecting physiological data • Testing interaction • Data driven models • Human/hardware in the loop	**New frontiers** • Harsh environments • Autonomous vessels • Testing rare scenarios	**Technology readiness** • Sensor technology • Validity and reliability • Physics in co-simulation

3.3 Case Study

This section lists simulator applications according to the Norwegian Coastal Administration Pilot Service (NCA PS), followed by a bullet-point highlight of their research and development strategy.

Simulator applications

Five simulator applications according to the NCA PS are listed below:

I. During the preparations of the pilotage of Sleipner platform into Haugesund port; that is a maneuver with a huge platform and tiny margins. Part of the training for this operation took place at Heerema simulator centre.

II. In the recruitment process, the NCA shifted their focus towards people skills, learning ability and the ability to acquire knowledge. Since 2018 the NCA is using, among other tools, simulators at NTNU to achieve this objective. They use general mental abilities (GMA) tests, personality tests, ability and skill tests, stress tests, structured job interviews and simulator exercises. In the simulator exercises, factors such as blackouts, lack of GPS, gyro-errors, and ocean currents are inserted into the scenarios to make them as challenging as they can possibly get in real-life. The NCA is using a panel of pilots, pilot director staff members, HR consultant, and the leader of the pilot district, which is a widely exposed assessment group, structured assessment forms describing what to evaluate and occasional pauses are scheduled to adjust the candidates and give them feedback and see if they can learn from their earlier mistakes. Correspondence between previous tests and real time impressions are checked. A lot is revealed about the candidates, and simulators create a suitable environment for research. The NCA's practical experience with simulators for the final cut assessments is that simulators are well suited; for they unveil the candidates' strengths and weaknesses. Still, the NCA would need to have objective ways of measuring candidates' conditions (pulse/stress/forms) and assessing candidates' overall performance.

III. Simulators are used for safety critical port operations. Ports are the same, ships are increasing in size, weather is sometimes harsh, simulators can be used to test external limits to operations that may have previously been deemed too risky. Simulator port studies consist of**:**
   - Risk assessments: define a given risk for a vessel on arrival / departure under various meteorological conditions.
   - Mooring analysis: identifies mooring opportunities towards the harbour, the risk associated with this and the outer meteorological limits of the mooring. For ex: "*can MS lona at 340 m length berth in Stavanger with 35 knots wind?*"

IV. Simulators are used for operational training (demanding operations). Can be a general training or a specific training. Can focus on technical skills, coordination, cooperation, leadership, and/or communication. Can be general training such as ship handling, tug courses, VTS, and bridge resource management (BRM) courses. Can be specific training on predefined assignments such as the entering and leaving of Nexans in Halden. Can be training for distribution of learning across the organisation, organisational culture, and safety culture.

V. Ship handling training through virtual reality simulators. The NCA is developing a VR simulator with adaptable ship models for pilotage training in advance of the real operation. Beside that, this tool can be used for BRM, teamwork and risk assessment studies.

Key areas for NCA's R&D strategy.

- Bridge Resource Management (BRM)
- Pilot – Vessel Traffic Service (VTS) co-operation
- E-Navigation (enhanced navigation such as decision support using digitalization)
- Sensors and sensor technology
- Safety culture

- Recruitment and leadership

4 Discussions

The results from the three data collection methods are merged into a mind-map showing the extent of the usage of maritime simulators. The applications are categorised in 6 categories as such:

Fig. 3. Simulator applications mindmap.

i. Education and training
ii. Operator training

iii. Assessment
iv. Development and testing
v. Research and innovation
vi. Digital twins

Where, AIS: Automatic identification system,
DP: Dynamic positioning,
HCD: Human centred design,
HCI: Human-computer interaction,
LNG: Liquified natural gas,
LPG: Liquified petroleum gas and

shows that simulators are not only used for maritime education. Simulators are becoming more vital in industry processes such as design and operations. Simulators are multidisciplinary labs that can gather expertise with a variety of roles for achieving specific purposes challenging the harsh and remote offshore environment. The sixth category (Digital twins) is an emerging umbrella of applications that naturally can be performed in a simulator. In Digital twins, the ships on the screens are representing real assets in operation. Simulators can be used to manage these assets, or as could be expected, to remotely control them.

One of the interviewees described the accuracy of physics in simulations as a challenge. Connecting this point with the aggregated range of applications. It is identified that some applications require higher functional fidelity than others. Functional fidelity represents the accuracy of the physics of ship movement in water (Hontvedt & Øvergård, 2020). For example, the application of training of nautical students probably requires a more relaxed functional fidelity than that of the application of pilot recruitment assessments. Such a challenge is raising awareness of the maritime simulator standard on accuracy requirements, which is elaborated in Section 4.3.

4.1 Simulator's Role in Our Lives

Simulators are no longer mainly used for nautical education. The offshore industries are rapidly growing with examples such as bottom-fixed wind turbines, floating wind farms, fish farming, subsea completions, bridges, tunnels, and the ocean surveying industry. Together with growth of the quantity and quality of offshore operations, the challenges imposed by distance-to-shore, environmental loads, weather, and the IMO energy efficiency regulations force the industry to evolve into a safer and more efficient one. Therefore, our methods for collaboration, design, and training have to evolve. There is a need for a development medium and simulators naturally fill this gap, and give us the potential to sit in the same room with our various roles from management, operations, nautical, designers and researchers.

In this sense, simulators can be viewed as enablers of operations that are usually deemed as impossible. We foresee that the demand for simulators will continue to rise.

Simulators will help us design and build the ships of tomorrow. They will help us remotely control surveying robots going as deep as the deepest point of the ocean goes. Simulators will help us enhance the way we install floating wind turbines. Simulators will help us enhance port infrastructure and waterways. They will help us in pilotage of huge containerships with autonomous tugboats. Simulators will train us to work together, with our different roles, different languages, and cultures. Likewise, simulators will help us manage our risks and achieve more with what we have.

4.2 Opportunities and Challenges

Simulators offer proof of concept capability to innovations in ship-bridge design, port design, and research ideas. Simulators are a haven for human factors and sociocultural diversity research. Nevertheless, the research and development of autonomous and remotely controlled vessels will depend largely on simulator experiments.

Main advantages of simulators are compressed into the following features: simulators enable human-in-the-loop and hardware-in-the-loop investigations. They allow investigations in harsh conditions, and in all kinds of weather, including winds, waves, and ocean currents. Simulators save time, they enable us to perform trials on a specific route relieving us from the duty of sailing back. Finally, simulators enable us to control variables, such as weather, that are impossible to control in real-world experiments.

Besides limitless opportunities, ship simulators have challenges of their own, some challenges are philosophical, linked to the fact that simulators *mimic* real-world, but they are not so. Other challenges are physical, related to the fact that ship simulators are not available upon demand, they are scarce and usually fully booked. The rest of the challenges are technological, even though advanced simulators provide a seamless performance that cannot be parted from reality, simulators do, occasionally, glitch, requiring updates and maintenance. In addition, the immersive feeling of a top notch navigation simulator does not imply realistic physics.

4.3 Simulator Accuracy Concerns

The broad scope of ship simulators' applications is raising the validity concern. In this paper, the concern is limited to hydrodynamic model fidelity that governs ship maneuvering behaviour in a simulator. Noting that most ship simulators included in this study are developed for education and training purposes, nevertheless, they are actually used for a much wider application. In the maritime industry, ship models undergo subjective validations. Subjective testing is basically the acceptance of an experienced officer, which is an important consideration. However, the introduction of objective testing, in the certification of simulators and / or ship models is crucial. Objective testing is a quantitative assessment based on comparison with validation data. Validation data is derived from full-scale sea trials done with the specific ship the model is replicating, or from free-running basin trials (model tests).

The airline industry, according to the Certification Specifications for Aeroplane Flight Simulation Training Devices (CS-FSTD) of the European Aviation Safety Agency (EASA), is addressing accuracy concerns (CS-FSTD, 2018). The concerns are addressed within the certification specifications. Qualification guidelines include objective testing in addition to pilot acceptance (subjective testing) and functional testing. The objective testing covers a range of plane behaviour details including flight dynamics, the response of the aeroplane to drag, thrust, attitude, altitude, temperature, centre-of-gravity, and etc. Among others, test categories also cover ground effects, wind shear effects, simulator computer capacity, aerodynamic modelling, stall characteristics, icing, mass properties and others.

Taking the full flight simulators (FFS) as an example, they are classified in four levels, A, B, C, and D (level D has highest functionality) according to their functionalities and match against validation data given defined tolerances. The maritime industry should account for such certification specifications for ship models taking into consideration maneuvering behaviour in calm water and environmental effects.

In the maritime industry, a DNV Standard exists for Maritime Simulator Systems that gives requirements of the performance of maritime simulator systems. The objective of the standard is to provide appropriate levels of physics and behaviour realism in accordance with training and assessment objectives (DNVGL-ST-0033, 2017). The standard recognizes different types of simulators such as crisis management, oil spill, mobile offshore unit, high-speed craft, fishery and other simulator types, but does not provide certification specifications per type. Type specific requirements can be dealt with separately using compliance statements.

This standard lists requirements related to behavioural realism, physical realism, operating environment, and dynamic behaviour. Few of the general requirements specified therein relevant to ship dynamics are summarised as: Own ship shall be based on a 6 degree-of-freedom mathematical model. The model shall realistically simulate own ship hydrodynamics in open water conditions including effects of winds, waves, tidal stream and currents. Class A simulators, in addition, are required to simulate realistically own ship hydrodynamics in restricted waterways including shallow water effects, bank effects, interaction with other ships and direct, counter, and sheer currents.

An appendix is added to the standard version of 2017 for the documentation specifications of mathematical and hydrodynamic models used in simulator systems. This includes the documentation of speed data, tactical diameter, and crash stop distance. The mentioned data shall be modelled, documented and verified.

It is obvious that the standard aims to provide ‘fit-for-purpose’ simulators and touches upon ship behaviour and hydrodynamic modelling. Despite that, it is also observed that there are two main shortcomings of such a standard. First, the standard recognizes only education and training types of simulator applications. The other application categories, presented in , are neglected. Second, the standard requires the verification of maneuverability indicators such as full speed and tactical diameter. This set of indicators is not elaborate enough to describe maneuverability of a ship and does not comply with the indicators specified in the maneuverability standards (IMO MSC.137(76), 2002). In addition, the standard does not specify how to verify the given indicators. The verification is indeed a challenge and it lies in the core of the matter of the objective of such a simulator standard: "providing appropriate level of physics and behaviour realism…"

4.4 Limitations

The three data collection methods used herein provide a solid base to answer the research questions, mainly on the application of simulators in the maritime industry. However, the used methods are not absolutely comprehensive in this endeavour reasons such as the following:

- The literature review provides insight about simulator application in the last 12 years, however, it is blind on the evolution of the use of simulators since they were first introduced in both academia and industry.
- Interviews may suffer from a selection bias because all the interviewees except one are from North-European countries. The representation of Asia, Africa, the Americas, and Australia is overlooked. In addition, other type of users exist that were not considered in the selection, such as nautical teachers and simulator developers.
- The case study provides a rich, relevant and up-to-date perspective that cannot be found in the literature, however, this is an eye-opener that there exist other perspectives not covered herein such as: Navy; Oil and gas industry and emerging blue economy industries.

4.5 Contribution

The combination of the three methods shows great potential in the use of simulators for both research and industry. The literature review provided examples from the research domain. The interviews provided deeper insight into experts' experiences, and the case study supplemented the results with relevant and up-to-date operational input. The primary contribution of this work is answering the research questions connected with the use, opportunities and challenges associated with maritime simulators. The primary contribution can be mainly manifested in the overview of application presented in **Fig. 3**.

The additional contribution is the identification of the accuracy concern. Some applications require high functional fidelity, meaning, high accuracy in ship dynamics during maneuvering. For example, assessment applications such as port studies, recruitment, and risk analysis. Outcomes of such simulator applications could drive decisions with considerable ramifications. In such cases, the simulator application could leap beyond the scope of its intended application. Raising an alarm on the ship dynamics fidelity, and after reviewing the maritime simulation standard, a gap in the requirements for ship dynamics evaluation was identified. A contrast is made with aeroplane simulator standards to confirm the relevance of the gap. This gap is clarified in Section 4.3.

5 Conclusions

5.1 Main findings

Ocean economy is addressing vital challenges such as food security, energy security and climate change. Emerging ocean operations face a multitude of challenges where simulators can serve as multidisciplinary laboratories for research, development, and innovation.

It is observed from the literature review that simulators invite researchers from various academic backgrounds, meaning that simulators are used for investigations concerning different perspectives such as human factors, development, training, learning and others. It is also observed that there is a lack of research contribution from the academic field of nautical science, probably because nautical students tend to fulfil the basic levels and proceed with operational careers instead of academic or research careers.

The interviewees agree on the potential simulators have in research, innovation and in changing industry workflows towards more inclusive design procedures and more collaborative operational mindsets.

Norwegian Coastal Administration Pilot Service uses ship simulators in recruitment, training, and innovation. Among other challenges, they face operational challenges, such as ships becoming larger, and waterways remain the same. They also have technological, interpersonal, fatigue-related, and practical challenges. NCA pilot service sees simulators as fit to contribute to training to the various kinds of challenges.

Simulators are used for applications beyond education and training. They are used for operator training, assessments, development and testing, and research and innovation. Some applications require higher fidelity in the ship dynamics than others. An accuracy concern in the maritime simulator standard is identified, raising awareness of the fitness of simulators for some of the high accuracy demanding applications.

5.2 Future work

- Develop a more comprehensive maritime simulator accuracy standard and specifications for validating simulators against these standards.

- Investigate the use of state-of-the-art Virtual Reality simulators in the maritime industry.

6 Acknowledgements

Thanks to my colleagues and the time they shared with me in good discussions. Thanks to the interviewees for accepting my invitations and taking part in this research. Thanks to the Pilot services of the Norwegian Coastal Administration for their cooperation.

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Appendix C

List of other works

Other research work I participated in that is not part of this thesis.

C.1 Zghyer, R., & Halse, K. H. (2020, October). Description of ship motion and comparison of a real-time unified hydrodynamic model with free running tests in calm water and regular waves. In The 30th International Ocean and Polar Engineering Conference. OnePetro.

C.2 Dimmen, K., Næss, B., & Nääs, O. (2020). Chasing the Perfect Rudder Angle–Evaluating the feasibility of a decision support system. A pilot study (Bachelor's thesis, NTNU).

C.3 Major, P., Zghyer, R., Zhang, H., & Hildre, H. P. (2021). A framework for rapid virtual prototyping: a case study with the Gunnerus research vessel. Ship Technology Research, 1-13.

Proceedings of the Thirtieth (2020) International Ocean and Polar Engineering Conference
Shanghai, China, October 11-16, 2020

ISBN 978-1-880653-84-5; ISSN 1098-6189
www.isope.org

Description of ship motion and comparison of a real-time unified hydrodynamic model with free running tests in calm water and regular waves

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ABSTRACT

Ship bridge simulators are well established in education practices of seafarers and mariners. The use of simulators in research is ramping up due to the EU motivation towards Blue Growth, where the quantity and quality of offshore operations are evolving. There is a need of deeper understanding of ship motion in waves within hydrodynamics research.
Simulators solve both the seakeeping and maneuvering problems simultaneously in order to represent the ship response in real-time. Methods that solve both the seakeeping and maneuvering are referred to as unified models. This study will present and describe ship motion, in calm water and regular waves, as experimented in free running maneuvering model tests (Rabliås & Kristiansen, 2019) and will compare the result of the model tests with simulations using the unified model; Fossen's vectorial unified model (2005). Fossen's model uses frequency dependent hydrodynamic coefficients and solves ship motion in 6 degrees of freedom, and the fluid memory effects are computed using ShipX (VERES).

This study investigates the performance of a hydrodynamic simulation method in regular incident waves. The container carrier Duisburg Test Case (DTC) hull is considered. Model tests including Zig-Zag 20/20 and Turning Circle maneuvers were performed in the Ocean basin at SINTEF Ocean in Trondheim, Norway. Simulation and experiments cover a range of wavelengths, approaching the vessel from different directions including head seas, beam seas and following seas.

Presentation and description of ship motion in waves is challenging. Appropriate tools are required. Polar scatters were used for describing ship motion in waves. The comparisons show that simulation results are comparable with model tests, however the digital ship is a different ship.

KEY WORDS: Hydrodynamics; seakeeping; maneuvering; real-time; simulator; ship motion.

INTRODUCTION

In the maritime domain, real-time unified hydrodynamic models are not only used for education and training in full bridge simulators (International Maritime Organisation, 1995). They are also being recently used in navigation systems for aiding ship position estimations (Bryson & Sukkarieh, 2006; Crocoll et al., 2013; Khaghani & Skaloud, 2016; Vasconcelos et al., 2010). Today, the performance of hydrodynamic models is getting more important than it ever was. Hydrodynamic models will also be increasingly more crucial in the future, regarding the positioning and control of unmanned or autonomous vessels.

The world is becoming more interconnected and systems are getting larger and more complex. Hydrodynamic models are used as a building block in larger systems, whether it is the certification systems of pilots and DP operators or the intelligent systems that would navigate, guide and control the advanced ships of the future. Even the decision support systems that would support the operators in critical maneuvers. In both cases, it is essential to be aware of the limitations and the uncertainty of such models. The uncertainty in hydrodynamic models is without doubt affecting other blocks in the same system.

The first step in avoiding ripple effects caused by hydrodynamic models' is to highlight the limitations and uncertainties, and then, the second step would be to examine them at system level, in both, virtual and real world, if possible. That said, is the opposite of taking hydrodynamic models for granted, with the impression that they indulge high accuracy and almost close to reality performance, as is a commonplace opinion among recent talks towards the future technology called autonomous vessels. As repeatedly quoted: "Awareness is key", and our main motives for this study are: 1. The description of ship motion in calm water and in waves and 2. The comparison between experiment data and simulation data.

Standard maneuvers such as zigzag tests and turning circles are classic tools used as standards for documenting "ship behavior", "maneuverability" or "maneuvering capability" (International Maritime Organization, 2002). It should be noted that these Standards were developed for big ships (above 100 m in length) with traditional rudder-propeller system, and they apply at the following conditions: 1. Deep, unrestricted water; 2. Calm environment; 3. Full load even keel condition, and; 4. Steady approach at the test speed.

Standard maneuvers indicate dynamic instability using simple criteria, for example, for Turning ability, the standards (the acceptance limits) are based on measures from the turning circle maneuver; the *advance* should not exceed 4.5 ship lengths and the *tactical diameter* should not exceed 5 ship lengths. Where the *advance* is "the distance travelled in the direction of the original course by the midship point of a ship from the position at which the rudder order is given to the position at which the heading has changed 90º from the original course" and the *tactical diameter* is "the distance travelled by the midship point of a ship from the position at which the rudder order is given to the position at which the heading has changed 180º from the original course. It is measured in a direction perpendicular to the original heading of the ship" (International Maritime Organization, 2002). The measures are shown in Appendix A.I.

For Yaw-checking and course-keeping abilities, the standards are based on measures from the zigzag test; the *first and second overshoot angles* should not exceed certain values. For the case of 20º/20º zigzag tests, the *first overshoot* angle should not exceed 25º regardless of the length-to-speed L/V ratio. The *second overshoot* angle has no limit for the 20º/20º zigzag tests however, for the 10º/10º zigzag tests it has limiting values depending on the range of the L/V ratio. Where the *first overshoot* angle is "the additional heading deviation experienced in the zigzag test following the second execute", and the *second overshoot* angle is "the additional heading deviation experienced following the third rudder execute". The measures are shown in Appendix A.I.

The above mentioned maneuverability criteria are suitable for calm water conditions. However, interest in the last decade is increasing towards addressing ship motion in waves, including maneuverability in adverse weather (Kim et al., 2014). Additional reasons (besides the increasing importance of hydrodynamic models) arise such as the introduction of the Energy Efficiency Design Index (EEDI) for new ships, a major step in reducing ship emissions. The EEDI requirements can be achieved simply by reduction of engine size but this affects safety in offshore operations where practices are still based on pre-EEDI experience (International Maritime Organization, 2012; Shigunov, 2018).

Unified hydrodynamic models are state-of-art, fast (could run faster than real-time), numerical methods solving the seakeeping and the maneuvering problems simultaneously. Therefore, such models are appropriate for use in simulators and can simulate a ship moving in waves. Examples are: 1. the 6 degrees-of-freedom (6 DOF) model by Fossen that dates back to 1991 and is considered the "standard model" by the international community for marine control systems design (Fossen, 2011) 2. The two-time scale method that divides the time domain of the simulation into two time scales, a slowly varying one associated with the maneuvering and a rapidly varying one associated with the seakeeping problem. In this study Fossen's method is included as a tool for generating simulation data that is compared with model tests.

Free running maneuvering model tests were performed with the SHOPERA benchmarking hull, the Duisburg Test Case (DTC) (Papanikolaou et al., 2016; Zwijnsvoorde et al., 2019). The model tests were performed in the Ocean basin at the Marine Technology center in Trondheim, Norway. The tests include course keeping, turning circle and zigzags. They were performed in calm water and in regular waves. Repetitions include a range of wavelengths, a couple of wave steepnesses, and multiple wave directions (Rabliås & Kristiansen, 2019). The maneuverability of the DTC ship is described, and the model tests by Rabliås are compared with simulations. In the next section, Methodology, the simulation components and particulars are presented.

METHODOLOGY

The hydrodynamic model used in the simulation is presented as follows:

$$M\dot{v}_r + C_{RB}^* v + C_A^* v_r + D v_r - \tau_{drag} + G\eta + \mu = \tau_{cntrl} + \tau_{wave} \quad (1)$$

Where,

M: rigid body mass and added mass, $M = M_A + M_{RB}$,
v: velocity vector, $v = [u, v, w, p, q, r]^T$,
v_r: relative velocity vector, $v_r = [u - u_c, v - v_c, w, p, q, r]^T$,
u_c & v_c: current velocity in the surge and sway directions,
C_{RB}^*: linearized rigid body Coriolis and centripetal matrix,
C_A^*: linearized hydrodynamic Coriolis-centripetal matrix,
D: damping matrix, $D = D_P + D_V$,
D_P: linear potential damping,
D_V: linear viscous damping,
τ_{drag}: viscous loads calculated using cross-flow drag and surge resistance calculated as quadratic drag,
G: hydrostatic matrix,
η: position vector, $\eta = [x, y, z, \phi, \theta, \psi]^T$,
μ: fluid memory effects,
τ_{cntrl}: control forces such as rudder and propeller,
τ_{wave}: wave forces,

The matrices M_A, C_A and D_P, the fluid memory function μ and the transfer functions for τ_{wave} can be computed using hydrodynamics programs. The program ShipX (VERES) by SINTEF was used within the simulation process. VERES is short for Vessel Response and is a program that calculates ship motion and global loads, including the calculation of short term statistics, long term statistics and operability. VERES is based on linear potential flow theory and the classical STF strip theory (Salvesen et al., 1970). Comprehensive explanations about the underlying theories, assumptions, and reference frames in the formulation of the unified model are found in (Fossen, 2005).

The simulation process starts by obtaining model test parameters and ship parameters (scale dependent) from Rabliås (Rabliås & Kristiansen, 2019). The model scale is 1:63.65, the model is made at SINTEF Ocean in conjunction with SHOPERA. The ship hull graphical model is inserted into ShipX, the loading conditions is set according to model tests. The ship is modified by adding bilge keels according to the cad file "dtc cad" that is found on SHOPERA webpage http://shopera.org/benchmark-study/. Result files from ShipX are saved.

The open-source Marine System Simulator (MSS) Simulink®-based toolbox is used as a simulation platform (Perez et al., 2006). The results from ShipX are converted by MSS functions to files readable by the toolbox. A zigzag controller and a rudder command functions are added to the tool as well as a regular wave module. Rudder particulars in the simulation are found in (Sprenger et al., 2017). A propeller module has not been added to the simulation, a thrust force achieving the desired speed is used instead. Tests are made with a constant propeller rotation speed that results in a varying surge velocity profiles throughout the tests. Such profiles were taken into consideration in determining the varying thrust input.

A right-handed coordinate system is applied for the body frame of the ship, with the x-axis pointing forward towards the bow, the y-axis pointing to port side and the negative z-axis pointing downward. Positive yaw is counterclockwise rotation about the positive z-axis (rotation towards port side). Generally, a turn to port side is a result of a positive rudder angle. Wave heading direction convention is applied as follows: 0º refers to head sea, 90º to beam sea and 180º to following sea.

It is important to mention that the simulation method presented here follows a stepwise workflow and involves no parameter estimation. It requires a hull geometry file, ShipX license for calculation of hydrodynamic coefficients and Matlab® and Simulink® license to run the open-source MSS toolkit. Main ship parameters are found in Appendix A.II.

Model test data and simulation data used are presented in the next section. It is not a goal of this work to create an optimized ship model, therefore parameter estimation and optimization are not included in the scope. This study focuses on two points, description and comparison.

i. Description of ship motion (experiment data) in waves coming from different directions, and
ii. Comparison with simulation results. Simulations that involves standard workflows and excludes parametrization.

PRESENTATION OF DATA

Table 1: Presentation of 20º/20º zigzag tests dataset-matrix, both the number of experiments runs (upper values) and simulations runs (lower values).

Wavelength to ship lengths ratio	Wave steepness	Wave parameters	Number of runs Upper value: experiment data runs Lower value: simulation data runs				
			Wave direction				Total per wave height
λ/L_{pp}	H_s/λ	H_s & T_p	D= 0º	D= 45º	D= 90º	D= 180º	
0	0	Calm water	4 5	- -	- -	- -	**4** **5**
0.28	1/40	H_s=2.48 T_p=7.97	1 5	1 -	1 1	1 -	**4** **6**
0.438	1/40	H_s=3.88 T_p=9.97	5 5	5 5	1 5	5 5	**16** **20**
0.63	1/40	H_s=5.58 T_p=11.96	5 5	1 -	1 1	1 -	**8** **6**
0.858	1/40	H_s=7.6 T_p=13.96	5 5	1 -	1 1	1 -	**8** **6**
1.12	1/40	H_s=9.93 T_p=15.95	1 5	1 -	1 1	1 -	**4** **6**
0.28	1/60	H_s=1.65 T_p=7.97	1 5	- -	1 1	1 -	**3** **6**
0.438	1/60	H_s=2.59 T_p=9.97	1 5	- -	1 1	3 -	**5** **6**
0.63	1/60	H_s=3.72 T_p=11.96	5 5	- -	1 1	1 -	**7** **6**
0.858	1/60	H_s=5.07 T_p=13.96	1 5	- -	1 1	1 -	**3** **6**
1.12	1/60	H_s=6.62 T_p=15.95	1 5	- -	1 1	1 -	**3** **6**
0.53	1/40	H_s=4.69 T_p=10.96	1 5	1 -	1 1	1 -	**4** **6**
0.74	1/40	H_s=6.56 T_p=12.96	1 5	1 -	1 1	1 -	**4** **6**
Total per wave direction=			**32** **65**	**11** **5**	**12** **16**	**18** **5**	**73** **91**

Where,

λ: wavelength,
L_{pp}: length between perpendicular (ship length),
H_s: Significant wave height in meters,
T_p: Spectral peak period in seconds,
D: wave heading (0º for head waves),
SB: turning towards starboard direction,
PS: turning towards portside direction,

Model test data are part of the experiments performed by Rabliås and briefly reported in (Rabliås & Kristiansen, 2019). Zigzag tests and turning circles are included in this study. The experiments dataset includes 73 runs of 20º/20º zigzag tests and 25 runs of 35º turning circles. The simulation-generated dataset includes 91 runs of 20º/20º zigzag tests and 52 runs of 35º turning circles. Velocity of the tests is 16 kn unless indicated otherwise for a few calm water turning circle experiments. The tables below present the dataset contents.

Table 2: Presentation of 35º turning circle tests dataset-matrix, both the number of experiments runs (upper values) and simulations runs (lower values).

Wavelength to ship lengths ratio	Wave steepness	Wave parameters	Number of runs Upper value: experiment data runs Lower value: simulation data runs			
			Wave direction			Total per wave height
λ/L_{pp}	H_s/λ	H_s & T_p	D= 0º PS	D= 0º SB	D= 180º PS	
0	0	Calm water	2, 2* 6	2, 2* 6	- -	**8** **12**
0.28	1/40	H_s=2.48 T_p=7.97	1 5	- -	1 2	**2** **7**
0.438	1/40	H_s=3.88 T_p=9.97	5 5	- -	1 2	**6** **7**
0.63	1/40	H_s=5.58 T_p=11.96	1 5	- -	1 2	**2** **7**
0.858	1/40	H_s=7.6 T_p=13.96	3 5	- -	1 2	**4** **7**
1.12	1/40	H_s=9.93 T_p=15.95	1 5	- -	1 2	**2** **7**
0.53	1/40	H_s=4.69 T_p=10.96	1 5	- -	- -	**1** **5**
Total per wave direction= * Runs with velocity of 8kn			**16** **36**	**4** **6**	**5** **10**	**25** **52**

Visual representation of the zigzag plots is found in Appendix A.III. Next section presents and elaborates on test results.

RESULTS AND ANALYSIS

First, the variation in the measures of the standard maneuver is presented; the *1st overshoot* angle, *advance* and *tactical diameter*. As shown in Tables 1 and 2, the independent variables of the data are wave height and wave direction. The comparison of the measures with respect to the independent variables is essential for observing trends and relationships. Therefore, four cases are introduced to enable comparisons in respect to the independent variables. The four cases are defined as follows, and four figures, Figures 1-4, showing histograms of the main measures associated with the four cases are presented next:

i. All runs.
ii. Calm water.
iii. Fixed wave direction (head waves) for all wave heights.
iv. Fixed wave height ($H_s = 3.88\ m$) for all wave directions.

Referring to IMO's standard maneuvers, the dynamic instability standard set the limits to the measures as follows. The *1st overshoot* angle should not exceed 25º. The *advance* should not exceed 4.5 ship lengths ($\approx 1600\ m$) and the *tactical diameter* should not exceed 5 ship lengths ($\approx 1775\ m$). Such standard, as mentioned in the introduction, is only valid in calm water, depicted in Figure 2, shows:

- For the model tests, the ship is dynamically stable with *1st overshoot* not exceeding 11º and *advance* and *tactical diameter* not exceeding 1000 m.
- For the simulations, the ship is stable as well with tremendously low *1st overshoot angle*. *Advance* is below 1000 m and *tactical diameter* is below 1500 m.

Even though this standard in only valid in calm water conditions, it is worth it to mention that the dynamic instability criteria is not breached in any single run. Meaning that the ship remains stable (according to the criteria) even in runs with very high waves, as high as 10 meters.

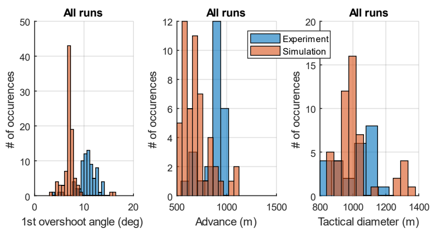

Figure 1: Standard maneuver measures histograms for case 1 (all runs)

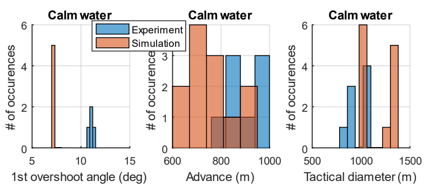

Figure 2: Standard maneuver measures histograms for case 2 (calm water)

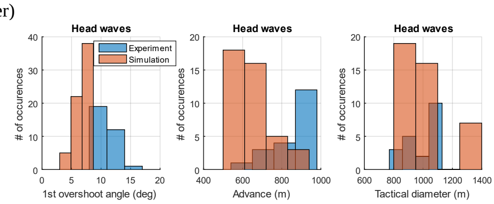

Figure 3: Standard maneuver measures histograms for case 3 (head waves for all wave heights)

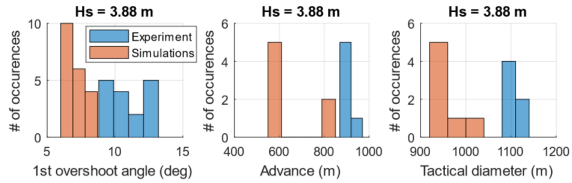

Figure 4: Standard maneuver measures histograms for case 4 (Hs=3.88 m for all wave directions)

DESCRIPTION OF SHIP MOTION

IMO criteria

The standard maneuvers criteria do not provide more information about the ship maneuverability, they are non-required pass/fail criteria from the Maritime Safety Committee (MSC) of the International Maritime Organization (IMO). Apart from the criteria, the measures themselves could provide some maneuverability insight.

From experiment data, it is observed that variation in wave height (Figure 3) has more impact on overshoot angle than variation in wave direction (Figure 4). Wave direction effects are deemed less important in turning circle tests because, while the ship is turning, the relative wave direction is covering the whole range of possible directions. The lack of following sea runs in the turning circle tests is limiting in terms of wave direction effects on advance and tactical diameter, though, it is trivial to observe that head waves affect advance in an inversely proportional manner. Tactical diameter is affected by wave height in the same way, while both measures increase in following sea conditions. Next section introduces new measures and investigates their insightfulness.

Introduction of additional measures

For the zigzag tests, the measure *reach* is introduced. *Reach* is defined as the time until the heading of ship crosses the reference heading of the original course, shown in Appendix A.I. In addition, *reach distance* is introduced and is defined as the distance along the path described by the midship point of a ship measured from the first rudder execute until the *reach* point is reached. For the turning circle tests, the measures *advance time* and *tactical diameter time* are introduced and they are defined as the time required until *advance* and *tactical diameter* points are reached respectively. The following figures, Figures 5-8, present the variation in the additional measures.

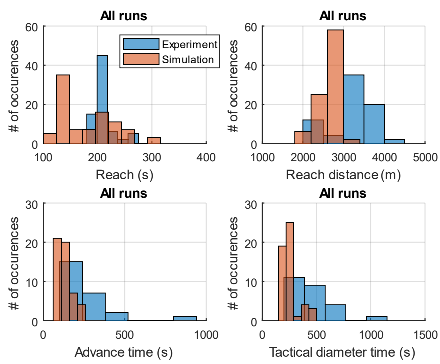

Figure 5: Standard maneuver 'additional measures' histograms for case 1 (all runs)

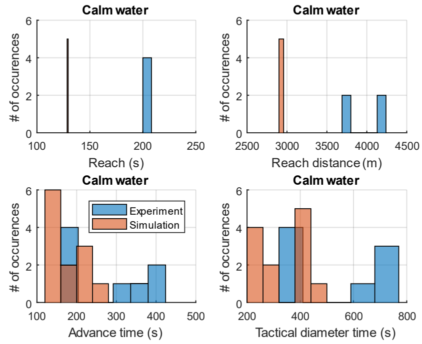

Figure 6: Standard maneuver 'additional measures' histograms for case 2 (calm water)

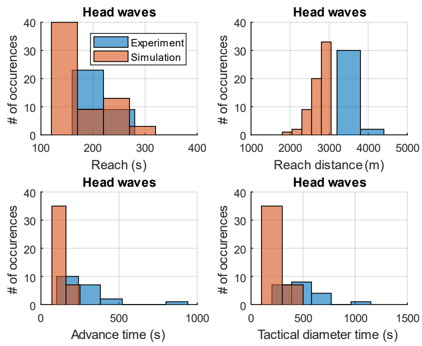

Figure 7: Standard maneuver 'additional measures' histograms for case 3 (head waves for all wave heights)

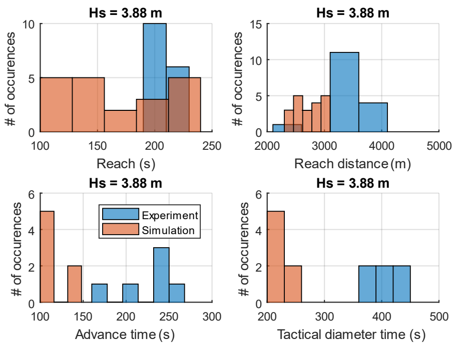

Figure 8: Standard maneuver 'additional measures' histograms for case 4 (Hs=3.88 m for all wave directions)

The main idea of the introduction of additional measures is to have both time and distance measures for specific points for each kind of test. This is helpful in showing the discrepancies between the experiment data and the simulation data, however, elaborating meaning from above data is challenging, because of multiple reasons that are worth mentioning, and are directly connected to the 'ship motion in waves' description problem. The analysis challenges are as follows:

i. The number of measures under consideration is increasing and thus is the number of figures.
ii. The dataset matrices are not symmetric. That is, the runs are not equally distributed among wave height and wave heading variables. For instance, there are 65 runs for head waves while only 5 runs exist for following seas within the zigzag simulation dataset. This bias (data distribution bias) is clearly shown in the histograms. Isolating this fact while analyzing the data is not a simple thing to do.
iii. Besides the bias across variables, data distribution bias across datasets is also affecting the figures; the distribution of runs in the experiment dataset is not the same as the distribution of runs in the simulation dataset.
iv. The number of cases is high to help the analysis but for every measure added, a multiple of figures are included. For every measure one figure per case is required, and that increases the complexity.

A different kind of figure is needed that shows more variables in an intuitive manner and does not require case by case isolation. A figure that shows wave height and wave heading (the independent variables), and the measure under consideration (the dependent variable) in one plot. Thus, reducing the number of plots and the complexity by 4 (the number of cases).

For example, the following figure, Figure 9, shows the variation in the measure "1st overshoot angle" among all experiments and simulations.

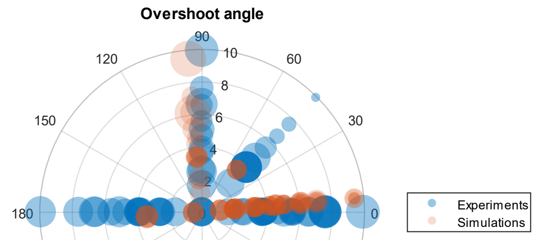

Figure 9: *1st Overshoot angle* variation in a polar scatter with the angular axis as wave heading and the radial axis as wave height (m).

The above figure shows dataset properties, for instance, it shows that for wave headings of 45º and 180º there are more experiment runs especially for waves higher that 4 meters, where the absence of simulation runs is clear. It also shows that, generally speaking, the overshoot angle in experiments is larger than that of simulations (every circle is a run, the size reflects the measure; the larger the circle is, the larger the overshoot angle indicated by that run is. The circles are transparent; the darker the color is, the more runs overlap on same conditions). It also shows the trend of larger overshoot angle as wave height increases. It also shows a strange behavior captured by experiment data. That, for wave heading of 45º, overshoot angle gets smaller as wave height increases. Investigation suggests that this is because the first rudder execute is done against the waves and the second execute with the waves, then the waves are supporting the execute where the 1st overshoot is measured. A linear scatter plot showing 1st overshoot angle versus wave height for $D = 45°$ is shown in Appendix A.IV, in addition to a zigzag and a North-East plot.

The analysis challenges addressed previously are relaxed with figures such as Figure 9 as follows:

i. Polar scatters reduce the number of required figures by four (the number of cases).
ii. Data distribution bias is not affecting the analysis in such a plot because the independent variables (wave height and wave heading) are visible. This enables better overview of trends such as in Figure 9, where overshoot angle increases with wave height except for bow seas.
iii. Polar scatters (for ex. Figure 9) show data of all runs, while the histograms (for ex. Figures 1-4) show data that is limited for the cases.

Figures 10 and 11 address zigzag measures such as *Reach* and *reach distance*. Figures 12 and 13 address turning circle measures such as *tactical diameter and tactical diameter time*. In Turning circle, according to dataset presentation in Table 2, runs occur only in two wave heading conditions (positive x-axis if for head waves and negative for following waves). Therefore, there is no need for polar plots for them, a linear coordinate scatter plot will be used instead.

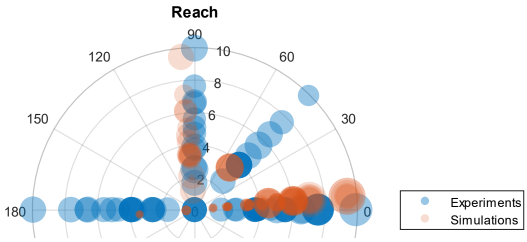

Figure 10: *Reach* variation in a polar scatter with the angular axis as wave heading and the radial axis as wave height (m).

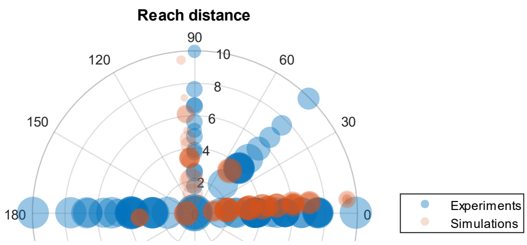

Figure 11: *Reach distance* variation in a polar scatter with the angular axis as wave heading and the radial axis as wave height (m).

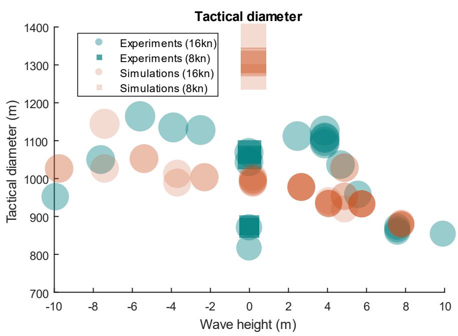

Figure 12: *Tactical diameter* variation in a linear scatter with the x-axis as wave height (m) in both directions (positive for head seas and negative for following seas) and the y-axis as tactical diameter in meters.

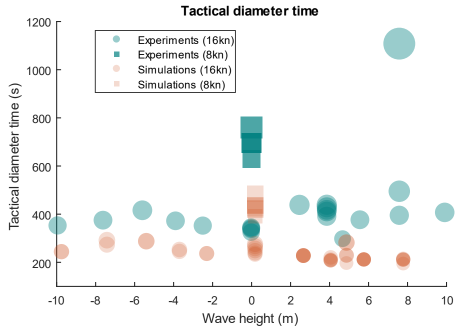

Figure 13: *Tactical diameter time* variation in a linear scatter with the x-axis as wave height (m) in both directions (positive for head seas and negative for following seas) and the y-axis as tactical diameter time in seconds.

From experiment data, it is observed that reach increases with wave height in head waves. It is also observed that reach decreases with wave height in bow seas, and that is a non-trivial observation. Regarding reach distance, it is smaller in beam seas and considerably larger in both head and following seas.

In turning circle datasets there are few runs with different ship speeds, these runs are highlighted in Figures 12 and 13 by a rectangular marker. These runs have calm water properties therefore they are in the center of the plots. It is observed that wave height does not influence neither tactical diameter nor tactical diameter time considerably. It is also observed that following sea conditions result in higher tactical diameter. From Figure 12 a non-trivial trend is observed where tactical diameter decreases as wave height increases above 4 meters. From Figure 13 an outlier experiment run is observed with about 8 meters wave height in head seas with tactical diameter time much higher than the average.

Drift motion

Investigation of ship drift requires the introduction of additional measures. Drift angle β is defined as the difference between course angle χ and yaw angle ψ, where the course angle is the velocity vector angle from the same reference of yaw (Fossen, 2011).

Drift (or sideslip) angle can be defined as:

$$\beta = \sin^{-1} \frac{v\ (Sway\ velocity)}{U\ (Forward\ speed)} \qquad (2)$$

Where the sway velocity contributes to drift and surge velocity contributes against it. It is suggested to introduce a measure that is based on sway velocity for the purpose of investigating drift. The measure to be introduced is pure drift distance (in the direction of sway; y-axis of the body coordinate system), which is calculated by integrating sway speed. The following figures, Figures 14 and 15, show drift measure in polar plots for zigzag runs. Figure 16 shows drift measure in linear scatter for turning circle runs.

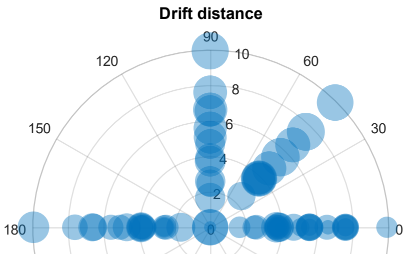

Figure 14: *Drift* variation in a polar scatter (zigzag experiments only).

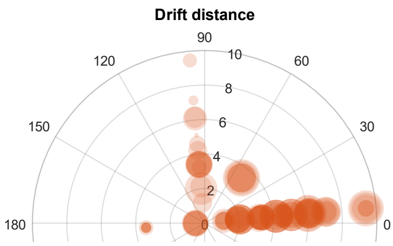

Figure 15: *Drift* variation in a polar scatter (zigzag simulations only)

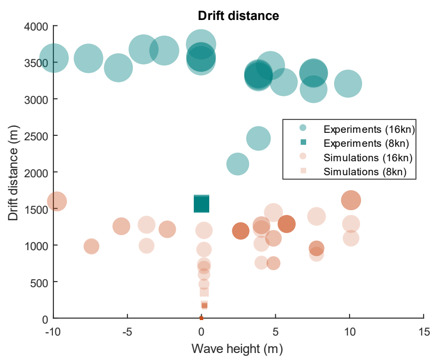

Figure 16: *Drift* variation in a linear scatter (all turning circle runs).

Zigzag experiments (Figure 14) show that as head waves grow larger, the drift does not increase, on the contrary it decreases. It indeed increases as waves from other directions grow larger, in the three remaining wave heading directions; bow seas, beam seas and following seas the drift motion is relatively large at highest waves. Its also obvious for head and following seas that drift motion alternates with wave height, it increases and decreases, this suggests a nonlinear relationship between drift loads and wavelength.

The turning circle experiments (Figure 16) show that there is slightly higher drift motions with following seas. It is also observed that the slower runs (8 kn) runs have considerably less drift motion.

COMPARISON WITH SIMULATIONS

IMO criteria

It is obvious from Figures 1-4 that the simulations do model a ship that zigzags with distinctively lower 1st overshoot angle, which is an alarming result despite the mild overlap in advance, tactical diameter and other measures.

Introduction of additional measures

From the additional measures, from the calm water case (Figure 5), it is obvious that simulations and experiments have distinctive yaw checking and course keeping abilities because the reach and reach distance are clearly different and the difference could be considered significant.

From the additional measures of the "$H_s = 3.88\ m$" case (Figure 8), further distinction is observed between the simulations and experiments in advance time and tactical diameter time measures. This distinction is also clear in advance and tactical diameter measures in Figures 4, 12 and 13.

Drift motion

The alternating drift behavior that is observed in simulations (Figure 15) is also observed in experiments (Figure 14). This alternating behavior suggests dependence of drift loads on wavelength. The importance of wavelength on drift loads is elaborated in (Skejic & Faltinsen, 2008).

Figure 16 shows drift in turning circle experiments is much higher than in simulation, this result shows agreement with the North-East plot of Figure 19. North-East plots of highest waves ($H_s = 9.93\ m$) for both zigzags and turning circles are introduced next, in Figures 17-19.

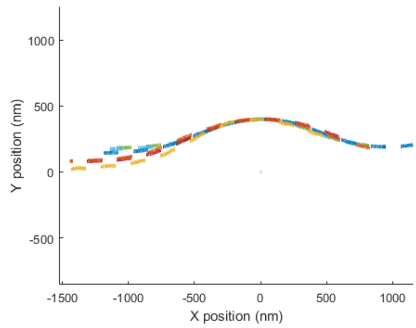

Figure 17: North-East plots for highest waves zigzag runs (solid lines for experiments and dashed lines for simulations).

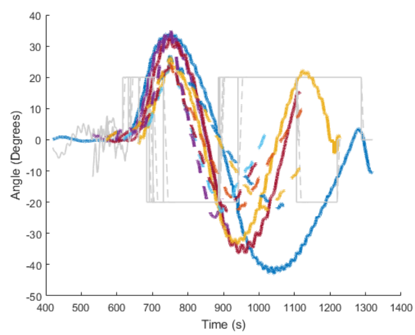

Figure 18: Zigzag plots for highest waves zigzag runs (solid lines for experiments and dashed lines for simulations).

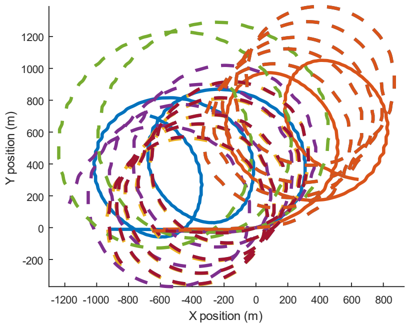

Figure 19: North-East plots for highest waves turning circle runs (solid lines for experiments and dashed lines for simulations).

DISCUSSIONS

Description of ship motion

Maneuvering in waves is challenging to describe because it includes seakeeping and maneuvering theories combined. It also includes propagation in the in-plane motions and oscillation in the out-of-plane motions. It also includes the impact of wave height and wave directions on ship motion. The combination of variables in play make it hard to describe ship motion in waves. We need the ability to describe ship motion in waves and the ability to compare ship to ship. Such comparisons enable digital ship (maritime simulators) maneuverability (in waves) analysis.

Machines take response amplitude operators (RAOs) as a tool for description of ship motion. RAOs are ship response amplitudes (divided by wave amplitude) for every possible wave frequency. These frequency-domain transfer functions (they transfer from wave amplitude to ship motion) are key in how machines calculate ship motion in a seaway after solving the hydrodynamic models. RAOs are great tools for seakeeping analysis however, they are not capable to express ship motion in a maneuvering study. Other tools are required to enable communication about performance of simulation models among hydrodynamics, control and nautical professionals (seafarers).

Standard maneuvers criteria are developed for big ships and they only apply for deep unrestricted water and calm weather. It is required to have the standard maneuvers developed to accommodate adverse weather, shallow water and special conditions related to specific operational demands.

The standard maneuvers are helpful because the maneuvers and the measures are well defined. Therefore they enable comparisons of well-defined constructs. However, they could be more fruitful if adapted to industry demands. The measures and the criteria are limited in terms of the “maneuverability” information they transfer. Additional measures such as, power consumption and efficiency measures could be promising.

This study was limited to standard maneuver test. The polar scatter plots introduced enable the relative comparison of a selected measure across all wave directions and wave heights. It enables the observation of trends such as, from Figure 9, that the overshoot angle is decreasing as wave height increases in bow sea conditions. The analysis using histogram is challenging as the number of figures required to cover the measures of interest is high. The main advantage of histograms in ship motion analysis is that they show values in absolute terms.

In any way, the description of a compounded dynamic system such as ship motion in waves requires multiple tools in order to communicate and elaborate transparently. Analysis included hereby is suitable for calm water maneuverability, while its applicability to maneuverability in waves is herein studied.

Simulations in general

Ship motion is compounded dynamics based on multiple components such as hull properties, waves, currents, wind, steering system, propulsion system, etc. In real life, it is hard to isolate such factors because it is hard to measure their impacts accurately. In simulations every factor requires a model such as hull geometry model, wave model, current model, propulsion model, etc. Basically, each model has its own assumptions and simplifications, while end users of such technologies could have different expectations of the overall performance of ship dynamics simulators.

Taking performance of models for granted could be risky for operations. Continuous visibility and challenging of the assumptions (limitations) is crucial as industry is pushing the limits towards new frontiers with the extra-large container-carriers and cruise vessels that are becoming a trend in the last decade and with the development of autonomous technologies that is becoming a hype in the last few years.

Experiments, in this case, model tests, do provide thorough information about ship motion in certain maneuvers. Such experiments are necessary for validation of numerical models. Where it is harmless to note that from real-life to experiments there is one stage of uncertainties and from experiments to simulations there is another. Two stages of uncertainties are affecting ship motion as we ever simulate it regardless of the maneuver specifics. The former stage, between real-life to experiments, is dominated by the differences among the two. For example, are there regular waves in real-life? The latter is governed by differences between simulation and experiments. For example, would the simulated perfect regular waves be comparable with the basin-generated waves?

The comparison of simulations with experiments is an important step in model validation process. Component level comparisons such as viscous loads module or rudder module are back-end tools. In order to communicate these comparisons with operational professionals, operational variables need to be selected for presentation. Variables that are intuitive and require no background knowledge. Distances, time, rudder angle, ship speed, ship drift and power consumed are examples of intuitive measures. While, frequency-domain measures and hydrodynamic coefficients do not reflect the holistic (overall) operational performance of such (simulated) ship maneuver.

Comparison with simulations

From Figures 1 – 8, both agreements (overlap) and disagreements (separation) are observed. There is a total of 28 histograms in those figures, where 8 out of the 28 show complete disagreement. Besides the disagreement, there is one more thing in common among those 8 histograms, all separations are as follows: the experiment data lies on right hand side and the simulation data lies on the left. Meaning that the simulations underrate the measures.

The measures with clear disagreement are divided into two groups, the zigzag measures are: 1st overshoot angle; reach; reach distance, and the turning circle measures are: advance; tactical diameter; advance time and tactical diameter time. In addition to the drift disagreement that is observed in Figure 16.

This being said reveals a trend that the simulated ship has better maneuverability; less time and distance in general to reach a certain point. Better means different, therefore, the conclusion here is that the simulations are indeed comparable with experiments, however the digital ship is a different ship, it maneuvers differently in calm water and in waves. Whereas the applicability of such digital model depends on the purpose. The reason behind the difference could be hydrodynamic coefficients estimation, rudder module or even linearization limitations. Methods for parameter estimation / optimization could be helpful (and necessary) in this case to optimize the simulations' to best fit the experiments.

CONCLUSIONS

Model tests of a container carrier in calm water and regular waves are used to describe ship motion in waves and to compare it with simulations. Simulation data is generated using an industry-accepted method. Software is used for calculating hydrodynamic coefficients and no model parametrization was involved.

Ship motion in waves is a compounded dynamics where a number of variables are involved. It is still a challenge to describe maneuverability in waves. Frequency domain functions are helpful for calculation of ship response, but for description of operational-level measures, measures such as distances, time and power are recommended to be considered. The measures included in IMO standard maneuvers are limited in the information they hold however the defined maneuvers themselves are promising. IMO standard maneuvers are meant for calm water, and big ships, adaptation to adverse weather and ships of all sizes is crucial for maneuvering in waves analysis.

Describing ship motion in waves involves describing the measures of interest against possible ranges of wave height and wave direction. Polar scatter snapshots show potential in holding and delivering information about ship motion in waves of all heights and directions.

The simulation results are indeed comparable with the model tests, however the digital ship is a different ship, it maneuvers differently in calm water and in waves. Whereas the applicability of such digital model depends on the purpose.

ACKNOWLEDGEMENTS

The authors acknowledge the support of Professor Trygve Kristiansen and the PhD candidate Øyvind Rabliås from the Department of Marine Technology (IMT) at the Norwegian University of Science and Technology (NTNU) and SINTEF Ocean for providing experiment data.

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APPENDIXES

A.I. Standard maneuver descriptive plots

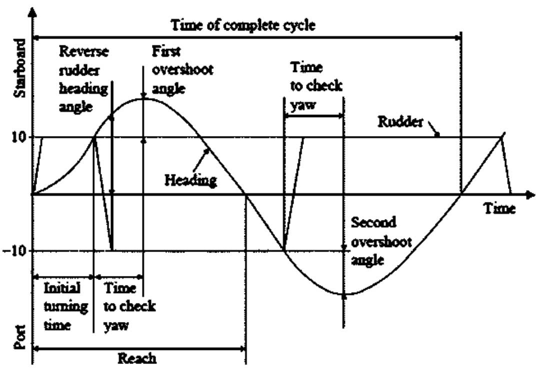

Figure 20: Zigzag maneuver measures

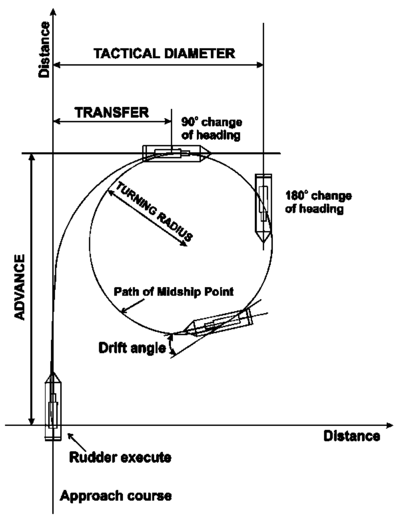

Figure 21: Turning circle maneuver measures

A.II. Main ship parameters

Table 3: Main ship parameters

	Full scale	Model scale
Length, L_{pp} (m)	355	5.58
Beam, B (m)	51.0	0.8
Draft, T (m)	14.5	0.23
Displacement, Δ (kg)	173,468,000	672.6
Block coef. C_B (-)	0.661	0.661
Longitudinal center of gravity, X_{COG} (m) from aft perpendicular	174.06	2.72
Lateral center of gravity, Y_{COG} (m)	0.00	0.00
Height from keel to center of gravity, KG (m)	19.85	0.31
Metacentric height, GM (m)	5.1	0.01

Table 4: Rudder particulars (full scale)

Twisted rudder with costa bulb	-
Base profile	NACA 0018
Twist angle (deg)	5º
Height from skeg to baseline (m)	12.9
Area (m^2)	255.0
Rudder rate (deg/s)	3.1

Table 5: Bilge keel particulars (full scale)

Number of segments per side	5
Length per segment (m)	14.85
Height per segment (m)	0.4
Chamfer length at the forward (m)	1.2
Chamfer length at the aft ends (m)	1.2
Gap between segments (m)	3.0

A.III. Visual overview of experiment data and simulation data

The overview in the three figures below just shows (some sense of) the variability in overshoot angles, overshoot time, and positions. Part of the postprocessing, the data is translated (shifted) to facilitate easier reading. The zigzag plots are aligned so that 1st overshoot happens at the same time for all tests. The zigzag NE plots are translated so that peak of the maneuver (along the y-axis) happens at the same location (x and y coordinates). The turning circle plots are translated so that the beginning of the turn occurs at coordinate (0,0).

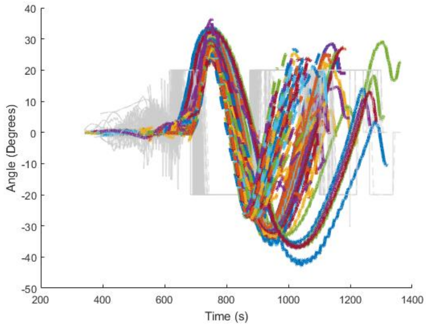

Figure 22: All zigzag test runs. Experiments in solid lines and simulations in dashed ones.

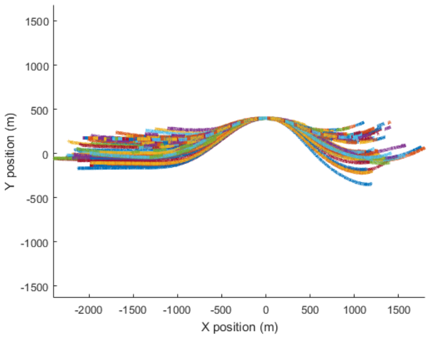

Figure 23: All zigzag North-East plots. Experiments in solid lines and simulations in dashed ones.

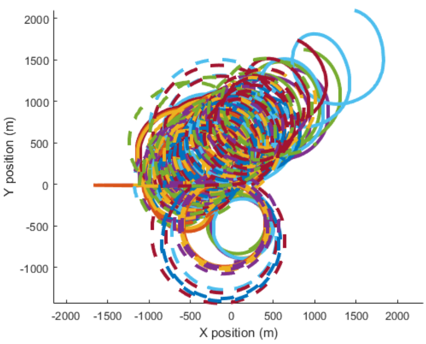

Figure 24: all turning circle plots. Experiments in solid lines and simulations in dashed ones.

A.IV. Overshoot versus wave height for $D = 45°$.

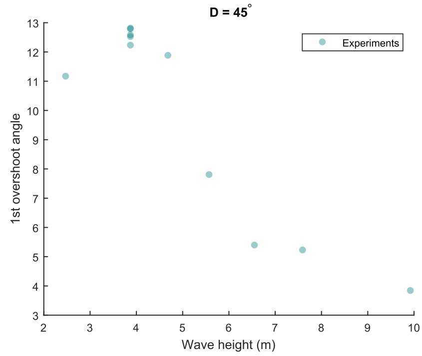

Figure 25: 1st overshoot angle variation in a linear scatter for wave direction $D = 45°$.

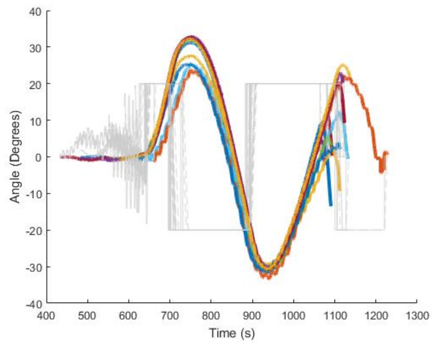

Figure 26: Zigzag plot for experiments with wave direction $D = 45°$.

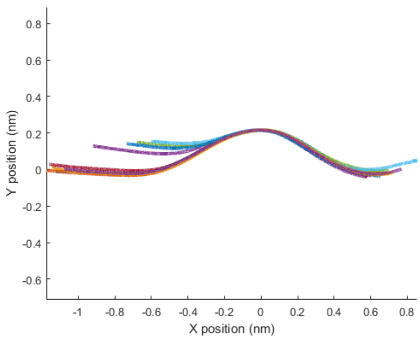

Figure 27: North-East plots for zigzag experiments with $D = 45°$.

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Ocean Operations and Civil Engineering

Bachelor's project

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Næss, Bjørn
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Chasing the Perfect Rudder Angle

Evaluating the feasibility of a decision support system. A pilot study.

Bachelor's project in Nautical Studies
Supervisor: Zghyer, Rami
May 2020

NTNU
Norwegian University of
Science and Technology

Abstract

The aim of this bachelor thesis was to do a pilot study to test the hypothesis that a support system can aid in increasing safety during navigation. In order to achieve this, a support system needed to be created and experiments carried out.

In order to substantiate the beneficial value of such a support system, accident reports for ships involving grounding, contact and foundering were studied. All vessels involved in the accidents were large and modern ships, and only accidents caused by a failure to properly execute a planned manoeuvre were considered for the thesis. Accident reports show that navigating under demanding weather conditions pose great challenges; the contention is that a support system could assist the navigator in avoiding critical misjudgments.

The first idea was to use matrices to calculate force vectors. This approach was abandoned in favour of using long-established hydrodynamic modelling. The support system was developed for the sole purpose of testing the hypothesis in a commercial simulator using a specific scenario; its use beyond this is therefore extremely limited. Additionally, it was not feasible to facilitate a direct connection between support system and simulator. These factors resulted in the adoption of certain assumptions and limitations early in the development process.

Current and wind were not collected from measurements from simulated instruments, but inserted manually into the support system. As a result, current and wind were identical in simulator and support system. Nor were there any real time updates during testing. No user interface was ever created; in its current form the system requires a basic knowledge of coding to use. Consequently, the system was controlled by the thesis authors, and the results from its calculations presented to the test participants in a format readable by navigators.

Programming was done in Matlab with the Simulink add-on. Test were performed in a bridge simulator in order to optimise an already existing mathematical model. For the optimisation, standard manoeuvre test were performed. Monte Carlo simulations were used to adjust hydrodynamic derivatives, in order to predict ship movements in the simulator. In the experiment, students at the Norwegian University of Science and Technology in Ålesund participated in a simulator test in Vatlestraumen. The ship used for the experiment was a very large crude carrier 305 metres in length.

The difficulty in defining a good manoeuvre led to a simple pass/fail system being used for statistical analysis. The pass criteria was set at successfully navigating through the area of the simulation without making contact with land or touching bottom. A chi-square test was used to analyse this data.

The null hypothesis for the statistical analysis was that there is no significant difference whether the support system was used in the first or second passage with the very large crude carrier. The null hypothesis was rejected at $p < .10$. Despite the lack of statistical significance at $p < .05$, a p-value of 0.0543 cannot immediately be written off as a result of pure chance.

In addition to fewer groundings in tests performed with the support system or after its use, data show that it resulted in a more controlled use of rudder. When the time required to find a close to optimal rudder angle has been reduced or eliminated, the navigator has more time and attention to spare for other critical aspects of navigation. The authors contend that this increases navigational safety.

Further research is recommended to confirm or reject the hypothesis. Tests performed using identical pre-planning for all participants would aid in isolating positive or negative effects of using a support system similar to the one used for this thesis.

For any development of a system for practical use, tests on real ships would be required; the hydrodynamical model used in this thesis should be replaced by a more suitable modern alternative. It is the authors' opinion that the model used for optimisation should be further developed and tested in order to facilitate the building and optimisation of mathematical models during normal ship operations. This would lead to an increased selection of models, aiding research in hydrodynamics.

"If my weakest troops fail to eliminate a hero, I will send out my best troops instead of wasting time with progressively stronger ones as he gets closer and closer to my fortress."

—The Evil Overlord List – (Anspach 1996, Item 80)

"The pilot initiated the turn using three degrees of port rudder, followed by successive increases to five and 10 degrees' rudder when he realised the ship was wide in the turn."
—Azamara Quest accident report – (Transport Accident Investigation Commission 2002, p.5)

ACKNOWLEDGEMENTS

Numerous people both inside and outside of NTNU have generously contributed their time and assistance in the completion of this project. Naming them all individually would make for a thesis-length list in itself, but they have not been forgotten.

We would like to thank the entire teaching staff at NTNU in Ålesund. Without their open door policy providing us with access to their time and knowledge, progress would have ground to a halt on an almost daily basis. Our footprints are indelibly etched in the office corridors.

In particular, the help of Arnt Håkon Barmen has been invaluable. Without him, the project would have been dead before it started. He said “yes” when the sensible thing would have been to say “no”, even as the scope of our plans threatened to shatter the confines of a bachelor thesis. If we have succeeded, it is because he allowed us to fail.

Finally, our most sincere gratitude goes to our supervisor, Rami Zghyer. His assistance has been above and beyond even our wildest expectations. Without him, this thesis would have been a bleak shadow of its current form.

Even the most dedicated of helpers cannot eliminate all errors committed during the development of this project. Any remaining mistakes are ours, and ours alone.

Contents

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1 Introduction

Manoeuvring a ship is a process of constant evaluation and estimation. There are simply too many variables to keep track of for it to be anything else. A captain may sail the same route every day for decades and never experience the exact same conditions twice. A skilled officer with experience in how his ship behaves uses that experience to estimate correctly – or close enough not to matter – most of the time. Some do it all of the time. When that skill and/or experience is lacking, the likelihood of getting into dangerous situations increases.

To execute a manoeuvre, one must first apply an initial rudder command, then wait for the rudder to affect the ship. Once the effects become observable, one must evaluate whether the chosen rudder angle is the correct one and if not adjust accordingly. The cycle of apply, wait, observe, evaluate, adjust is then continuously repeated throughout the manoeuvre.

Using too little – or too much – rudder in the initial phases of a manoeuvre means that a large correction will soon be needed. If this correction is not done quickly and with a suitable rudder angle, it becomes difficult to execute the manoeuvre as planned. In restricted waters, such errors can have catastrophic results.

It is obviously desirable to choose an initial rudder angle as near perfect as possible. An inexperienced navigator might be tempted to make use of the ship's autopilot. Unfortunately, a traditional Proportional Integral Derivative (PID) autopilot is wholly unsuitable for precise manoeuvres, even if perfectly tuned. It is a system designed for keeping a course and simple course changes. It is also a "dumb" system, where the input is based on a set of standard conditions, and corrections made if it is discovered that the ship is not following the intended course.

At the opposite end of the scale there is Dynamic Positioning, which uses a combination of mathematical models and constant measurements of wind and current. Usually this is used as a means to keep a ship in a fixed position using thrusters, but it can also, to some extent, be used to move.

What all known existing systems have in common is that they are largely reactive. Whether making a first estimation based solely on standard conditions or in combination with wind and current measurements, they all work based on what is happening in the moment.

The authors of this thesis have chosen to look at the problem from a different angle. Instead of an automated system reacting to what is happening, they have sought to devise and test a system to assist the navigator in planning manoeuvres well in advance. Additionally, rather than having the system take control, it remains in an advisory function, leaving decision and execution in the hands of the navigator. This thesis will explore the hypothesis that safety is increased with the assistance of such a system.

1.1 Motivation

The motivation for writing this thesis is quite simple: manoeuvring a vessel affected by external forces is hard. This is a subjective statement; attempts to make it objective are made in Section 1.2.1 – Accident Reports. Some captains might guide their vessels through difficult manoeuvres in adverse conditions without ever feeling anxiety, or doubting the decisions they make. However, unless this is true for *all* people piloting ships all the time, it makes sense to try to solve this problem.

"At any given time, there will be a number of different forces affecting a manoeuvre. It would be impossible and not very relevant to calculate the influence of all these forces at all times in a given manoeuvre. We must therefore assess the situation on the fly – using a master's accumulated experience" (Kjerstad 2017, p.1-1, own translation). It is naïve to seek a simple mathematical solution to something so complex as ship path prediction. Constant changes to one input sends ripples that affect the overall output. Any equation that fails to take account of this will fail at its job. Kjerstad (2017, p. 1-1) writes that at any one time there will be several forces that impact on a manoeuvre. Perfect modelling of all forces would indeed be impossible, at least by today's computers. Much of the idea behind the hypothesis explored in this thesis springs from a disagreement over the irrelevance of trying to calculate those forces. Perfection being unattainable is a poor argument against an effort to create something useful.

Developing something to be of immediate benefit aboard real vessels would be infeasible. Such a project falls well outside both the discipline of nautical studies and the time allotted for the completion of a bachelor thesis. Consequently, focus will be on designing a system with the sole purpose of testing a concept: Will a path predictor that gives ship specific information about the execution of planned manoeuvres increase navigational safety?

In order to test hypothesis, the authors of this thesis set out to complete the following tasks:

- Create a decision support system being able to predict ship movements in a commercial simulator.
- Test this systems on participants in navigator in-the-loop experiments.
- Evaluate results and make a statistical analysis.

1.2 Literature Review

The literature review for this thesis is divided into four distinct parts. The first part mentions accident reports from across the world where, in one way or another, according to the authors, a Decision Support System (DSS) giving information about rudder orders in advance of a manoeuvre could have changed the outcome. Here, the focus has been on finding accidents where the consequence has been grounding, foundering or contact. Accidents that occur because of a misjudgment of the ship's manoeuvrability due to weather forces have been of particular interest. A good search function is a rare occurrence in the world of accident investigation. Because of this, over a hundred accident reports listed as being related to grounding, foundering, or contact were chosen and searched for relevance. All of these were with vessels above 100 gross tonnes.

These articles were then subjected to an elimination process to remove the least relevant. Accidents involving older ships, engine or steering failures, or remarkably poor seamanship were removed. The remaining reports all mention as a contributing factor a failure to properly plan for the effects of wind and current while executing a planned manoeuvre. A brief summary and discussion of how the most relevant relate to the thesis will be given in Section 1.2.1 – Accident Reports.

The second part is a summary of how the rate of turn approach to manoeuvring works. This is one of the more common methods of manoeuvring in restricted waters and the one taught to most students at Norwegian University of Science and Technology (NTNU) in Ålesund. The literature for this section comes mainly from that used to educate and train navigators.

The third part is about a similar work in path predicting decision support systems.

The fourth part covers hydrodynamic sources used in building the DSS. Searches for relevant terms gave many of the articles regarding pivot point and wind coefficients. Books regarding general knowledge about hydrodynamics were found via searches and suggestions by staff at NTNU in Ålesund.

1.2.1 Accident Reports

The following section contains brief summaries of accident reports deemed to be of particular interest for substantiating the usefulness of a system such as the decision support system devised for this thesis.

First report: According to the Marine Accident Investigation Branch (2002), the PI&O Nedlloyd Magellan ran aground at the entrance to the Thorn Channel at around 07:00 UTC on the 20th of February 2001, while approaching Southampton, England. The grounding was in main attributed to an error of judgment by the pilot. Restricted visibility, an incorrectly set electronic bearing line, and the bridge crew not properly monitoring the pilot were listed as contributing factors.

Second report: The Marine Accident Investigation Branch (2015) writes that at 15:15 on the 14th of July 2014, the Commodore Clipper grounded while approaching St Peter Port, Guernsey, UK. At the time of the grounding, the ship was supposed to be following a 220° line. However, tidal currents of 2-3 knots on the starboard beam was setting the ship to port of its intended track.

During the two minutes immediately prior to the grounding, new courses of 222°, 224° and 226° had been ordered in an attempt to get the ship back on the planned track. According to the accident report, “this heading was insufficient to avoid danger; a larger and earlier alteration of course would have been necessary to get Commodore Clipper back into safe water”. (Marine Accident Investigation Branch 2015, p.45) The data collected by the accident investigators show that at the time, the course over ground was consistently 4° to port compared to the course being steered.

Third report: Shoji, Kosuda, and Nemoto (2017) say that at about 12:25 local time on the 6th of June 2015, the Shin Heiryu allided with the East Light Buoy in the Port of Singapore, Singapore. At the time, the vessel had been travelling at a speed of 3 knots through the water in order to facilitate the pilot boarding. Unbeknownst to the master, there was at the time a rapidly increasing stern current. At 12:04, it had been approximately 0.5 knots on the starboard quarter; at 12:22 it was later estimated to have been 2.5 knots almost directly astern. The relatively strong current compared to the vessel speed meant that, as the ship turned to starboard to avoid the buoy, there was a large discrepancy between the vessel's heading and the course over ground. At times, this difference was more than 30°, and the vessel failed to make the turn in time.

Fourth report: According to Transport Accident Investigation Commission (2002), the Azamara Quest allided with Wheki Rock in the Eastern entrance of the Tory Channel on the way to Picton, New Zealand on the 27th of January 2016, at about 09:20, local time. At the time, the pilot had been aboard for 20 minutes.

The entrance to the channel is less than 0.5 nautical miles wide and has a 75° port turn. At the time of the incident, there was a projected following current of 6 knots in the centre of the channel. According to the accident report, the turn was started some 20 seconds later than intended. The master had informed the pilot that the ship would "turn on a dime", and that a 3° rudder angle would suffice to start a "good" turn. It soon became apparent that 3° was insufficient, so it was increased to 5° and 10° in quick succession, followed by 20°.

With no time to become familiar with the ship, the pilot only had the master's assessment to go by. A following current is likely to make it more difficult to assess how much rudder is needed, as it increases the speed over ground and decreases the effectiveness of the rudder with regards to distance over ground.

Fifth report: The Marine Accident Investigation Branch (2017) writes that on the 22nd of August 2016, at 00:32 local time, the CMA CGM Vasco de Gama ran aground at the entrance to the Thorn Channel, Southampton, UK. The Marine Accident Investigation Branch lists several reasons for the grounding, some of which are:

- The vessel approached the approximate 140° starboard turn from 260° to 037° too far to the North, resulting in a narrow turn being required.
- The combined effects of 20 knots of wind from WSW and a rising spring tide resulted in the vessel being unable to maintain the necessary Rate Of Turn (ROT) to complete the manoeuvre. Despite the rudder angle being increased to 35° from the initial 10° and engines set at full speed ahead, the ROT decreased as the turn progressed.

After the grounding, several simulator tests were carried out. Under the conditions that existed at the time, the turn as planned and executed by the pilot resulted in a grounding every time. However, when approaching from further south and thus allowing for a wider turn, the passage was successfully completed.

Sixth report: The Australian Transport Safety Bureau (2018) writes that at about 22:20, local time, on the 12th of February 2017, the Aquadiva nearly ran aground while leaving Newcastle, Australia. In order to make a port turn in excess of 90°, the pilot wanted a rate of turn of about 13° per minute. To do this, he first ordered 10° rudder. When it became apparent the ship was not turning fast enough, this was increased to 20°, and then later to hard over.

Eventually, nearby tugs managed to prevent the ship from grounding. The investigation concluded that not enough rudder angle was used, and used too late.

Common causes:

In addition to the items highlighted above, most of these accident reports mention the failure of applying proper bridge resource management as a contributing factor. This becomes particularly critical when there is a pilot involved. There is then a situation where the pilot knows the local area and its dangers, and the regular crew knows their ship and how it behaves. Combining these pieces of knowledge into a whole is crucial, but often made difficult by language problems and lack of time.

Reading these and other accident reports, it is common to see rudder command issued in 5° and 10° intervals. This is natural, as ships are commanded by humans, and humans tend to like round numbers. However, there is nothing inherently magical about a 10° angle. Sometimes it is indeed optimal, other times 8° or 13° would have been better.

In situations like the ones listed above, a DSS using accurate hydrostatic data could be useful in several ways. During the planning stage, it could provide exact wheel-over points, instead of relying on estimations by a pilot who might be wholly unfamiliar with the manoeuvring characteristics of the ship in question. It would be able to suggest more precise rudder angles to use; instead of a human guessing whether to use 5° or 10°, the system could calculate that, for example, 8° would allow the ship to follow the planned track.

If provided with live input from sensor data, the DSS could then adjust its initial assessments as the manoeuvre progresses. Should a projected 2-knot current from SW turn out to be 2.2 knots from WSW, small changes could be applied. The operative word here is "small". Properly adjusted and fed the best data available, the suggestions from a working DSS should never be too far from the optimal values.

1.2.2 Traditional Manoeuvring Practices

"For larger vessels sailing in narrow waters, it is absolutely necessary to plan which turn circle to follow. Depending on which radius is selected, the point at which you start the turn, the Wheel-Over Point (WOP) will differ from where the WayPoint (WP) itself is located." (Kjerstad 2017, p.2-17, own translation).

On large ships, it has become common in recent years to navigate by Rate Of Turn (ROT) (Kjerstad 2017). In navigator education courses, students are trained to work with physical charts where they set out waypoints, course lines, turn circles with predetermined radius, WOP and more. When the courses are drawn on a map, it is common to leave these at a WP where it is planned to change course. When this happens in narrow waters, it is beneficial to monitor the turn with a constant radius. This is illustrated in Figure 1. Due to inertia, there is a delay from when a rudder command is given to when the vessel has worked up a rotation. The rudder command thus needs to be issued before the vessel reaches the WP; this is called the WOP. The distance between the WOP and where the ship starts turning is called f. This distance has to be compensated for during the planning phase to secure the voyage.

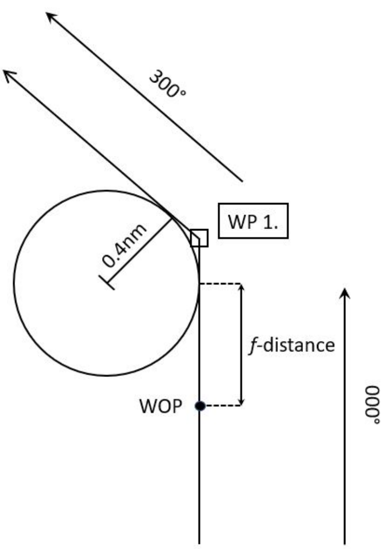


Figure 1. Turn using constant radius.

The f-distance will vary by ship type, rudder type, control system and current. If the f-distance is unknown it can be found on manoeuvre diagrams; those familiar with the vessel will often be able to make an estimation from experience. As a rule of thumb the f-distance is a ship's length; the size of f does not change with the selected turn radius. In addition to any uncertainty with the distance of f, another error factor will be that most ships lose speed while turning. This means that keeping a constant ROT will result in a smaller radius than if the speed remains constant (Kjerstad 2017). The vessel will also be subjected to external forces such as wind, tide and current, which must be compensated for while manoeuvring. In shallow waters, the shallow water effect, channel effect or general bottom topography will also affect the vessel's manoeuvrability.

For each manoeuvre, the navigator will try to work up a ROT when the vessel reaches its WOP. With the vessel speeding through the water, the rudder is put over in the direction of the desired turn. Inertia will cause a delay of varying length before the vessel starts to rotate, also known as turning. As mentioned earlier, there are several influences and external forces that affect the rotation of the vessel; thus it is difficult to know exactly how much rudder angle one must give to get the desired rotation. Accurate estimations, testing, accumulated experience, and/or luck determine whether one has given the right rudder command so that the vessel follows its intended path. If the correct rudder angle for the desired ROT is not found on the first try, it has to be compensated for by giving more or less rudder.

1.2.3 Path Prediction Practices

Path prediction systems are to some extent already common aboard ships. One example of this is vectors showing speed over ground or speed through the water on radars and chart machines. The most common versions are ground velocity vectors showing only ship speed or a curved line including rate of turn. The length of this line can be changed to show estimated tracks for different lengths of time. The ground velocity vector is not a helpful tool for turning, because it is hard to get an accurate reading of how a turn is developing from a straight line showing direction of travel at a given moment. The curved line taking rate of turn into account fails to adjust for decreasing speed because of sway movement. In addition, because it is based on the speed and ROT in that exact moment it is not a good path predictor. It is entirely possible for the path predictor to show the ship heading for the starboard bank of a channel when, in reality, port rudder applied means that the ROT is increasing at such a rate that – unless the rudder is immediately changed to starboard – the ship will hit land on the port side. The accuracy of both these systems was thoroughly tested by van Breda and Passenier (1998). They compared conventional path predictors, a relatively simple mathematical model, and path prediction based on an accurate hydrodynamic model. They also compared results in accuracy in navigation with conventional methods such as parallel-indexing and ground velocity vectors. Simulator tests conducted showed significant reduction in positional error between planned and actual track when path predictors took both speed and rotation into account. The greatest reduction was seen in the path predictor which used fast iterations of input to the mathematical model. This effect was most notable with larger course changes.

One negative side of this approach is that it is purely reactive. In some cases a wrong decision can lead to an unrecoverable situation where, regardless of how advanced the support system used, there is not enough time to make corrective measures.

1.2.4 Hydrodynamic Models

The Marine Systems Simulator (MSS) is a toolbox that uses the Matlab add-on Simulink Perez et al. (2006). It was created by merging previous systems developed to provide aid in the implementation of mathematical models of marine systems. Fossen (2011) has collected new results in hydrodynamic modelling and explains concepts with reference to tools found in the MSS. This has been an irreplaceable resource and an excellent introduction to hydrodynamics. It is safe to say that this thesis would not have existed without this book; if by chance anything of importance for the field is found in the following pages, it is because of work adapted from these sources.

A comprehensive study on the manoeuvrability of large tankers was done by van Berlekom, Goddard, and The Society of Naval Architects and Marine Engineers (1972). The purpose of this was to investigate the manoeuvrability of new ship designs during the design stage. A mathematical model was created for tankers of the Osaka class and tested against existing vessels for its capability in predicting ship movements. This mathematical model was incorporated into the MSS toolbox by Trygve Lauvdal in 1994 and revised by T. Fossen in 2001 and 2004. Because of the similarity of the Osaka class to the vessel chosen for testing of the DSS in the commercial simulator, this model was chosen for optimisation to match the trajectory of the commercial simulator vessel. The article gives a comprehensive description of what the hydrodynamic derivatives are and their meaning and importance in the mathematical model.

For an increased understanding of how hydrodynamic models are created and the values of hydrodynamic derivatives calculated, Lewis (1989) wrote about how tank tests can be used to gather information about forces acting on a model hull and then use the data gathered to predict the ship's motion. In an effort to better understand hydrodynamic equations, the lecture notes of Zaojian (2006) have been of considerable help and the explanations are adapted from these two sources.

In order to understand the tools for wind coefficients included in the MSS toolbox, source material for these programs has been consulted. Isherwood (1972) used a method of multiple regression techniques in order to fit calculated coefficients into experimental data. Blendermann (1994) used a method based on *Helmholtz-Kirchhoff* plate theory. Both methods need only the size of the windage areas and the general shape of the vessel to compute coefficients. Blendermann uses a list of parameters that differ for different types of vessels while Isherwood's formulas produce generic coefficients.

Problems with the moment lever arm led to literature regarding the pivot point and its impact on manoeuvring. Capt. Cauvier (2008) points out that the concept of the apparent pivot point is often misunderstood. This point is in fact not a point to be used to understand moments acting on the vessel. This topic is also covered by Jeong (2012) and Seo (2017). A mathematical method to estimate the apparent pivot point is given by Tzeng (1998), whose method uses the rotation of the vessel and sway speed in its calculation.

1.3 Educational Background

The following is a brief overview of the parts of the three-year curriculum that are directly related to navigation. This is included for two reasons. It describes how the competence attained through the course of the studies relates to the writing of this thesis. Furthermore, it demonstrates the experience of the participants used for the experiment (see Section 2.1.1 – Participants).

During the first semester, students receive training in Navigation 1. This subject includes collision avoidance rules, astronomical navigation, terrestrial navigation and simulator training. In the simulator, students are trained and tested in the aforementioned subjects to verify that they have understood the theory and can use it in practice.

In the second semester, the students receive training in Navigation 2. This subject mainly consists of theory about the navigation systems; the theory is tested in both desktop and bridge simulators. During the semester, students are expected to familiarise themselves with RAdio Detection And Ranging (RADAR) and use of Automatic Radar Plotting Aid (ARPA), compass and gyro systems, satellite- and earth-based navigation systems, Automatic Identification System (AIS), and different electronic chart systems.

The third semester contains no elements directly related to navigation techniques.

The fourth semester is demanding, both when it comes to theory and practice. The previous semesters lay a foundation, so now students are expected to dive in-depth into the complexity of marine operations. The focus of the academic content is divided into several small topics, which merge into a large one. It includes how to read and understand nautical publications such as sea charts, pilot guides, tidal tables, current maps, beacon lists and several more. The use and limitations of the Electronic Chart Display and Information System (ECDIS) and advantageous usage of ROT and Parallel Indexing (PI) to secure the voyage is covered, along with the advantages, disadvantages and limitations of the practical use of manoeuvring characteristics and standard manoeuvre tests; also how to operate a vessel in narrow waters and canals, and how the shallow water and channel effects will affect the vessel.

Students must have in-depth knowledge of mooring and anchoring arrangements, including offshore systems, as well as towing and use of tugs. They are taught how to operate the vessel in harsh and icy conditions. Voyage planning includes planning of overseas and coastal voyages, risk assessments, as well as the assessment of necessary margins for safe sailing. For the administrative parts, there is establishing watchkeeping and bridge routines, and logging and documenting the voyage. Use of the Vessel Traffic Service (VTS) and their reporting points and working with a pilot are important aspects the students must become familiar with. They will also learn how to act in case of war or emergencies with the help of the Naval Co-operations and Guidance for Shipping (NCAGS). The Navigation 3 course covers the theoretical knowledge requirements in the STCW (International Convention on Standards of Training, Certification and Watchkeeping for Seafarers) Chapter II, section A-11/2.

In the fifth semester, students start with the last part of the navigation subjects. Maritime communication contains topics on the Global Maritime Distress and Safety System (GMDSS). Medium-, high- and very high frequency transmitters and receivers, Digital Selective Calling (DSC) and satellite communications. It also includes the use of emergency equipment such as Emergency Position-Indicating Radio Beacon (EPIRB), Search and Rescue Transponder (SART) and Search and Rescue Device (SARD). The settings, practical use and testing of the equipment is of great importance in this subject. Protocols and proper procedures for emergency and safety traffic are described in Admiralty List of Radio Signals, vol 5. At the end of the course students receive a General Operators Certificate.

Maritime communication is intertwined with the Navigation 4 course. In Navigation 4, there is great emphasis on bridge resource management with a focus on human factors and leadership. It includes an introduction to how the rescue service in Norway is structured, as well as other countries' similar services. There are mandatory exercises in Search and Rescue (SAR) operations on the bridge simulator, where both management and general execution of theory is used. This course covers the theoretical knowledge requirements in STCW Chapter II Table A-II / 1-2.

Students also have the opportunity to take the elective course position and survey system during this semester. This is more in-depth on how global navigation satellite systems work. An introduction to several position reference systems is given.

During the sixth and final semester, there are no mandatory navigational courses. Apart from courses not relevant to navigation, this semester focuses heavily on bachelor thesis writing.

2 Method

Method is divided up in three parts. The first part details the experiment carried out as part of this bachelor thesis and the second part focuses on the use and creation of the DSS. The last part concerns the choice of statistical method used for analysis of data.

2.1 Experimental Setup

The experiment was carried out using the commercial simulator at NTNU in Ålesund. Participants were picked from the fourth semester nautical school course Navigation 3. This course contains a simulator exercise that with little modification could be used for an initial test of the hypothesis: a decision support system similar to the one devised for this thesis improves navigational safety. As an added benefit, mandatory participation secured a good number of participants. Ideally, these would have been people with experience as deck officers, such as the teaching staff in nautical sciences. However, the larger sample size obtained by using second year students was deemed to far outweigh the use of less experienced participants.

The vessels used for the experiment are listed in Table 1.

Table 1. Vessels used for experiments.

Ship name	Vessel 1	Vessel 2	Vessel 3
Ship type	LNG carrier	Very large crude carrier	Container vessel
Length overall	295m	305m	399m
Beam	45.8m	47m	59m
Displacement	101800t	214943t	249931t
Draught fore	11m	19.8m	16m
Draught aft	11m	17.6m	16m
Block Coefficient	0.71	0.68	0.69
Rudder type	Normal	Normal	2 Normal
Max rudder angle	45°	35°	35°
Max rudder rate	3.6°/s	1.4°/s	5.3°/s
Top speed	20.5kn	16.0kn	19.0kn
Propeller	Fixed pitch	Fixed pitch	2 Fixed pitch
Propeller rotation	Clockwise	Clockwise	Clockwise

2.1.1 Participants

As already mentioned in Section 2.1 – Experimental Setup, the participants for the experiment carried out in this thesis were students in their fourth semester. See Section 1.3 – Educational Background for further details. At the end of the fourth semester, students have completed all courses related to navigational techniques in their nautical education. Their next step in regards to navigational techniques will be aboard ships as deck cadets. With no navigational courses involving sixth semester students, fourth semester students were the best option available in sufficient numbers.

Each class is divided into two groups. Approximately one half of the class have taken the academic route, qualifying for the course through a diploma earned at the end of thirteen years in school. The other half have spent two years at a maritime high school, followed by two years as deck trainees aboard ships, qualifying as able seamen.

In the beginning of the first semester, each student completes a Carl Gustav Jung personality test several times. Students are then paired based on their educational background and the personality test results. One student with an academic background and one with an able seaman background are put together based on the results of this test. This pairing lasts throughout the three years and usually does not change.

The trials for this study were held in the middle of the participants' fourth semester, when they were already familiar with the instruments needed to complete the experiment. They worked in their regular pairs, to simulate a real world environment where two navigational officers have spent considerable time together.

3 weeks prior to the experiment students signed a consent form. The form stated that data about ship movements would be collected and used for the purpose of this bachelor thesis. It also mentioned that no video or pictures of the participants would be included and that the logged data would be saved and kept confidential. Consent could be revoked until the 27th of February 2020, the day before the experiment.

All students in the fourth semester signed the consent form and no one revoked the right to used their data prior to the deadline. The consent form can be found in Appendix A – Consent Form (in Norwegian).

2.1.2 Manoeuvre Tests Using Desktop Simulators

In preparation for the experiment, manoeuvre tests were carried out by the participants on desktop simulators. The desktop simulator consists of two regular computer screens, with a keyboard and mouse for each screen. One screen has a working ECDIS, the other has radar, autopilot and a first person view from the command bridge.

Once a week, students have four hours of desktop simulation and two hours of bridge simulation. The laboratory work is important and a large part of their one-day-a-week practical education. The participants had been doing manoeuvre tests for several types of vessels during the course.

Two weeks prior to the experiment students were given a mandatory exercise. Their task was to do manoeuvre tests of Vessel 2 from Table 1. The setup was identical to manoeuvre tests done previously during the semester, with the addition of a zigzag test. At this point, the students were unaware that this vessel would be used during the experiment. Having the students do manoeuvre tests with the vessel prior to experiments gave them an introduction to the vessel. The thinking behind this was to increase their time spent manoeuvring very large crude carriers in particular and directionally unstable ships in general. This was something with which most of these students had little experience. The familiarisation of Vessel 2 was divided up into eight parts. The parts were as follows:

Part one was a short exercise to find ship specific information in the Wheelhouse Poster, Pilot Card and Manoeuvring Booklet. This is information provided by the company that created the commercial simulator and is available for all vessels. It contains information such as Length OverAll (LOA), beam, draft, displacement, max rudder angle, max rudder rate, and propeller specifics. For example, information given to a navigator about draft and displacement will give an idea about a vessel's manoeuvrability as well as to what extent it will be affected by current. Information in the Manoeuvring Booklet in particular will give a good indication as to the manoeuvrability of a vessel. It is of importance to know the f-distance when using the rate of turn method described in Section 1.2.2 – Traditional Manoeuvring Practices. Figure 3b on page 14 gives a graphical depiction of the f-distance and other terms used in this exercise. This is usually learned from experience but can be found from documents such as the three mentioned at the start of this paragraph (Kjerstad 2017). A rule of thumb is that the f-distance in nm is the ship's LOA divided by $1852m$. For a vessel $185.2m$ in length, this formula would give a f-distance of $0.1nm$. Current has a great effect on this distance and will alter it proportionally to its speed and direction.

A northbound vessel travelling in a southbound current will be "pushed" backwards. This will make the f-distance shorter. If the current is travelling *with* the vessel it will "push" it forward, making the f-distance longer, and the vessel needs to start the turn earlier.

Another thing that has an impact on the manoeuvrability is the propeller's direction of rotation (see Figure 2). For all vessels used in this thesis, the propeller has a clockwise rotation. On a ship that travels in a straight line without any rudder command, a propeller rotating clockwise will cause the stern of the vessel to move toward starboard. This makes the bow move in the opposite direction. Because of forward momentum, this will cause the ship to turn toward port. This knowledge lets the student know that the vessel will turn easier to port, reducing advance and transfer compared to a starboard turn.

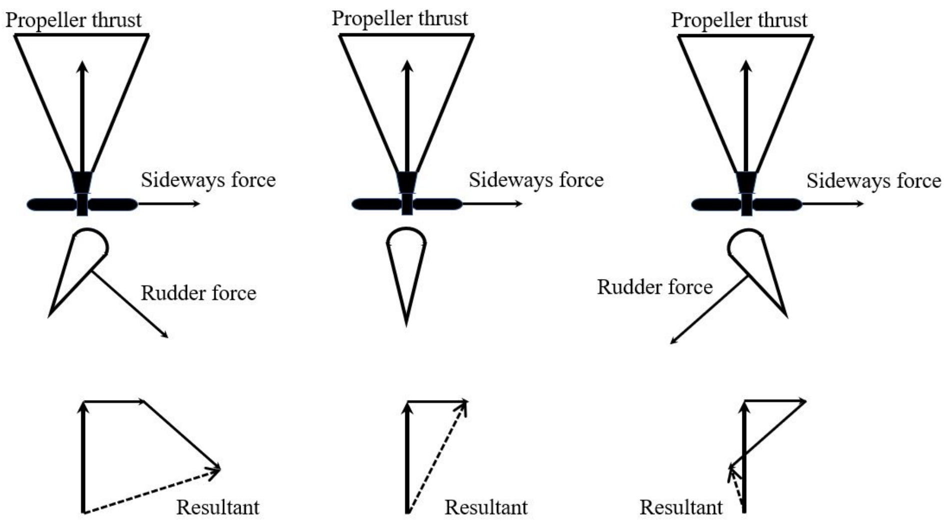


Figure 2. Description of propeller and rudder forces for a clockwise propeller. Original picture by (Kjerstad 2017, p.1-31).

Parts two and three of the manoeuvring tests were intended to test the vessel's turn characteristics with manual rudder angles in deep and shallow water. This was done with no current, waves or other elements that could interfere with the results. This was also the case for the rest of the test conducted. The tests were carried out in a collaboration between all the students.

With ten desktop simulators running in tandem; half of the ships turned to starboard and the other half to port. Rudder angles ranged from $5°$ to $25°$ with $5°$ intervals. When the vessels achieved equilibrium with the water, meaning surge, sway and rate of turn became static, the test was stopped. Data gathered from all vessels was shared between the students. Relevant data from this test is advance, transfer, tactical diameter, turning radius and the f-distance.

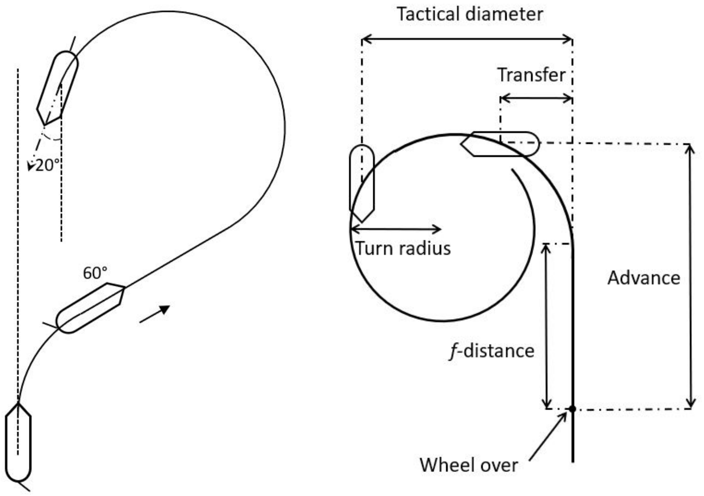
Advance is the distance the midships point travels in the original direction, from the position where the rudder order is given until the course change is $90°$. Transfer is the distance the midships point travels perpendicular to the original direction until the vessel's course has been changed by $90°$. Tactical diameter is the distance the midships point travels perpendicular to the original direction, from the position where the rudder command is given until the course has changed $180°$. Turning radius is the radius of the circle described when the ship has entered an equilibrium with the water. The f-distance is the measured distance the vessel travels from when a new rudder order is given until the vessel starts turning. This data is valuable information when it comes to planning a turn with manual rudder. It also gives an indication of what the expected turn radius is with changing rudder angles and how shallow water will affect the turning capabilities of the vessel.

Part four of the tests measured the capabilities of the autopilot in deep water. Course changes of between $15°$ and $90°$ degrees were tested in $15°$ intervals. Again, several tests were run in tandem. When the vessel had achieved a straight and stable course, the tests were stopped. Data gathered were max rudder angle, advance and transfer to the new course. Knowing the max rudder angle that the autopilot will give is valuable information about the limits of course changes when using the autopilot. Measurements of advance and transfer follow the same principles as in tests two and three. The difference is that the distances were measured when the vessel obtained the new set course, and not at $90°$ off the original course. This is essential information in planning a manoeuvre using autopilot as well as the limitations of doing so.

Part five was similar to part four. A manoeuvre diagram was created using the fixed radius function on the autopilot. Students used the autopilot to turn 90° off the original heading with a fixed radius ranging from 0,1nm to 0,7nm. The purpose of this test was to observe how much rudder angle was used and how narrow a turn the autopilot can make with its inbuilt limitations.

Part six built on the same general principles as the previous two. The students set a course $90°$ off the original course to both port and starboard. They programmed the autopilot to turn with a fixed rate of turn ranging from $10°/min$ to $50°/min$ in $10°/min$ intervals. Again students monitored the max rudder angle and what radius the different settings resulted in. The idea with tests four, five and six was to give the students a general idea about how sharply one can turn using the autopilot.

After tests four to six, the results were analysed. Students engaged in discussions with



(a) (b)

Figure 3. Williamson turn (Kjerstad 2017, p.2-112) (a) and description of advance, transfer, tactical diameter, f-distance and turn radius (b).

the teacher about what propeller rotation the vessel had, the limitations of the autopilot and comparisons between the turning radius expected and the one achieved. Theoretical turning radii were approximated using Equation 1.

$$\text{Radius} = \frac{\text{Vessel speed}}{\text{Rate of turn}} \tag{1}$$

Part seven had the students perform a Williamson turn (see Figure 3a). In a man overboard situation, it is of the utmost importance to perform a fast and effective manoeuvre to turn the vessel around and return to where the person fell overboard. For a smaller, more manoeuvrable vessel, a regular turning circle is sufficient, but this is ineffective for larger vessels. A Williamson turn is one way of turning the vessel around and returning to the same position where the manoeuvre was started. This is done in three steps:

- Give hard rudder to the same side as the person fell overboard. This pushes the propeller(s) away from the person in the water.
- At a heading of $60°$ off the initial course, give hard rudder in the opposite direction.
- When the vessel is $20°$ off the reciprocal course, the rudder is put midships.

The efficiency of following the standard instructions was evaluated and students were asked to make their own ship specific instructions for a second attempt. A limit of three rudder commands were set on these instructions.

The optimal solution for Vessel 2 turned out to be the following:

- Give hard rudder toward the side of the man overboard

- Once the vessel is 20° off the original course give hard rudder in the opposite direction
- When the vessel is 120° off the reciprocal course, put the rudder midships.

Vessel 2 reacts slow to changes in rudder angle and has a huge momentum. Once a decent rate of turn is achieved, it takes a long time for counter rudder to have any effect. This is more or less what is expected from a heavy, directionally unstable vessel.

Part eight in the familiarisation of Vessel 2 was a zigzag 20°/20° manoeuvre. The purpose of this test is to study the vessel's response to changing rudder angles. Essential parameters are the time between subsequent rudder movements and the first and second overshoot angle (Kjerstad 2017). The test was conducted by having the vessel hold a steady course without any rate of turn. A rudder command of 20° to either side was given. When the vessel was 20° off the original heading, 20° rudder to the opposite side was given. The overshoot angle is the number of degrees the vessel turns from the moment the new rudder command is given until the rate of turn is stopped and the ship starts changing its heading in the opposite direction. The time from first command to second is also of importance. This procedure was done two to three times, and the data are sufficient to conclude how the vessel responds to changing rudder commands. Tests showed that the vessel responds slowly to rudder commands and will most definitely overshoot by a minimum of 20° with a rudder angle of 20°. To reduce overshooting during manoeuvres, it is advised that smaller rudder angles be used during course changes.

2.1.3 Bridge Simulators

There are six bridge simulators located at NTNU in Ålesund. For the sake of simplicity, they will be numbered 1-6 in this thesis. The bridges are similar in equipment and structure with slight variations. Ideally, identical bridges would have been used to reduce outside factors from having an impact on results. However, ensuring the bridge used was the same for each test would have meant that just one pair at a time could perform the experiment; this was therefore ruled out.

Bridge 1, 2 and 3 are all very similar. Two projectors show the field of view from the perspective of the command bridge on a curved wall approximately two metres in front of the helmsman. The command module is equipped with a centrepiece containing dials and levers for the autopilot, radar screens—one on either side—and conning display. The bridges are also equipped with a lookout post and an ECDIS. The positions of these vary slightly in between the separate bridges. A steering wheel for manual steering is located in the middle of the command module. A TV screen is located at the opposite side of the curved wall, showing a stern view.

Bridge 4 has the same general setup as Bridge 1, 2 and 3. Bridge 4 does however lack a steering wheel, which means you must use a rotary lever to steer the vessel manually.

Bridge 5 is designed to work as a ferry simulator. Instead of projectors, two TV screens at either end of the bridge show a clear view in both directions. With the push of a button, you are able to change the defined forward direction of travel and the bridge is equipped with levers and dials at both ends for steering.

Bridge 6 is a bridge simulator designed as a Dynamic Positioning (DP) simulator. It is built with five TV screens placed to provide a 90 degrees field of view forward, and one screen behind to show a stern view. The conning display and binoculars are placed above the TV screens. The radar and ECDIS have a separate section on the starboard side. The DP operating station is on the port side. The main command module with steering wheel, dials and levers sits in the centre.

2.1.4 Students' Assignment

Five days prior to the experiment, the assignment was given to the participants. Maritime regulations put size and cargo restrictions on passage through Vatlestraumen (Sjøtrafikkforskriften 2015, § 128). Students were asked to disregard this in their planning. While this makes the assignment somewhat unrealistic, it increases the level of concentration and skill required to perform it successfully. Additionally, using the test vessel in confined waters it has no business going near was deemed a suitable stress test of the DSS.

The content of the assignment included information about two of the three vessels, learning objectives, learning goals and a small map of Vatlestraumen, where the exercise was to take place (see Figure 4). This is an area that the students were familiar with from previous simulator exercises. Also included in the assignment were the time and date so they would have the possibility of finding tide and current information. Initial data, coordinates for their starting position and an approximate last waypoint were also included.

Their initial position was $1.31nm$ due south of Hilleren lighthouse, and the vessel started with a speed of 16 knots at a heading of 000°. In Vatlestraumen, the current reverses with the tidal flow at high tide and low tide: north with rising and south with falling water. The time of the exercise was set to daytime with a southbound current of 1.5 knots. Since the exercise took place in full daylight, the navigational lights were set to light up brighter so the students could see them clearly and use them as navigational aids. Visibility was good. The scenario ran without wind; the details around that decision is discussed in Section 2.2.7 – Wind.

Figure 4. Map of Vatlestraumen and example track. Chart by (Kartverket 2003).

Prior to the day of the exercise, students were tasked with creating a description of Vatlestraumen using The Norwegian Pilot Guide. Using this source in conjunction with information gained from manoeuvring booklets and wheelhouse posters they were to:

- Plan how to secure the voyage using variable PI, Electronic Bearing Line (EBL) and Variable Range Marker (VRM) to find their wheel-over points.
- Create a passage plan with necessary information, including a simple-to-follow detailed list of instructions.

The goal for the students was to learn to navigate a large vessel in narrow water at high speed. Using a constant rate of turn technique, VRM, EBL and PI were to be used together with paper charts. Maintaining and controlling the position of the vessel and deciding the wheel-over point with a high level of accuracy was of utmost importance. Furthermore, they were to practice creating a pilot guide, learn to read and understand published pilot guides and put their manoeuvre test results into practice.

2.1.5 Experiment

Table 2. Vessel sequence for experiment.

Group A	Vessel 1	Vessel 2	Vessel 3	Vessel 2 DSS
Group B	Vessel 2 DSS	Vessel 1	Vessel 2	Vessel 3

Four runs through Vatlestraumen were planned, using two different sequences (see Table 2). Group A started by showing their passage plan and pilot guide to their instructor. If students had questions relating to the exercise, they could ask them at this point. They were then sent to their randomly assigned bridge simulator. After completion of their first run a debrief was held with the instructor. The debrief consisted of the students giving a brief summary of high and low points from their own performance. This process was repeated for run 2 and 3. After the debrief of run 3 the students were given a short presentation of the DSS. This included how the DSS was constructed, how it calculates the trajectory and the limitations of the system. It was emphasised that this was an offline system and that the calculated rudder commands were not to be treated as instructions cast in stone. It was also explained that if students were to initiate the manoeuvre at any point other than the decided wheel-over point, the rudder commands would be progressively less valid with increasing distance to the intended wheel-over point. They were further told that in calculating the trajectory, the assumption was made that the ship had travelled in a straight path from the starting position to the wheel-over point. Students were asked to follow the calculated commands from the DSS unless they deemed it unsafe to do so.

Finally, a paper sheet was handed out with the calculated rudder commands shown in Table 3. Prior to being sent to the bridges students had the possibility to ask questions about the presentation, the experiment or the calculated rudder commands.

Table 3. Calculated rudder commands given prior to experiment.

5° Port	Until you reach a heading of 327°
9° Starboard	Until you reach a heading of 330°
7° Port	Until the ROT is zero

Group B was given the same setup and procedure to complete their tasks as group A, apart from the change of order described in Table 2. They started the experiment by getting the presentation described above.

To preserve the integrity of the experiment, they were also asked not to speak about their experience with the DSS with classmates before the end of the day.

2.2 Decision Support System

The following section will focus on the creation and use of the DSS in its current form. Because this is a system created within a limited time span and by people with little prior knowledge of hydrodynamics, both limitations and assumptions have been made to reduce the workload. These will be examined in Section 2.2.1 – Limitations and Assumptions. Ship handling is hard and external forces add complexity. The DSS is motivated by this statement and is a suggested solution to this problem. It is important to note that this is a system built for the sole purpose of being able to test the hypothesis of this thesis and not made for real life applications. It is therefore not to be considered a finished product and was at no point during its creation intended to become one. The DSS in its current form is an expansion of an idea to test the limitations, possibilities and feasibility of this idea. The challenges posed by building a system for decision support of rudder angles made for real life application are far greater than what can be addressed within the scope of a bachelor thesis; this is therefore merely a dip to test the waters.

The DSS is built using the Marine systems simulator toolbox (Fossen and Perez 2004) in Simulink. The main working principle behind the DSS is to take the navigator's best estimation as to how a manoeuvre should be executed and plot the resulting ship trajectory taking weather and current into account. This can then be compared to a chart overlay and modifications can be made prior to execution of the actual manoeuvre. A simplified description of the DSS is shown in Figure 5.

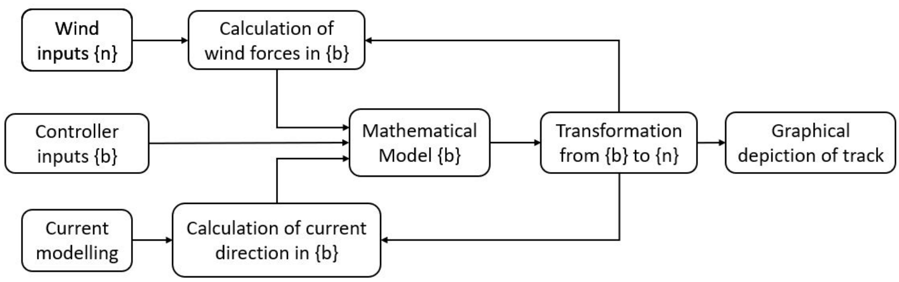


Figure 5. An overview of the Decision support system.

2.2.1 Limitations and Assumptions

The DSS was created, optimised and operated in tangent with the commercial simulator available at NTNU in Ålesund. Assuming that a simulator, however well built, is equal in realism to the real world is a hard sell to even the most ardent simulator enthusiast. It was however a necessity to make this assumption due to the practical impossibility of testing the DSS on actual ships. It would require both access to large tankers and would add a large amount of complexity to building the DSS as mentioned in Section 2.2 – Decision Support System.

The participants never used the decision support system by themselves but were given system output by the authors. The main reason for this was that in its current form, the DSS does not have a user interface. Neither creating a user interface nor teaching all the participants about the inner workings of the system was deemed feasible. It was therefore decided that one operator would use the DSS and present the knowledge gained by the system in an easy to understand and intuitive way. Rudder orders in the mathematical model are given at specific times counted from the wheel-over point. It is not considered normal procedure on a ship to count the seconds between events; this is therefore far from ideal because it would add another aspect to manoeuvring in restricted waters. However, the heading is kept track of continuously. On the basis of this, rudder orders were calculated as a rudder angle to be held until a certain heading was reached, upon which a new rudder order was to be given. The navigators participating in the test were provided with these rudder orders. This system was tested by both the authors and their peers in advance of the experiment and showed great success because it was both easy to follow and provided enough accuracy for the DSS to be effective in use.

Use of the system by the participants was made more difficult by the fact that the system was not permitted to interact with the commercial simulator in any way. The reasons for this are several and integration to some extent could have been possible. However, an application for such integration was deemed unlikely to be successful, and in any case the processing of an application would have taken time away from the testing that needed to be carried out. It was therefore decided to keep the two systems separated. This means that the DSS and the commercial simulator are two completely separate systems and that no real time updates can be shared between the two. Because of this, a few assumptions were made when it came to weather inputs.

Due to the separation of the two systems, wind and current being fed into the DSS did not originate from sensors on the ship. In a real life application, wind and current would be a combination of current table data, weather forecasts, sensor data and best estimations. During the experiments this was reduced to the authors trying to mimic real life currents and giving the same information to both commercial simulator and DSS. Wind was excluded from the experiment because of several issues with the calculation of wind forces and moments; these are discussed in Section 2.2.7 – Wind.

Another limitation of the DSS is that it uses Maneuvering Theory. This is ill suited for real life applications because it assumes zero wave excitation, something that is more of an exception than the norm in ship day-to-day operations. Maneuvering Theory will be described in detail in Section 2.2.4 – Mathematical Model and Seakeeping Theory is mentioned in Section 2.2.2 – The Classical Models of Naval Architecture.

Wind and current data is loaded into the DSS scenario by the navigator. For this experiment, this has been loaded in to the program by the same person creating the simulator scenario, meaning that actual weather conditions are the same as those loaded into the DSS.

2.2.2 The Classical Models of Naval Architecture

The classical models of naval architecture can be divided into two theories. These are Maneuvering Theory and Seakeeping Theory. Maneuvering Theory assumes that the hydrodynamic coefficients are *frequency independent* (no wave excitation) (Fossen 2011). Seakeeping theory can be used at zero or constant speed in waves where the hydrodynamic coefficients and wave forces are computed as a function of the wave excitation frequency using the hull geometry and mass distribution (Fossen 2011, p. 8). Simplified this means that:

Seakeeping Theory: Only calculates the forces and moments induced by waves but not other forces and moments.

Maneuvering Theory: Does *not* calculate forces and moments induced by waves. It considers control input forces and moments of a moving ship in calm water.

To create a system for path prediction using the classical models of naval architecture, one is compelled to use Maneuvering Theory. Seakeeping could only calculate the path of drifting objects. For simultaneous calculation of both wave and control input forces there are some newer methods such as Unified Theory (Fossen and Sagatun 1991) and Two-time Scale Method (Skejic and Faltinsen 2008).

2.2.3 Reference Frames

Motion is meaningless without a reference frame. Defining forces, speeds, accelerations and angles is absolutely crucial when calculating the movement of a ship. A car could not care less whether the wind force felt by the windshield was from the car moving through the air or gale force winds. When calculating the motion of a vessel it is often more convenient to express forces acting on the vessel in reference to a coordinate system with its origin moving with the vessel itself. For the purpose of this thesis, one Earth-centred coordinate frame and two geographic reference frames have been used. These are explained in greater detail by Fossen (2011), but a brief summary of his explanations will be given below.

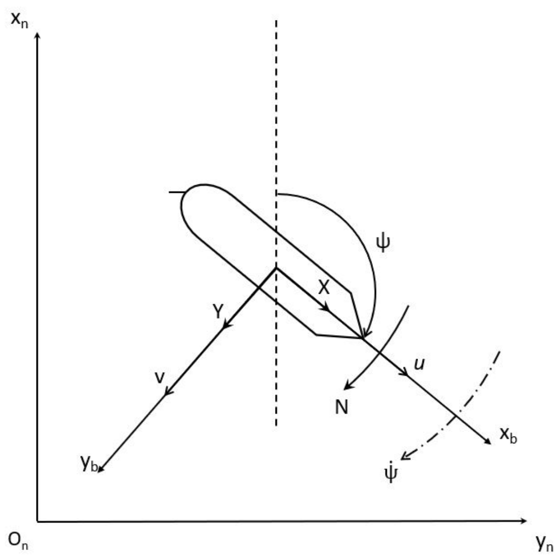


Figure 6. Forces, velocities and accelerations in $\{b\}$ frame with axis in $\{n\}$ frame shown in the bottom left.

ECEF: The Earth-centred Earth-fixed reference frame is rotating with the rotation of the earth. Its origin, as the name implies, lies at the centre of the Earth. For vessels moving at low speed this reference frame can be considered inertial, but for drifting vessels the rotation of the Earth must be considered. Coordinates in this reference frame are usually given as latitude and longitude; it is most commonly used in long distance navigation. Its sole use during the experiments was because data extracted from the commercial simulator needed transformation from the ECEF frame to a North-East-Down reference frame.

NED: The North-East-Down reference frame $\{n\} = (x_n, y_n, z_n)$, henceforth referred to as the $\{n\}$ frame, is the most intuitive reference frame and the most commonly used. The x-axis points toward north, y-axis toward east and the z-axis points toward the centre of the Earth. This is the same reference frame as one would use while looking at a common paper chart. For vessels operating within a local area the $\{n\}$ frame is sufficient for navigation. The origin usually travels with the vessel with $z_n = 0$ defined by a reference ellipsoid. For the purpose of this thesis the origin was chosen to coincide with the position of the wheel-over point used for the DSS trials.

BODY: The body-fixed reference frame $\{b\} = (x_b, y_b, z_b)$ has its origin at the vessel's centre of gravity and moves with the vessel. The $\{b\}$ frame is shown in Figure 6. Control forces are most commonly described in terms of the $\{b\}$ frame.

2.2.4 Mathematical Model

Nomenclature Section 2.2.4

X_b = Forces along the x-axis in $\{b\}$ frame $\left[\mathrm{kgm/s^2}\right]$	δ = Rudder angle [rad]
Y_n = Forces along the y-axis in $\{n\}$ frame $\left[\mathrm{kgm/s^2}\right]$	n = Shaft velocity [Rpm]
N = Moments around the z-axis $\left[\mathrm{kgm^2/s^2}\right]$	v = Sway speed [m/s]
I_z = Moment of inertia around the z-axis $\left[\mathrm{kgm^2}\right]$	u = Surge speed [m/s]
$\ddot{\psi}$ = Angular acceleration around the z-axis [rad/s^2]	$\dot{\psi} = r$ = Rate of turn [rad/s]
$\ddot{x}$ = The second time derivative of x = [m/s^2]	ψ = Heading [rad]
u_G = surge speed at vessels centre of gravity [m/s]	Δ = Diplacement of vessel [Kg]
V_t = Tangential velocity of circle [m/s]	$\otimes$ = Midship point
ω = Angular velocity of circle [rad/s]	β_w = True wind direction [rad]
γ_w = True wind direction with respect to true north [rad]	V_w = True wind speed [m/s]
γ_{rw} = Relative wind direction with respect to the bow [rad]	V_{rw} = Relative wind speed [m/s]

In this context, "mathematical model" is a set of equations describing the motion of a particular vessel. The aim of the mathematical model is to predict what motions external forces create on the vessel it describes. Several approaches to building a mathematical model exist. Because of the authors' limited knowledge of hydrodynamics prior to starting this bachelor thesis, it was decided to use an existing mathematical model and alter it in ways so as to describe the movement of a vessel available in the commercial simulator. This process is described in greater detail in Section 2.2.5 – Parameter Optimisation. The following part of this section will describe how Newtons second law can be applied to calculate the accelerations of a vessel and therefore its position. This will be explained in 11 steps following the explanation of Lewis (1989, p.193)

Step 1: Newton's Second Law (forces in the $\{n\}$ frame).

Because the $\{n\}$ frame is considered inertial, Newton's second law of motion $F = ma$ can be applied. The motions of a ship in three degrees of freedom (3 DOF) in the $\{n\}$ frame can therefore be described by the following equations:

$$\begin{aligned} X_n &= \Delta \ddot{x}_n \\ Y_n &= \Delta \ddot{y}_n \\ N &= I_z \ddot{\psi} \end{aligned} \tag{2}$$

Where: X_n and Y_n = Total forces in the x and y direction in $\{n\}$ frame
N = Total moment around the z-axis
Δ = displacement of the vessel
I_z = Moment of inertia around the z-axis
$\ddot{\psi}$ = The second time derivative of vessel heading.
The two dots over x,y and ψ indicate that it is the second time derivative of the symbol with respect to time. If the unit of x is metres then $\dot{x} = m/s$ and $\ddot{x} = m/s^2$.

Step 2: Transformation between $\{b\}$ and $\{n\}$ frame.

Equation 2 looks simple, but once one starts calculating it soon becomes apparent that it is of great inconvenience to describe the motions of a vessel in terms of the $\{n\}$ frame. Conversion between $\{n\}$ frame and $\{b\}$ frame is done using rotation matrices. Equation 3 uses the heading of the vessel ψ to transform back and forth between $\{n\}$ and $\{b\}$ frame in the following manner:

$$\begin{bmatrix} X_n \\ Y_n \end{bmatrix} = \begin{bmatrix} \cos\psi & -\sin\psi \\ \sin\psi & \cos\psi \end{bmatrix} \begin{bmatrix} X_b \\ Y_b \end{bmatrix} \tag{3a}$$

$$\begin{bmatrix} X_b \\ Y_b \end{bmatrix} = \begin{bmatrix} \cos\psi & \sin\psi \\ -\sin\psi & \cos\psi \end{bmatrix} \begin{bmatrix} X_n \\ Y_n \end{bmatrix} \tag{3b}$$

Step 3: Velocity in $\{n\}$ frame as a function of motion in $\{b\}$ frame.

Transformation between frames for position, velocity and acceleration work the same way. In Equation 4, velocity in the $\{n\}$ frame is described as a function of velocity in the $\{b\}$ frame.

$$\begin{aligned} \dot{x}_n &= u\cos\psi - v\sin\psi \\ \dot{y}_n &= u\sin\psi + v\cos\psi \end{aligned} \tag{4}$$

Where $\dot{x}$ and $\dot{y}$ are the first time derivatives of position in $\{n\}$ frame and u and v are surge and sway speeds in $\{b\}$ frame.

Step 4: Acceleration in $\{n\}$ frame as a function of motion in $\{b\}$ frame.

By differentiating Equation 4 with respect to time, $\ddot{x}$ and $\ddot{y}$ become:

$$\begin{aligned} \ddot{x}_n &= \dot{u}\cos\psi - \dot{v}\sin\psi - (u\sin\psi + v\cos\psi)\dot{\psi} \\ \ddot{y}_n &= \dot{u}\sin\psi + \dot{v}\cos\psi + (u\cos\psi - v\sin\psi)\dot{\psi} \end{aligned} \tag{5}$$

Step 5: Forces in $\{n\}$ frame as a function of motion in $\{b\}$ frame.

By inserting Equation 5 into Equation 2, a new expression for X_n and Y_n emerges:

$$
\begin{aligned}
X_n &= \Delta\dot{u}\cos\psi - \Delta\dot{v}\sin\psi + \Delta(-u\sin\psi - v\cos\psi)\dot{\psi} \\
Y_n &= \Delta\dot{u}\sin\psi + \Delta\dot{v}\cos\psi + \Delta(u\cos\psi - v\sin\psi)\dot{\psi}
\end{aligned}
\tag{6}
$$

Step 6: Transformation of forces from $\{n\}$ to $\{b\}$ frame.

Equation 6 can now be put into the rotation matrix described in Equation 3b and simplified in the following steps for forces in the X direction:

$$
\begin{aligned}
X_b &= [\Delta\dot{u}\cos\psi - \Delta\dot{v}\sin\psi + \Delta(-u\sin\psi - v\cos\psi)\dot{\psi}]\cos\psi + [\Delta\dot{u}\sin\psi + \Delta\dot{v}\cos\psi + \Delta(u\cos\psi - v\sin\psi)\dot{\psi}]\sin\psi \\
X_b &= \Delta\left[\dot{u}\cos^2\psi - \dot{v}\sin\psi\cos\psi + \left(-u\sin\psi\cos\psi - v\cos^2\psi\right)\dot{\psi} + \dot{u}\sin^2\psi + \dot{v}\cos\psi\sin\psi + \left(u\cos\psi\sin\psi - v\sin^2\psi\right)\dot{\psi}\right] \\
X_b &= \Delta\left\{\dot{u}\left(\cos^2\psi + \sin^2\psi\right) - \dot{v}\sin\psi\cos\psi + \dot{v}\cos\psi\sin\psi + \left[-u\sin\psi\cos\psi + u\cos\psi\sin\psi - v\left(\cos^2\psi + \sin^2\psi\right)\right]\dot{\psi}\right\} \\
X_b &= \Delta(\dot{u} - v\dot{\psi})
\end{aligned}
\tag{7}
$$

Step 7: Forces as function of motions, all in $\{b\}$ frame.

The same can be done for Y Forces. Moments around the z-axis go unchanged. This results in the following rewriting of $F = ma$ for forces in the $\{b\}$ frame:

$$
\begin{aligned}
X &= \Delta(\dot{u} - v\dot{\psi}) \\
Y &= \Delta(\dot{v} + u\dot{\psi}) \\
N &= I_z\ddot{\psi}
\end{aligned}
\tag{8}
$$

Step 8: Transformation of speeds from centre of gravity to midships.

It is often more convenient when calculating forces to have the origin of the $\{b\}$ frame midships ($\otimes$) than in the centre of gravity (G). This has little to say for surge speed; vectors can be moved along their path with no effect. This is not the case for sway speed and angular velocity. The formula for tangential velocity, $V_t = r\omega$, can be applied. The distance between $\otimes$ and G, x_G, represents r. The angular velocity on a vessel is the first time derivative of the ships heading ψ. ω is therefore replaced with $\dot{\psi}$. Any sway speed the ship experiences needs to be accounted for as well. The full equations for surge and sway transformation look like this:

$$
u_{\otimes} = u_G, \quad v_{\otimes} = v_G + x_G\dot{\psi}
\tag{9}
$$

For simplicity, $u_{\otimes} = u$ and $v_{\otimes} = v$ from this point onward.

Step 9: The right hand side of the force equations in $\{b\}$ frame at midships.

Substituting these new values for surge and sway into Equation 8 we get our final equations of motion:

$$
\begin{aligned}
X &= m\left(\dot{u} - vr - x_G r^2\right) \\
Y &= m\left(\dot{v} + ur + x_G\dot{r}\right) \\
N &= I_z\dot{r} + m x_G(\dot{v} + ur)
\end{aligned}
\tag{10}
$$

Keep in mind that $\dot{\psi} = r$. A similar process is done for moments and is described in greater detail by Zaojian (2006)

From Equation 10, van Berlekom, Goddard, and The Society of Naval Architects and Marine Engineers (1972) describe how the mathematical model is created. It is incorporated into Matlab by Trygve Laudal (see Appendix C.3 – Mathematical Model). A short description will however be given here as well. The initial state vector is a list of values that the simulation is given as starting conditions. The output from the mathematical model is a time derivative of the initial state vector and therefore needs to be integrated before it is fed into the model as simulation step two. The initial state vector for this mathematical model is given in Equation 11

$$x = [u\ v\ \dot{\psi}\ x_n\ y_n\ \psi\ \delta\ n] \tag{11}$$

where:
u = surge
v = sway
$\dot{\psi}$ = first time derivative of ψ
x_n = position along the x axis in $\{n\}$ frame
y_n = position along the y axis in $\{n\}$ frame
ψ = heading
δ = rudder angle
n = propeller shaft rotation in revolutions per minute.

Step 10: Giving the forces a mathematical expression.

The hydrodynamic and control surface forces in the model can be described by Equation 12:

$$\begin{aligned} X &= F_x(\dot{u}, \dot{v}, \dot{\psi}, \delta, n) \\ Y &= F_y(\dot{u}, \dot{v}, \dot{\psi}, \delta, n) \\ N &= F_N(\dot{u}, \dot{v}, \dot{\psi}, \delta, n) \end{aligned} \tag{12}$$

To give the left hand side of Equation 10 a mathematical expression a method developed by Abkowitz (1964) is used. Abkowitz suggested using Taylor Series to model the forces and moments acting on a ship. The resulting hydrodynamic derivatives are then added in the following fashion to calculate the overall forces in X, Y and N. Below, there is an example of forces in the X direction in $\{b\}$ frame with respect to surge speed:

$$F_x(u) = X_0 + X_u \Delta u + \frac{1}{2} X_{uu} \Delta u^2 + \frac{1}{6} X_{uuu} \Delta u^3 \tag{13}$$

Where: X_0 = The initial forces in the X direction, $\Delta u = u_1 - u_0$, $Xu = \frac{\partial X}{\partial u}$, $Xuu = \frac{\partial^2 X}{\partial u^2}$, $Xuuu = \frac{\partial^3 X}{\partial u^3}$.

Step 11: The model.

Added mass is a force felt by the hull of a vessel moving through a liquid. This force comes from the fact that the vessel is not moving through a vacuum and therefore needs to clear a path through the medium in order to progress forward. In everyday language, words like aerodynamic and hydrodynamic often refer to the magnitude of the added mass. If an object is streamlined, less matter needs to be moved away from the path to be replaced by the object. By making the object streamlined, m in Newton's second law is reduced and therefore less force is needed to accelerate the object. In the case of naval architecture, this is often denoted $X\dot{u}$, $Y\dot{v}$ and $N\dot{r}$ for surge, sway and yaw respectively. A square box of volume V would have more added mass in the surge direction than a torpedo shaped object of the same volume. With this extra component of mass in the equations, the second time derivative of u (acceleration) in the surge direction is calculated using Equation 14:

$$\frac{F_x(u, v, \psi, \delta, n)}{(\Delta - X\dot{u})} = \dot{u} \tag{14}$$

2.2.5 Parameter Optimisation

The mathematical model used in the DSS was built for a vessel similar in shape to the one chosen for experiments but not equal in manoeuvring characteristics. The need for optimisation becomes apparent when comparing tracks from the unmodified model and the commercial simulator for a 35° turning circle to port (see Figure 8 on page 28). Optimisation was carried out in three steps. These will be explained in greater detail below. One of the great problems with not calculating the forces but using data science to optimise against a cost function arises when wind forces are added into the mathematical model. In the model prior to optimisation, hydrodynamic derivatives are calculated after model tests (van Berlekom, Goddard, and The Society of Naval Architects and Marine Engineers 1972). These forces are then plotted as a function of acceleration in its respective degree of freedom in a process better described in 2.2.4 – Mathematical Models. In optimisation, the process is somewhat reversed. Data of accelerations in three degrees of freedom were gathered from the commercial simulator and these were then matched to accelerations calculated by the DSS. When changing the hydrodynamic derivatives described in Equation 13, careful consideration needs to be taken to make sure that both mass and added mass are given their correct values with respect to the Bis System described by Norrbin (1970). A lack of data about the vessel meant that added masses could not be calculated. This means that in theory, and with high probability in this case, the model is able to describe the movements of the vessel because the product of the equations for acceleration still yield the correct result. It is however difficult to know if m in the equation $a = \frac{F}{m}$ is given a correct value, or has just been scaled in such a way that it accurately predicts the motion of the commercial simulator.

Step 1: Gathering data from the commercial simulator.

Gathering data on the manoeuvrability of Vessel 2 was done in sea trials in a simulator. Because the simulator is constructed in such a way as to give the user full control of weather, the sea trials could be done under somewhat unrealistic conditions to the authors' benefit. Trials were conducted in an open environment with a water depth of 200 m and with no current, wind or waves. The vessel started at equilibrium with all values of the initial state vector being equal to zero, apart from surge being equal to speed over ground and shaft velocity being equal to 74 rpm. In the list of trials (Table 4), this is true unless otherwise stated. The following manoeuvre trials were carried out:

Table 4. Manoeuvre test performed for parameter estimation.

Coasting stop 1	Shaft speed set to zero
Coasting stop 2	Standard setup
Crash stop	Standard setup
Turning circles	Rudder angles ranging from 5°–35° in 5° intervals.
Zigzag test	Both 10°/10° and 20°/20° tests

Position, accelerations and both linear and angular velocities were logged. Manoeuvre trials are described in more detail in Section 2.1.2 – Manoeuvre Tests Using Desktop Simulators.

While it would not have been possible to perform the coasting stop with zero shaft velocity in reality, it did help in estimating the parameters, since for this particular test propeller forces could be excluded. Optimisation was therefore started with the estimation against coasting stop 1, and once trajectories and velocities matched those of the simulator trials proceeded to coasting stop 2. In the second round of estimation only forces concerning propeller forces were altered. The third step in the process estimated rudder forces using data gathered from turning circle trials. In these tests hydrodynamic derivatives modelling rudder forces were estimated. The final fit between the DSS and the simulator was done on the zigzag tests. Here all parameters were estimated again, but harsh limits on the deviation from previous estimations were used.

Step 2: Using Monte Carlo Simulation to narrow down the search.

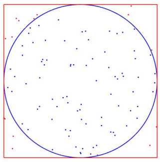
Before step two can be explained, Monte Carlo Simulations need a proper introduction. A useful experiment is to estimate the value of π using a dartboard. The first step is to put a frame around the dartboard so that the square created is tangent to the circle on all four sides. The area of the dartboard is $\pi \times r^2$ and the area of the square is $(2r)^2$, making the ratio of circle to square $\frac{\pi}{4}$. Throwing darts at random, the ratio between darts inside the circle to darts outside it would be equal to the ratio of area within the circle to area outside it, giving us the equation $\frac{\pi}{4} = \frac{Number\ of hits\ inside\ the\ circle}{Total\ number\ of\ throws}$. Any darts hitting outside both circle and square are disregarded and not counted as thrown. Solving this equation with respect to pi gives: $\pi = 4 \times \frac{N_{inside}}{N_{total}}$. The first throw will be either a hit or a miss. This would make the estimated value of π either 0 or 4. With increasing number of throws, or iterations, the estimated value would slowly get closer to the actual value of π. This process is illustrated for an increasing number of iterations in Figure 7. Figure 7e shows that the error in calculating π using this method is close to zero after 400,000 iterations.

In the example above, the darts have an equal chance of hitting any point within the square and thus follow a uniform distribution. For this thesis, values for the hydrodynamic derivatives followed a normal distribution. Values for 1 σ were set by taking values from two other vessels. Both were supertankers with one being slightly smaller and one slightly larger than the vessel for which the model was being optimised. If for example the derivative Yvv were to be optimised, the values for Yvv for ship 1 and ship 2 would be set as -1σ and 1σ respectively. For any randomly generated numeric value for Yvv there would be a 68% chance of it being within this range. One hundred and fifty randomly generated numbers were created and the simulation was run with each value. The resulting sway speeds of these simulations were compared to the logged sway speed from the commercial simulator trials described in Table 4. To evaluate the size of the error a cost function needs to be used. In the example above the cost function would be π - estimated value of π, but for optimisation of the mathematical model Mean Square Error (MSE) was used (see Equation 15).

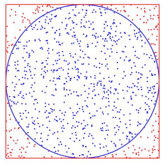
$$\frac{1}{n} \sum_{i=1}^{n} \left(Y_i - \hat{Y}_i \right)^2 \tag{15}$$

Where n is the number of iterations, Y_i is the speed or acceleration values gathered from the commercial simulator and $\hat{Y}_i$ is the values of the same parameter calculated by the DSS.

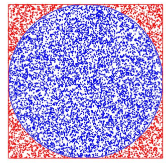
Whenever more than one derivative is optimised at the same time, the list of random numeric values is put together in random order. This process was repeated for all hydrodynamic derivatives in the model with careful consideration taken to keep values within a reasonable limit. In the mathematical modelling done in Simulink, $(\Delta - X\dot{u})$ (see Equation 14 on page 25) is referred to as "$m11$". In the Bis System, displacements for semi submerged vessels are always converted to



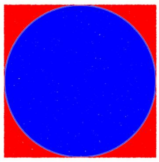
(a) N = 100. π = 3.4000.



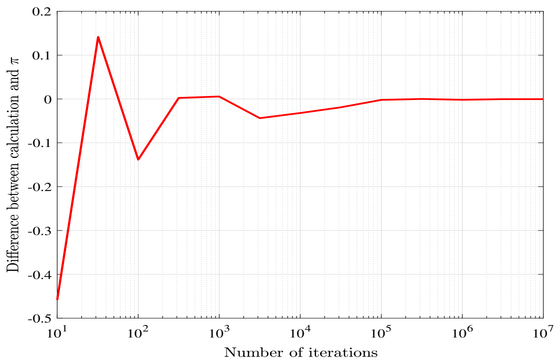
(b) N = 1000. π = 3.1760.



(c) N = 10,000. π = 3.1516.



(d) N = 100,000. π = 3.1476.



(e) Error in value of π with increasing number of iterations.

Figure 7. Values of π with increasing number of iterations N.

1 (Fossen 2011, p.149). The value of $m11$ is calculated by subtracting the added mass component of surge, $X\dot{u}$, from the nondimentionalized displacement, Δ. Because $X\dot{u}$ is a negative, small number, $m11$ will have a value close to 1 but not smaller than 1. Consideration was therefore taken to keep $m11$ within reasonable limits.

Step 2 also gives information about how sensitive speeds in their respective degree of freedom are to changes in hydrodynamic derivatives. Yvv is a negative number and it is reasonable that the vessel would encounter a large amount of resistance from being pushed sideways through the water. This means that Yvv is a large number and sway speeds would be very sensitive to changes in this particular derivative. Unfortunately, it is not always obvious what derivatives reduce the radius of a turning circle without reducing surge speed.

Step 3: Fine-tuning of hydrodynamic derivatives.

The last step of optimisation was done in a somewhat crude manner. Part of the optimisation was to match the trajectory from a turning circle between the DSS and a commercial simulator. Optimisation for trials with no use of the rudder had been done before and gave satisfactory results, thus it could be assumed that most of the derivatives that did not account for rudder forces were somewhat accurate. The focus then became changing the derivatives that did account for rudder forces.

$Nccd$ calculates Yaw moment with respect to water flow over the rudder c^2 and rudder angle δ_r. The numeric value of $Nccd$ would start at the best estimate from step 2; then be changed in tandem with changes in other derivatives that control rudder forces. Again mean square error is used to track the difference between logged values and values from the DSS. It is important to note that it is not the position X_n and Y_n that are compared, but $\dot{\psi}$, u and v. This process continues for as many iterations as are needed to give a satisfactory result. Whenever fine-tuning needs to be done within a limited amount of time, the greatest enemy of progress can often be perfection. For this

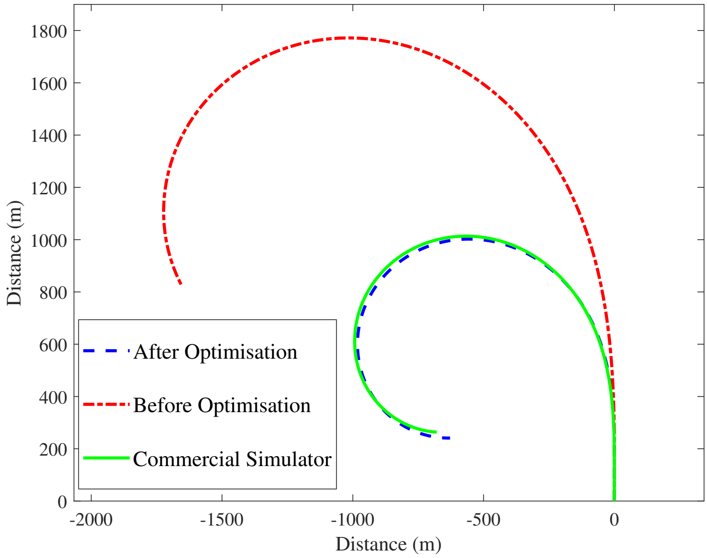


Figure 8. Comparison of turning circles to port post and prior of optimisation.

thesis, a deviation in position by 15 metres and heading by 5° is equal to a position error at the bow by 28 metres. It would be exceptionally poor seamanship to plan a voyage in coastal waters such that a position of the ship being off by 28 metres could spell disaster; this was therefore accepted as a negligible error for inland waters.

2.2.6 Current

Tidal currents change in direction and intensity with the topography of the seabed. In straits and fjords, the current is confined to travel parallel to land and changes with high and low tide (Kjerstad 2017). Because of this, the DSS needed to be able to accept different current inputs with changing positions. This was solved by adding a program that took in coordinates for rectangular boxes and created a specific current direction and velocity. This differs from the method of input in the simulator where a polygon is created and specific weather is added into this polygon. For the case of current, this is done by adding vectors of specific lengths and directions. If several vectors are added into the polygon, the program interpolates between them and current therefore seamlessly changes between vectors. In the DSS, the current is divided into its north and east components with southerly and westerly current given as negatives. Lastly, the current is converted into body frame and given as input to the mathematical model as components of surge and sway speed. This is subtracted from the surge and sway speed of the vessel and converted into relative surge and sway speed. This is described graphically in Figure 9.

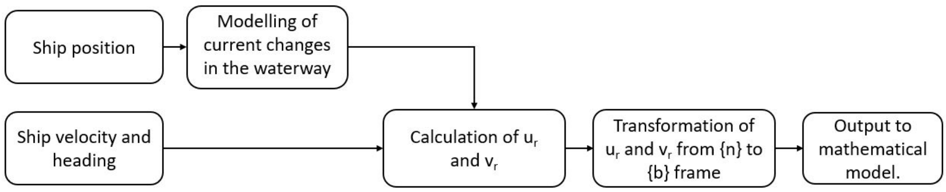


Figure 9. Expansion of current calculations in the DSS.

2.2.7 Wind

A graphical description of how wind is included in the DSS is shown in Figure 11. The definition of wind is the horizontal movement of air over the surface of earth. The direction is defined as the opposite of the direction the air travels. This can be illustrated by dropping a plastic bag and letting it drift with the wind. The direction opposite to the direction the bag travels is said to be the wind direction. Kjerstad (2017) write that because wind direction is irregular, it is common to measure the mean direction over a period of 10 minutes. Input into the simulator is given as a direction between 0-360 degrees and the value then fluctuates around that value by plus or minus 10 degrees. Because of limitations in time, a function such as this has not been built into the DSS in its current form. True wind direction is instead given as a constant input.

Two things need to be known to calculate the force of wind felt on a vessel at any given time. The first is the relative wind speed and direction with respect to the bow, V_{rw} and γ_{rw} respectively. A graphical depiction of wind angles are shown in Figure 10. The second is the wind coefficients. The equation to calculate forces from wind found in most physics textbooks is $F = \frac{1}{2} \times \rho \times v^2 \times A \times C$, where F is the force, ρ is the density of wind, v is the *relative* velocity of wind, A is the projected area affected by wind and C is a dimensionless drag coefficient. The wind coefficients are calculated by tools found in the MSS Toolbox. These are programs made based on research done by Isherwood (1972) and Blendermann (1994). Both are briefly described in Section 1.2.4 – Hydrodynamic Models. The code for both Blendermann and Isherwood can be found in Appendix C.1 – Wind.

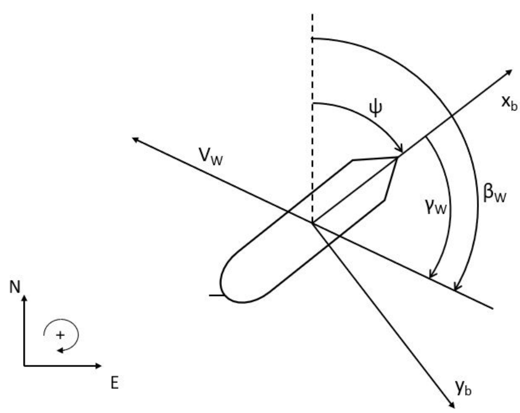


Figure 10. Graphical description of wind angle of attack, γ_W relative to the bow, wind direction β_W and wind speed V_W.

Calculation of relative wind speedV_{rw} and relative wind angle γ_{rw} is done in the three boxes to the left in Figure 11. Heading ψ, ship speed through water U, V_w and β_w are used to calculate the relative wind direction in $\{n\}$ frame using Equation 16.

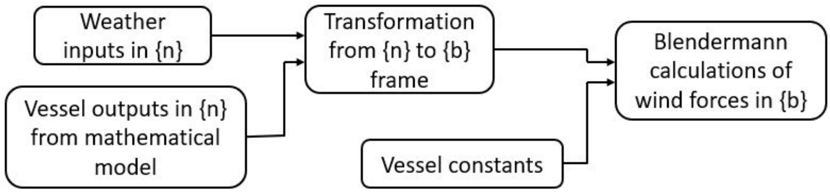


Figure 11. Expansion of wind calculations in the DSS.

$$\beta_{rw} = \text{arctan}\,2\left(\begin{bmatrix} \sin\beta_w * V_w + \sin\psi * U \\ \cos\beta_w * V_w + \cos\psi * U \end{bmatrix}\right) \tag{16}$$

Relative wind speed and angle is then calculated using Equation 17 and Equation 18

$$V_{rw} = \sqrt{(\sin\beta_w * V_w + \sin\psi * U)^2 + (\cos\beta_w * V_w + \cos\psi * U)^2} \tag{17}$$

$$\gamma_{rw} = |\psi - \beta_{rw}| \tag{18}$$

Wind was built into the DSS, but the decision to exclude it from the experiments was made for two reasons. The manoeuvring booklet provided by the commercial simulator includes wind forces and moments. When comparing the forces and moments from this document with forces calculated using the formulas of Isherwood and Blendermann, the moments from the manoeuvring booklet were an order of magnitude greater than those calculated using MSS. Great care was taken to make sure that both inputs were correct and units were equal to those stated in the manoeuvring booklet. The differences in wind moments can be seen in Figure 12.

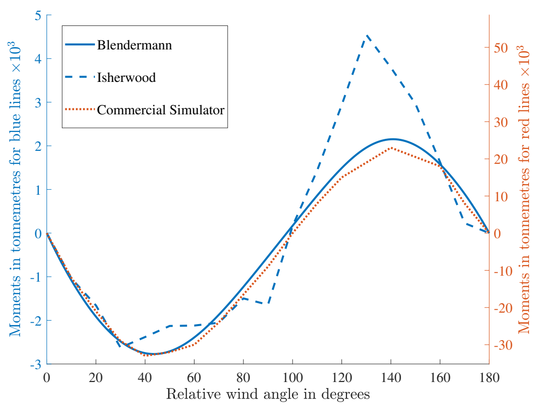


Figure 12. Wind moments calculated using Blendermann and Isherwood compared to moments taken directly from the manoeuvring booklet. Blue lines uses the left y-axis and red lines the right y-axis.

Comparing the general shape of the graphs given by the commercial simulator and by Blendermann, seen in Figure 12, it is likely that they use his method to calculate wind coefficients. It is, however, unlikely that the moments and forces given in the manoeuvring booklet are the same as those used by the simulator. Because the simulator acts as a black box for the authors of this thesis, extensive testing would need to be carried out to find out if the size of wind forces and moments are realistic. Because of this, it could not be confirmed that the effects of wind were realistic enough for them to be accurately predicted by well-established formulas.

The second reason wind was excluded from the experiment had to do with the lever arm at which forces create a moment around the centre of rotation. Blendermann (1994) defines the Yawing-moment arm lever as a distance X_F away from the centre of gravity. He shows that this distance will vary with different angles of attack and the general shape of the vessel. However, this only calculates the distance between the centre of gravity and the point of attack. This is *not* synonymous with the Yawing-moment lever arm in *any* case but for one. A ship that is dead in the water with no trim and has no forces or accelerations acting on it will pivot around its centre of gravity.

According to Rowe and Nautical Institute (2000) the lever arm should be calculated from the centre of effort of wind and the *apparent* pivot point. Recent studies into the nature of the pivot point emphasise that this is to be considered more of a cause than a consequence. The pivot point is not the lever arm of anything. Seo (2017) brings up some common misconceptions about the pivot point.

- *It moves toward the bow or toward the stern with surge motion.*
  This is not the case and disproved by both Seo (2017) and Capt. Cauvier (2008).
- *It is the centre of rotation.*
  The pivot point is an imaginary point. In a famous example two tugs are fastened to the stern and bow respectively. With stern movement of the vessel the proper explanation is that the *centre of lateral resistance* moves about 10% of the ships length toward the stern and the ship starts turning to starboard. This turning makes the pivot point appear to be 1/4 of the ships length toward the stern when in reality it is still very close to midships (Capt. Cauvier 2008).
- *The pivot point is the fulcrum of the turning moment.*
  It is not a physical entity and thus is *not* the point from which lever arms should be calculated (Seo 2017).

For wind forces to be seamlessly fed into a mathematical model, the lever arm needs to be properly calculated. No formula to calculate the position of the centre of lateral resistance was found and solutions to this problem in Dynamic Positioning systems or simulators could not be obtained.

How and whether this problem has been solved in simulators and DP systems is still uncertain. For the latter case, this would make no noticeable difference as velocities are generally low and forces not accounted for are dealt with by the Kalman filter. In the case of simulators, testing would need to be carried out. This was deemed too time consuming and together with the fact that the simulator works as a black box for the authors, it was decided to drop wind from the experiments.

2.3 Method of Analysis

Data gathered from the experiment was sorted on the basis of a pass or fail criteria. A vessel that had no contact with either land, navigational marks or the seabed was registered as pass.

For evaluating the relationship between two categorical, nominal values, Marshall and Boggis (2016) suggests a χ^2-test. Four of these were carried out with the null hypothesis that there would be no significant change in results with the DSS being introduced early in the experiment. The results of these tests are shown in Section 3.2 – Statistical analysis. Calculations of p-values and the raw data from the experiment are presented in appendix B.

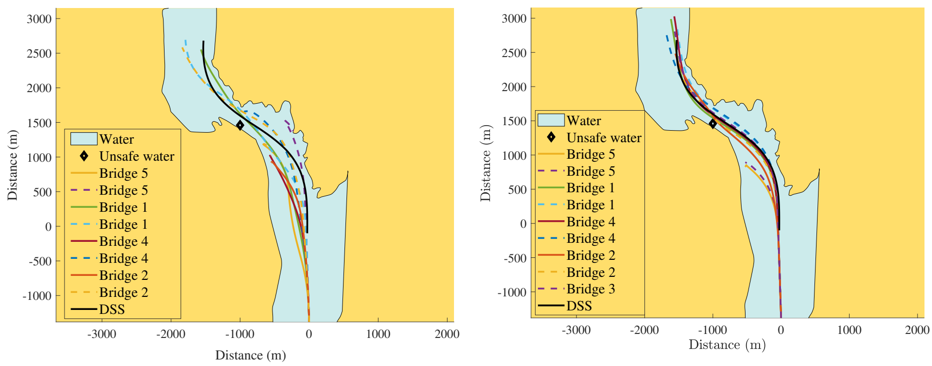
3 Results

3.1 Overview

During this study, one experiment was carried out with the purpose of proving the hypothesis that the DSS increases navigational safety. The results gathered during this experiment will be presented in the sections below.

3.1.1 Track Graphs

Figures 13 and 14 show tracks made by the participants during the experiment. It should be noted that some of the runs that appear to have passed through Vatlestraumen have made contact with the seabed. This fact comes out poorly in graphs showing just tracks but they are counted as failed attempts in the statistical analysis.



(a) Group A without DSS assistance. (b) Group A with DSS assistance.

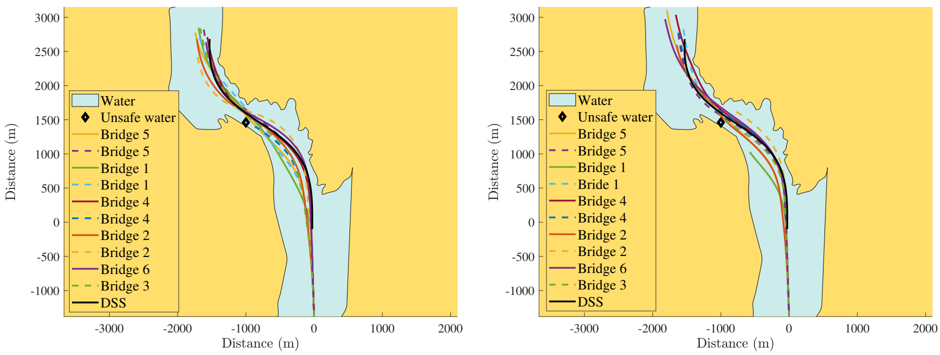
Figure 13. Tracks from Group A. The black track is the predicted track obtained using the suggested rudder commands from the DSS.

Group A:

Group A were first taken through the exercise with Vessel 1 from Table 1 on page 10 and later tried an unassisted attempt with Vessel 2, making it their second run at the Vatlestraumen passage that day. The tracks from these runs with Vessel 2 are shown in Figure 13a. They proceeded to do the exercise with Vessel 3 before their final attempt with Vessel 2, which was with the assistance of the DSS. The tracks for these runs are shown in Figure 13b.

Group B:

Group B started the experiment with a passage through Vatlestraumen assisted by the DSS using Vessel 2. This is shown in Figure 14b. They proceeded with Vessel 1 followed by an unassisted attempt with Vessel 2. Tracks from these runs are shown in Figure 14a. The last run was with Vessel 3.

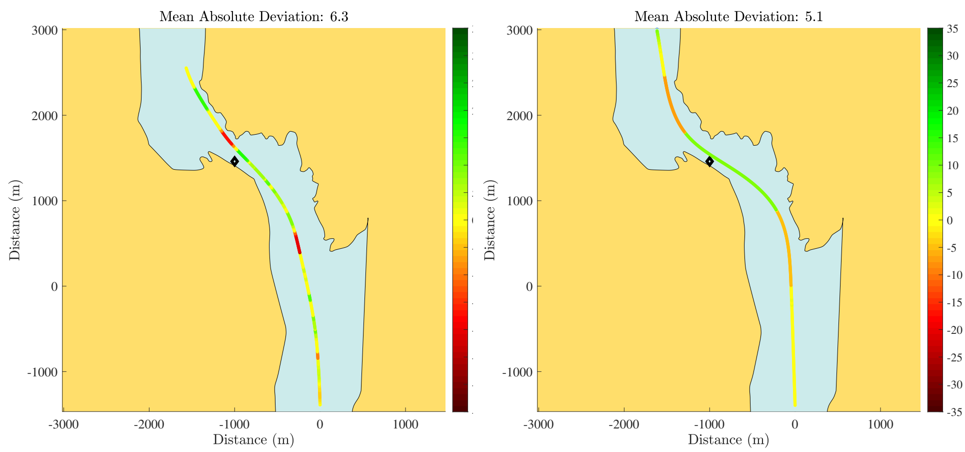


(a) Group B without DSS assistance. (b) Group B with DSS assistance.

Figure 14. Tracks from Group B. The black track is the predicted track obtained using the suggested rudder commands from the DSS.

3.1.2 Rudder Graphs

Figure 15 shows the tracks of an individual run during the experiment. The track is colour coded to indicate rudder angles used at all points throughout the run.



(a) Rudder angles without DSS assistance. (b) Rudder angles with DSS assistance.

Figure 15. Rudder angles for a single pair of participants with and without the DSS.

To add a numerical value to what is shown in colours in Figure 15, Mean Absolute Deviation (MAD) was applied. This takes the mean rudder angle for an individual run and compares it to the rudder angle given at any time during the run. Some bridges ran aground and left the rudder at a steep rudder angle. A limit to the data points counted was set to whenever the speed dropped below 8 knots. This method applied to a zigzag test would give a value close to zero. Counter rudder and rudder would be of equal size and applied for approximately equal time.

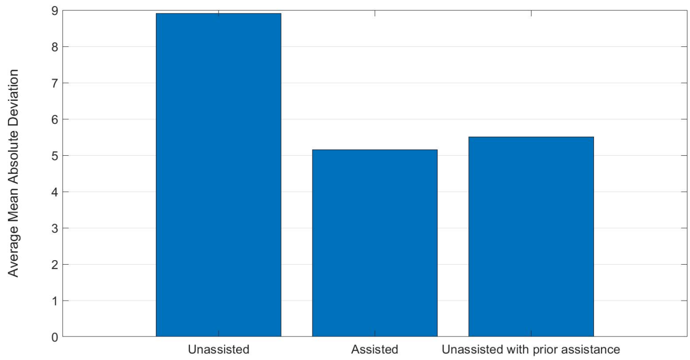


Figure 16. Comparison of Mean Absolute Deviation of different types of runs.

3.2 Statistical Analysis

Statistical analysis was carried out on the results from the experiments. Logged data from experiments show some vessels hitting sand bottom. This occurs at a position marked out by a diamond in rudder graphs from the experiment. Because of this, some of the vessels that appear to pass the exercise in the graphs in Section 3.1.1 – Track graphs are counted as failed attempts for the purpose of statistical analysis. P-values were calculated using χ^2 statistics for different data sets. The main results of the analysis are presented below, but they are shown in full in Appendix B – Statistical Analysis. The Null hypothesis is that there is no significant change in results whether the DSS was used in the first or second Vessel 2 run.

Results for all vessels: The null hypothesis is that there is no significant change in results whether the DSS was used in the first or second Vessel 2 run, at $p < .05$.

χ^2 (2, N = 74) = 0.5572, p = 0.4554

Results for Vessel 2 & DSS runs only: The null hypothesis is that there is no significant change in results whether the DSS was used in the first or second Vessel 2 run, at $p < .05$.

χ^2 (2, N = 38) = 3.7021, p = 0.0543

Results for all vessels except DSS: The null hypothesis is that there is no significant change in results whether the DSS was used in the first or second Vessel 2 run, at $p < .05$.

χ^2 (2, N = 55) = 0.5562, p = 0.4558

Results for all vessels except Vessel 2: The null hypothesis is that there is no significant change in results whether the DSS was used in the first or second Vessel 2 run, at $p < .05$.

χ^2 (2, N = 37) = 0.5787, p = 0.4468

4 Discussion

It is mentioned in the introduction that all known current systems for path prediction are largely reactive. A perfectly planned track in a chart machine gives little help to a person not familiar with the manoeuvring characteristics of the particular vessel. This problem is to a certain extent solved in Dynamic Positioning systems by removing control from the navigator. This thesis is an attempt to create a system that transforms the navigator's desired path into a set of suggested rudder commands. The idea is to leave the planning in the hands of the navigator and help him in executing manoeuvres.

The discussion section is divided up into three parts. The first part discusses the results from the experiment performed. The second part is an attempt at identifying factors that might to some extent invalidate the results obtained from said experiment. The last part is the authors' suggestions for further research and development.

4.1 Results

During this study, one experiment was carried out, with the purpose of proving the hypothesis that the DSS increases navigational safety. Results from the experiment carried out show promising results, but statistical analysis shows that further experiments are needed in order for these results to be statistically significant.

To keep this section organised and clear, a division had to be made. For the sake of simplicity, the subdivisions were organised so that it is possible to see the results for individual parts.

4.1.1 Track Graphs

Defining a good manoeuvre might seem like a straightforward task at first, but how a good manoeuvre is defined differs significantly between navigators. Instead of trying to define an optimal trajectory in the form of some number or quantifiable value, the decision was made to show the tracks and let the readers decide for themselves. In this section, the authors present their interpretation of these graphs with respect to the hypothesis.

Looking at the graphs in Figures 13 and 14, things appear very promising for the use of a DSS in navigation in restricted waters. When the participants tried the run without the help of the DSS, several failed to find an appropriate WOP. As a result of starting their turn too early or too late, they quickly left the centre of the channel. Those who did not spot the danger in time to make corrective measures ended up running aground. In contrast, when the participants tested with the help of the DSS, more of them were close to the predicted track that the DSS had proposed and fewer ran aground.

In Figure 14, the unassisted and assisted attempts at first glance show similar results. At closer analysis some of the attempts with DSS hit sand bottom. This is discussed further in Section 4.1.3 – Statistical Analysis.

4.1.2 Rudder Graphs

Estimating the best rudder angle on a vessel without directional stability is usually harder than on a ship with directional stability. Effects from changes in rudder angle happen slowly at first and once a decent rate of turn is achieved it takes longer for counter rudder to have an effect. As a rule, this problem will become greater with increasing draft. Information about the time it takes for counter rudder to have an effect is usually gathered from zigzag tests. In the case of Vessel 2, large rudder angles tend to give the ship a rate of turn too great for counter rudder to be effective. This has the effect that counter rudder needs to be applied early or at a greater angle than the initial rudder angle. Limits to safe water only increases this problem where the navigator on one side wants to make narrow turns and on the other is dependent on effective and quick responses to rudder and counter rudder. As a way of illustrating the amount of control in a manoeuvre, illustrations of rudder angles along the tracks during experiments is a good measure of how much control the navigator has.

Examining the rudder graphs in Figure 15 and Appendix D – Rudder Graphs, a clear pattern emerges. When using – or having previously used – the DSS, the rudder is used with more confidence. For both the initial turn to port and the counter-turn to starboard, the participants start with rudder angles that are close enough to optimal so that only minor adjustments are required. In contrast, the completely unassisted trials show a lot of guessing and second-guessing. Frequent and large changes in rudder angle are common.

As a supplement to the graphs, the mean absolute deviation (MAD) of the rudder angles used have been calculated. This numerical value is a means to directly compare individual trials. An individual number alone is meaningless; it is referencing one specific instance of this specific manoeuvre. However, when compared, they illustrate who found a good plan and stuck to it, and who were forced to make many and/or large corrections throughout.

A manoeuvre executed using small rudder angles is not automatically the best one. There are times when it is prudent or even necessary to use the full capabilities of the rudder. There is, however, a difference between confidently and purposefully using large rudder angles and rapidly changing rudder angles back and forth.

The beneficial side effects of using smaller rudder angles are obvious. The reduced drag means that the manoeuvre can be performed with a reduced loss of speed, which again saves on both time and fuel consumption.

Results from Figure 16 clearly show smaller values for assisted or previously assisted runs in comparison with unassisted ones. This means that navigators that were given or had been given assistance from the DSS self-corrected themselves less. When the time required to find a close to optimal rudder angle has been reduced or eliminated, the navigator has more time and attention to spare for other critical aspects of navigation.

4.1.3 Statistical Analysis

An initial look at the analysis for the different χ^2 tests the authors ran suggests the hypothesis of the thesis has been disproved. However, there are some things that need to be addressed before it can be concluded that this is the case. The hypothesis for this thesis was that a decision support system showing ship trajectories would improve navigational safety. This could not be the null hypothesis for the statistical analysis for one crucial reason:

Data gathered on all vessels indicate that no significant difference can be shown between using the

DSS first or last. This is however more or less in line with what has been mentioned in Section 1.1 – Motivation about systems giving little input about the manoeuvrability of a vessel. For Vessel 2, the DSS gives a good idea about how the passage through Vatlestraumen could be carried out. For the other vessels it might just add confusion and even harm the navigator's own idea about what rudder angle is more suitable. The fact that Vessel 2 is directionally unstable and 1 and 3 are both directionally stable would add to this effect. Results from all vessels, apart from assisted and unassisted attempts with Vessel 2 (Table 7 on page 48), show a slight trend for navigators that started with the assisted attempt performing worse on the other vessels. It should however be noted that this result could just as likely have happened by chance. Group B showed an improvement of 8.2% compared to Group A. This is only slight and therefore the null hypothesis from Section B – Statistical Analysis cannot be rejected at $p < .05$.

Results for vessels except those with the assistance of the DSS show a slight improvement with a success rate of 73% for Group B to 64% for Group A. Both the difference between the groups and the sample size is rather small so little weight can be put on these numbers. One can, however, speculate about where the difference comes from:

- Group B, learning from their experience with the DSS.
- Group A, following instructions from the DSS instead of their learnt expertise from previous attempts.
- The difference happening by pure chance.

It should be noted that because the DSS assisted attempt was either at the start or end of the exercise, attempts 1, 2 and 3 are counted for Group A while attempts 2, 3 and 4 are shown for Group B. It is therefore impossible to say if this improvement is because of more experience in Vatlestraumen, more experience with Vessel 2 or because of improvements from being assisted by the DSS.

The data gathered from the use of *only* Vessel 2 show promising results. This is a comparison between attempt 2 and 4 for Group A versus 1 and 3 for Group B. Group B had a success rate of 75% compared to Group A with 44%. The fact that Group B shows better results despite the fact that they achieved them on earlier attempts goes against the interpretation that people learned the task, improving with later attempts. An interesting side point is the fact that both groups had relatively equal success rate using the DSS: 55% for Group A compared to 60% for Group B. The unassisted attempt show Group B getting 90% and Group A 38%, a significant difference. This would seem to indicate that given prior input from the DSS, Group B showed great improvements when they took the information gathered and created their own instructions more suited to their previous plan. While not statistically significant at $p < .05$ the p-value is 0.0543. This result is harder to explain away as pure chance.

4.2 Experimental Limitations

The authors formed their research group in the spring of 2019 and decided which topic they wanted to pursue in-depth. The work started and went on during the autumn of 2019. The development process was left open; no precautions were taken to keep things secret. Among other things, information about the concepts behind the system and the progress made was freely available. It is conceivable that some of the participants in the experiment had advance knowledge of what to expect, and that preconceived notions had an impact on how they approached the experiment.

The information provided in the briefing before the participants were to use the DSS was not entirely consistent. The thesis authors intended that the instructions were to be followed unless the participants deemed it unsafe to do so. This was not conveyed in a clear and unambiguous manner. Because of this, the degree to which participants trusted the instructions may have varied and potentially influenced experimental results. The authors should instead have created a script or a pre-made video of the presentation, taking careful consideration to use neutral language. A frequently asked questions list with pre-determined answers should have been used. Questions asked outside this list would be left unanswered as to not influence participants.

The experiment was carried out as part of a navigational course. This imposed certain limitations on how it could be set up. It was required that participants perform the same tasks; the only aspect open for adjustment was the order. Thus a proper control group could not be set up. Two more rounds of experiments were planned, one in mid-March, and one in late March or early April. These were intended to include a group doing repeated runs without DSS assistance. This would have made it possible to better isolate the learning effect from multiple runs. Unfortunately, three days before the first additional experiment was set to take place the campus closed down, and remained closed for the duration of the semester.

During the experiment, participants were debriefed between each vessel change. This allowed participants to ask questions that had occurred to them while they were in the bridge simulator. One case that stood out was a question about how to use a PI. Since the experiment was incorporated with teaching sessions, the instructor answered and demonstrated its use. The instructor then drew the area, showing where to put out two offset VRMs and EBLs, as well as explaining how a PI across the bow could be used to determine the WOP for the vessel. As a result, this group received far more information regarding a solution to the navigational challenge than the other groups. Although this is something that the participants should already master at this stage in their course, had the authors had a script to adhere to this would not be a source of error. It is unlikely that this became a major source of error, but it did give one group an advantage as they had this opportunity to refresh their knowledge while the other participants did not.

Another disadvantage of having the experiment as part of a navigational course was that the participants did their own planning beforehand. Adding to this, the challenge involved in defining a well executed manoeuvre precluded deviations from the planned track from being used as a measure of success. A pre-designed passage plan loaded into the ECDIS would alleviate this problem, by making it possible to measure the participants' ability to follow the planned track, with or without the aid of the DSS.

The group composition of the participants was not something the authors had control over. As mentioned earlier, students work in a set pair after doing a personality test and considering their background in the maritime industry, to plausibly obtain the optimal composition. The decisions behind the creation of pairs may result in some people working very well together and others not; this factor should not be ignored. To avoid this, random pairs could have been used, or single participants. As a best available option, the selection of who would do their first run with Vessel 2 unaided and who would use the DSS first was randomised.

On the day of the experiment, participants also had training on the desktop simulators detailed in Section 2.1.2 – Manoeuvre Tests Using Desktop Simulators. This work was unrelated to the experiment, but used Vessel 2, the one the DSS was built for. Half of them did this before the experiment and half after. Consequently, half of the participants had had a very recent opportunity to refamiliarise themselves with the manoeuvring characteristics of Vessel 2, something which may have aided their performance during the experiment. However, these participants were evenly divided between groups A and B, which should limit any influence on the experimental results.

The first half of Group A (see Appendix B – Statistical analysis), had a pair who had to start on a bridge simulator originally not intended for use. The pair started on Bridge 6 and had to run all four of their trials there. This happened because there had been a double booking of bridge simulators that day. To minimise the chance of a source of error, the pair placed on this bridge were already familiar with it. This only affected one half of Group A; with the exception outlined in the next paragraph, the other half and the whole of Group B ran their trials on bridge simulators with which they were already familiar.

Bridge 5 was in use throughout the experiment. This bridge is considerably different from bridge 1-4 (see Section 2.1.3 – Bridge Simulators). This is a potential source of error, as the participants were less familiar with this bridge compared to the others. This could mean that pairs using this bridge underperformed compared to their peers using the conventional bridge designs.

4.3 Further Research and Development

This section contains suggestions from the authors for further research and development, listed in order of importance. Primarily, further experiments are needed to test the hypothesis. If results from these prove the validity of the DSS, a natural next step would be to expand into real life applications.

4.3.1 Additional Experiments

As discussed in the section on statistical analysis, the single experiment performed did not yield enough or good enough data to reach any firm conclusions. This was not at all unexpected. The sample size was small, and the constraints of the educational format meant that setting up a proper control group was not possible.

Before any serious consideration can be given to taking this research further, the weaknesses identified above should be addressed. In particular, the issue about the extent to which improvements seen in second-run performances were due to learning by trying versus having seen and used the suggestions from the DSS. To facilitate this, repeated runs without DSS input are necessary in order to isolate the different learning factors involved.

4.3.2 Real Life Applications

A natural step after conducting experiments in a simulator created to mimic the real world is to move the experiments to said real world. The first thing that comes to mind is safety. Before a system can be tested aboard real ships in any scale at all, a DSS would need to go through extensive testing to eliminate problems with the system itself. The first phase of implementing a tool made to increase safety would naturally be to make sure that the system itself is safe. Due to external factors the current DSS and the commercial simulator run as separate systems. This would obviously not be the case for a real DSS. Because navigational safety is dependent on knowledge of seabed topography, the DSS created for this thesis could greatly benefit from integration with an electronic charting system. A system made for real life applications would not be static in the same way as the DSS is in its current form. The trajectory would be updated at regular time intervals with changes in sensory data. None of these issues would presents insurmountable technological hurdles.

A system such as the DSS in this thesis does however face several challenges that all need to be addressed. Most of these problems have solutions already. The likely place to start is to change to a mathematical model using the Unified theory by Fossen and Sagatun (1991) instead of Maneuvering Theory. Among other benefits, this has the added advantage of working with wave excitation in 6 degrees of freedom.

Conducting an experiment such as the one described in the pages above on a real ship out on the ocean would require rebuilding the experiment from the ground up. It is close to impossible to say how much extra effort this would take. Integrating systems that are created to work separately is its own field of engineering. Path prediction is a subject that, while not solved in a maritime context, is far more advanced than that which has been used during the course of this thesis.

The Norwegian Forum for Autonomous Ships (Rodseth and Nordahl 2017) mention that advanced Aids to Navigation (AtoN) and Automatic Identification System (AIS) could be used to supply advanced or autonomous ships with information about waves, current, wind and other parameters. Data that are gathered close to narrow straights or harbour entrances could be an excellent source of sensor data for a system trying to predict ship trajectories for the benefit of the navigator.

The optimisation process mentioned in Section 2.2.5 – Parameter Optimisation could be used in a real life setting with data about ship accelerations and external forces gathered from sensors. Motion reference units, wind sensors and measurements of current or current modelling could be used in tandem with GPS tracks gathered during normal operations. Comparing data from sensors and GPS tracks against tracks calculated by the DSS could, in theory, be used for optimisation. To the best of the authors' knowledge, this is not something that has been attempted on real ships, but is a common approach for optimisation of mathematical models. This could prove a method for both building and continuously optimising a mathematical model while in use. The system would be installed with data from a similar vessel and work in a sleep mode until sufficient accuracy was obtained. Whether this method would be viable is left up to future tests. If it does work, it could be a possible way of implementing a DSS such as this on ships on a large scale.

The problems mentioned with the lever arm of wind is also a subject for further research before a system could be implemented in real life applications. The problem with defining a position of the actual centre of rotation for an object at motion is something for which no adequate answer was found during the work on this thesis. The reasons for this may range from the fact that it is an imaginary problem invented by the authors, to that it disappears in a vector based method such as the Unified Theory.

5 Conclusion

The intention of this thesis has been to explore the hypothesis that a path predictor suggesting ship specific rudder inputs improves navigational safety. The first goal was to build a system to test this hypothesis. This goal was achieved: the system was built, and it works.

The completed experiment indicates two things in support of the hypothesis:

- Tests performed using the DSS or having previously used the DSS have a marked tendency towards fewer groundings.
- Rudder usage appears to be under better control in tests performed using the DSS or having previously used the DSS.

When the time required to find a close to optimal rudder angle has been reduced or eliminated, the navigator has more time and attention to spare for other critical aspects of navigation. The authors contend that this increases navigational safety.

Once again, it must be stressed that while the results regarding success rates look promising, statistical significance is only achieved for $p < .10$, and not for $p < .05$. Further tests, employing a more rigorous use of control groups and with a better control over the associated variables, would go a considerable distance towards proving or disproving the hypothesis.

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Appendix

A Consent form.

Samtykkeskjema

Loggføring av data i simulator

NTNU Ålesund og vi bachelorstudenter ([redacted]), vil informere om at

det vil bli loggført data fra alle broer under simulatorøvelsen 'Stor-Større-Størst' fredag 28.Februar 2020 til bruk i Bacheloroppgave.
Loggføringen vil kun være av handlinger utført i simulator, ikke video eller bilder av deg. Dataen som blir hentet ut vil heller ikke kunne spores tilbake til deg som person.

Loggene vil ikke være tilgjengelig for noen andre enn bachelorgruppen. Videre vil loggene bli lagret og oppbevart digitalt i en trygg og designert sky med begrenset tilgang for andre en bachelorstudentene.

Samtykket kan trekkes tilbake. Tilbaketrekning av samtykket må skje skriftlig til [redacted] innen 27.februar 2020 klokken 16:00.

Samtykkeerklæring for loggføring av data

Jeg samtykker i loggføring av øvelsen 'Stor-Større-Størst', som er tatt av NTNU Ålesund og Bachelorstudentene, og informasjonen kan benyttes i forskningssammenheng.

Navn:...

Dato:...

Sted:...

Signatur:..

B Statistical analysis

The experiment was performed using four groups. In Table 5 below, these are labelled one through four chronologically. Groups one and three performed their first Vessel 2 run unassisted, while groups two and four performed their first Vessel 2 run with DSS assistance. As the table shows, the four groups were later combined into two based on run order, called A and B. This is how they are referenced throughout the text.

Table 5. Data gathered from experiments. Runs without incidents are counted as 1.

Group A				
	Vessel 1	Vessel 2	Vessel 3	DSS
Group number	One	One	One	One
Bridge 5	0	0	1	0
Bridge 1	1	1	1	1
Bridge 4	1	0	1	1
Bridge 2	1	0	1	0
Bridge 3/6				
Group number	Three	Three	Three	Three
Bridge 5		0	1	0
Bridge 1	1	1	1	1
Bridge 4	0	0	1	1
Bridge 2	0	1	1	0
Bridge 3/6	1		0	1
Score	5	3	8	5
Runs	8	8	9	9
Average	0.625	0.375	0.889	0.556
Group A Average				**0.618**

Group B				
	DSS	Vessel 1	Vessel 2	Vessel 3
Group number	Two	Two	Two	Two
Bridge 5	1	1	1	0
Bridge 1	0	0	1	1
Bridge 4	1	1	1	1
Bridge 2	0	1	1	1
Bridge 3/6	1	1	1	0
Group number	Four	Four	Four	Four
Bridge 5	1	0	1	1
Bridge 1	1	0	1	0
Bridge 4	1	1	0	0
Bridge 2	0	1	1	1
Bridge 3/6	0	1	1	1
Score	6	7	9	6
Runs	10	10	10	10
Average	0.600	0.700	0.900	0.600
Group B Average				**0.700**

Table 6. χ^2 Results for different data sets

Results for all vessels

	Fail	Pass	Row totals	
DSS last	13	21	34	
DSS first	12	28	40	
Column totals	25	49	74	Grand total

Expected values all vessels

	Fail	Pass	Row totals	
DSS last	11.49	22.51	34	
DSS first	13.51	26.49	40	
Column totals	25	49	74	Grand total
p-value =	0.4554	N =	74	
Statistic =	0.5572			

Results for vessels except Vessel 2 & DSS

	Fail	Pass	Row totals	
DSS last	4	13	17	
DSS first	7	13	20	
Column totals	11	26	37	Grand total

Expected values for vessels except Vessel 2 & DSS

	Fail	Pass	Row totals	
DSS last	5.05	11.95	17	
DSS first	5.95	14.05	20	
Column totals	11	26	37	Grand total
p-value =	0.4468	N =	37	
Statistic =	0.5787			

Table 7. χ^2 Results for different data sets

Results for Vessel 2 & DSS only

	Fail	Pass	Row totals	
DSS last	10	8	18	
DSS first	5	15	20	
Column totals	15	23	38	Grand total

Expected value Vessel 2 & DSS only

	Fail	Pass	Row totals	
DSS last	7.11	10.89	18	
DSS first	7.89	12.11	20	
Column totals	15	23	38	Grand total

p-value =	0.0543	N =	38
Statistic =	3.7021		

Results for vessels except DSS

	Fail	Pass	Row totals	
DSS last	9	16	25	
DSS first	8	22	30	
Column totals	17	38	55	Grand total

Expected values for vessels except DSS

	Fail	Pass	Row totals	
DSS last	7.73	17.27	25	
DSS first	9.27	20.73	30	
Column totals	17	38	55	Grand total

p-value =	0.4558	N =	55
Statistic =	0.5562		

C Matlab Code

C.1 Wind

The following is the code version of what is being described in Figure 11 on page 30. Both Blendermann and Isherwood are included.

Calculation of relative wind speed and angle with respect to bow:

```
function [out,k]   = fcn (in)
%Created for bsc thesis - 2020
%Calculations of relative wind speed and angle.

a = in(1); % True wind angle (deg)
b = in(2); % True wind speed (m/s)
c = in(3); % Heading (deg)
u = in(4); % Surge speed (m/s)
v = in(5); % Sway speed (m/s)

d = sqrt(u^2 + v^2); % ship speed over ground (m/s)

%Decomposition of wind.
e = sind(a)*b;
f = cosd(a)*b;

%Decomposition of ship speed.
g = sind(c)*d;
h = cosd(c)*d;

%Adding ship and wind speed.
x = [e;f];
z = [g;h];

%calculation of relative vector.
y = x+z;

%Wrapping value between 0-180.
h = atan2(y(1,1),y(2,1));
j = h*(180/pi);
if j < 0
    j = 360+j;
end

%Angle and lenght of relative wind vector.
negangle = (180/pi)*atan2(sind(c-j),cosd(c-j));
gamma_r = abs(negangle);
%y bytt till uu
U_rw = (y(1,1)^2+(y(2,1)^2))^0.5;

%k is positive for port and negative for starboard.
%k is saturated so value is -1 or 1.
```

```
k = negangle;

%output to Blendermann
out = [gamma_r U_rw]';
```

Isherwood calculation of wind coefficients:

The inputs used for Vessel 2 are: LOA: 305m, B: 48m, ALw: 2697.3m^2, AFw: 1550.2m^2, A_SS: 370.74m^2, S: 145.48m, C: 127m, M: 2st

```
function tau_w  = isherwood72(in)
% [tau_w] = isherwood72(gamma_r,V_r,Loa,B,ALw,AFw,A_SS,S,C,M) returns
↪  the the wind
% force/moment vector w_wind = [tauX,tauY,tauN] and the optionally wind
↪  coeffisients
% cx,cy and cn for merchant ships using the formulas of Isherwood
↪  (1972).
%
% INPUTS:
gamma_r = in(1); % relative wind angle (deg)
V_r     = in(2); % relative wind speed (m/s)
Loa     = in(4); % length overall (m)
B       = in(5); % beam (m)
ALw     = in(6); % lateral projected area (m^2)
AFw     = in(7); % frontal projected area (m^2)
A_SS    = in(8); % lateral projected area of superstructure (m^2)
S            = in(9); % length of perimeter of lateral projection of
↪  model (m)
%                      excluding waterline and slender bodies such as
↪  masts and ventilators (m)
C            =  in(10); % distance from bow of centroid of lateral
↪  projected area (m)
M       = in(11);% number of distinct groups of masts or king posts seen
↪  in lateral
k       = in(3); % k = 1 forces from port / k = -1 forces from starboard
%                      projection; king posts close against the bridge
↪  front are not included
%
% Author:    Thor I. Fossen
% Date:      10th September 2001
% Revisions: 19.04.2004, changed velocity from knots to m/s. This was a
↪  bug
%            20.11.2008, changed name from windcoef to isherwood72,
↪  updated
%                         signs and notation to comply with Blendermann
↪  (1994).
% Edited for bsc thesis December 2019
% if in~=10, error('the number of inputs must be 10');end

% constants
rho_a = 1.224;             % density of air at 20 C
```

```
% CX_data = [gamma_r
↪           A0          A1          A2          A3          A4          A5          A6          ]
CX_data= [...
0         2.152         -5.00         0.243         -0.164         0
↪   0         0
10         1.714         -3.33         0.145         -0.121         0
↪             0             0
20         1.818         -3.97         0.211         -0.143         0
↪   0         0.033
30         1.965         -4.81         0.243         -0.154         0
↪   0         0.041
40         2.333         -5.99         0.247         -0.190         0
↪           0           0.042
50         1.726         -6.54         0.189         -0.173         0.348         0
↪   0.048
60         0.913         -4.68         0
↪   -0.104         0.482         0         0.052
70         0.457         -2.88         0
↪   -0.068         0.346         0         0.043
80         0.341         -0.91         0         -0.031         0
↪   0         0.032
90         0.355         0         0         0
↪           -0.247         0         0.018
100         0.601         0         0         0
↪   -0.372         0         -0.020
110         0.651         1.29         0         0
↪   -0.582         0         -0.031
120         0.564         2.54         0         0
↪   -0.748         0         -0.024
130         -0.142         3.58         0
↪   0.047         -0.700         0         -0.028
140         -0.677         3.64         0
↪   0.069         -0.529         0         -0.032
150         -0.723         3.14         0
↪   0.064         -0.475         0         -0.032
160         -2.148         2.56         0         0.081         0
↪   1.27         -0.027
170         -2.707         3.97         -0.175         0.126         0
↪   1.81         0
180         -2.529         3.76         -0.174         0.128         0
↪           1.55         0         ];

% CY_data = [gamma_r
↪   B0          B1          B2          B3          B4          B5          B6]
CY_data = [...
0   0         0         0         0         0         0         0
10         0.096         0.22         0         0         0
↪           0         0
20         0.176         0.71         0         0         0
↪   0         0
```

```
30         0.225        1.38        0           0.023        0
↪   -0.29        0
40         0.329        1.82        0           0.043    0
↪          -0.59         0
50         1.164        1.26        0.121       0
↪   -0.242        -0.95        0
60         1.163        0.96        0.101       0
↪   -0.177        -0.88        0
70         0.916        0.53        0.069       0            0
↪          -0.65         0
80         0.844        0.55        0.082       0            0
↪          -0.54         0
90         0.889        0            0.138       0            0
↪          -0.66         0
100         0.799        0            0.155       0            0
↪          -0.55         0
110         0.797        0            0.151       0            0
↪   -0.55        0
120         0.996        0            0.184       0
↪   -0.212        -0.66        0.34
130         1.014        0            0.191       0
↪   -0.280        -0.69        0.44
140         0.784        0            0.166       0
↪   -0.209        -0.53        0.38
150         0.536        0
↪   0.176        -0.029        -0.163        0            0.27
160         0.251        0
↪   0.106        -0.022        0            0            0
170         0.125        0
↪   0.046        -0.012        0            0            0
180 0        0        0        0        0        0        0      ];

% CN_data = [gamma_r
↪   C0        C1        C2        C3        C4        C5]
CN_data = [...
0   0        0        0        0        0        0
10         0.0596        0.061        0            0            0
↪   -0.074
20         0.1106        0.204        0            0            0
↪   -0.170
30         0.2258        0.245        0            0            0
↪   -0.380
40         0.2017        0.457        0
↪   0.0067        0            -0.472
50         0.1759        0.573        0
↪   0.0118        0            -0.523
60         0.1925        0.480        0
↪   0.0115        0            -0.546
70         0.2133        0.315        0
↪   0.0081        0             -0.526
```

```
80         0.1827       0.254       0
 ↪  0.0053       0           -0.443
90         0.2627       0           0           0           0
 ↪  -0.508
100        0.2102   0           -0.0195         0
 ↪  0.0335       -0.492
110        0.1567       0           -0.0258         0
 ↪  0.0497       -0.457
120        0.0801       0           -0.0311         0
 ↪  0.0740       -0.396
130        -0.0189       0
 ↪  -0.0488       0.0101       0.1128       -0.420
140        0.0256       0
 ↪  -0.0422       0.0100       0.0889       -0.463
150        0.0552       0
 ↪  -0.0381       0.0109       0.0689       -0.476
160        0.0881       0
 ↪  -0.0306       0.0091       0.0366       -0.415
170        0.0851       0           -0.0122       0.0025       0
 ↪          -0.220
180 0       0       0       0       0       0       ];

% interpolate in the tables
A0 = interp1(CX_data(:,1),CX_data(:,2),gamma_r);
A1 = interp1(CX_data(:,1),CX_data(:,3),gamma_r);
A2 = interp1(CX_data(:,1),CX_data(:,4),gamma_r);
A3 = interp1(CX_data(:,1),CX_data(:,5),gamma_r);
A4 = interp1(CX_data(:,1),CX_data(:,6),gamma_r);
A5 = interp1(CX_data(:,1),CX_data(:,7),gamma_r);
A6 = interp1(CX_data(:,1),CX_data(:,8),gamma_r);

B0 = interp1(CY_data(:,1),CY_data(:,2),gamma_r);
B1 = interp1(CY_data(:,1),CY_data(:,3),gamma_r);
B2 = interp1(CY_data(:,1),CY_data(:,4),gamma_r);
B3 = interp1(CY_data(:,1),CY_data(:,5),gamma_r);
B4 = interp1(CY_data(:,1),CY_data(:,6),gamma_r);
B5 = interp1(CY_data(:,1),CY_data(:,7),gamma_r);
B6 = interp1(CY_data(:,1),CY_data(:,8),gamma_r);


C0 = interp1(CN_data(:,1),CN_data(:,2),gamma_r);
C1 = interp1(CN_data(:,1),CN_data(:,3),gamma_r);
C2 = interp1(CN_data(:,1),CN_data(:,4),gamma_r);
C3 = interp1(CN_data(:,1),CN_data(:,5),gamma_r);
C4 = interp1(CN_data(:,1),CN_data(:,6),gamma_r);
C5 = interp1(CN_data(:,1),CN_data(:,7),gamma_r);

% wind coeffisients
CX =  -(A0 + A1*2*ALw/Loa^2 + A2*2*AFw/B^2 + A3*(Loa/B) + A4*(S/Loa) +
 ↪  A5*(C/Loa) + A6*M);
```

```
CY =    B0 + B1*2*ALw/Loa^2 + B2*2*AFw/B^2 + B3*(Loa/B) + B4*(S/Loa) +
↪  B5*(C/Loa) + B6*A_SS/ALw;
CN =    C0 + C1*2*ALw/Loa^2 + C2*2*AFw/B^2 + C3*(Loa/B) + C4*(S/Loa) +
↪  C5*(C/Loa);

% wind forces and moment (changed value of tauX to *-1 to better match
% expected values)
tauX = (0.5*CX*rho_a*V_r^2*AFw)*-1;
tauY = 0.5*CY*rho_a*V_r^2*ALw;
tauN = 0.5*CN*rho_a*V_r^2*ALw*Loa;

if k <0
    tauY = tauY*k;
    tauN = tauN*k;
else tauY = tauY;
    tauN = tauN;
end

tau_w = [tauX,tauY,tauN]';
```

Blendermann calculation of wind coefficients:

The inputs used for Vessel 2 are: ALw: 2697.3m^2, AFw: 1606m^2, sH: -25,3m, sL: 7.3m, Loa: 305m, vessel no: 15

```
function [tau_w,CX,CY,CK,CN] =blendermann(gamma_r,V_r,AFw,ALw,sH,sL,Loa)
% [tau_w,CX,CY,CK,CN] =
↪  blendermann94(gamma_r,V_r,AFw,ALw,sH,sL,Loa,vessel_no) returns the
↪  the wind
% force/moment vector w_wind = [tauX,tauY,tauN] and the optionally wind
↪  coeffisients
% cx,cy and cn for merchant ships using the formulas of Isherwood
↪  (1972).
%
% INPUTS:
%gamma_r   = relative wind angle (rad)
%V_r       = relative wind speed (m/s)
%ALw       = lateral projected area (m^2)
%AFw       = frontal projected area (m^2)
%sH        = horizontal distance to centroid of ALw (from main section)
%sL        = vertical distance to centroid of ALw (from water line)
%Loa       = length overall (m)
%vessel_no = 15;
%   15. Tanker, loaded

%
% Author:    Thor I. Fossen
% Date:      20th November 2008
% Revisions:
% Edited for bsc thesis Feb 2020
```

```
% conversions and constants
rho_a = 1.224;             % density of air at 20 C

% BDATA = [CD_t        CD_l_AF(0)       CD_l_AF(?)       ?        ?
BDATA = [0.70        0.90        0.55        0.40        3.1];

CDt             = BDATA(1);
CDl_AF_bow      = BDATA(2);
CDl_AF_stern    = BDATA(3);
delta           = BDATA(4);
kappa           = BDATA(5);

Hm  = ALw/Loa;

% two cases for CDl

if gamma_r <= pi/2
    CDlAF = CDl_AF_bow;
else
    CDlAF = CDl_AF_stern;
end
% wind coefficients
CDl = CDlAF*AFw/ALw;
den = 1-0.5*delta*(1-CDl/CDt).*sin(2*gamma_r).^2;

CX = -CDlAF.*cos(gamma_r)./den;
CY =  CDt*sin(gamma_r)./den;
CK =  kappa*(sH/Hm)*CY;
CN =  (sL/Loa - 0.18*(gamma_r - pi/2)).*CY;

% wind forces and moment
tauX = 0.5*CX*rho_a*V_r^2*AFw;
tauY = 0.5*CY*rho_a*V_r^2*ALw;
tauN = 0.5*CN*rho_a*V_r^2*ALw*Loa;

tau_w = [tauX,tauY,tauN]';
```

C.2 Current

Code version of what is described in Figure 9 on page 29

Modeling of current in the waterway

```
function [Vangle,Vc] = fcn(x,y)

Vc = 1.5;
Vangle = 180;


if x <= 0.52*1852
```

```
    Vc = 1.5;
    Vangle = 183;
else if x > 0.52*1852 && x <= 0.63*1852
        Vc = 1.5;
        Vangle = 155;%205;

else if x > 0.63*1852 && x <= 0.86*1852
            Vc = 1.5;
            Vangle = 137;%223;

else if x > 0.86*1852 && x <= 1.03*1852
        Vc = 1.5;
        Vangle = 120;%240;

else if x > 1.03*1852 && x <= 1.32*1852
        Vc = 1.5;
        Vangle = 145;%215;

else if x > 1.32*1852 && x <= 1.67*1852
        Vc = 1.5;
        Vangle = 175;%195;

else if x > 1.67
        Vc = 1.5;
        Vangle = 180;

    end
    end
    end
    end
    end
    end
end
```

Decomposition of current

```
function nu_c = fcn(beta_c,V_c,psi)
%Decomposition of current in {n}
nu_c(1) = cos(beta_c)*V_c;
nu_c(2) = sin(beta_c)*V_c;

x = nu_c(1);
y = nu_c(2);

%transofmation from {n} to {b}
u_c = cos(psi)*x-sin(psi)*-y;
v_c = sin(psi)*-x+cos(psi)*y;

%Current speed decomposed in {b}
nu_c = [u_c;v_c];
```

C.3 Mathematical model

Mathematical model post edit

```
function [xdot] =tanker2(in)
% File edited for bsc thesis in november 8th 2019
% [xdot,U] = tanker(x,ui) returns the speed U in m/s (optionally) and
↪  the
% time derivative of the state vector: x = [ u v r x y psi delta n ]'
↪  for
% a large tanker L = 304.8 m where:
%
% u      = surge velocity, must be positive  (m/s)         - design speed
↪  u = 8.23 m/s
% v      = sway velocity                     (m/s)
% r      = yaw velocity                      (rad/s)
% x      = position in x-direction           (m)
% y      = position in y-direction           (m)
% psi    = yaw angle                         (rad)
% delta = actual rudder angle                (rad)
% n      = actual shaft velocity             (rpm)          - nominal
↪  propeller 80 rpm
%
% The input vector is :
%
% ui      = [ delta_c  n_c h ]'  where
%
% delta_c = commanded rudder angle                  (rad)
% n_c     = commanded shaft velocity                (rpm)
% h       = water depth, must be larger than draft (m)      - draft is
↪  18.46 m
%
% Reference : Van Berlekom, W.B. and Goddard, T.A. (1972). Maneuvering
↪  of Large Tankers,
%             Transaction of SNAME, 80:264-298
%rk
% Author:     Trygve Lauvdal
% Date:       1994-05-12
% Revisions: 2001-07-20, T. I. Fossen: added speed output U, changed
↪  order of x-vector
%            2005-05-02, T. I. Fossen: changed the incorrect expression
%                        c = sqrt(cun^2*u*n + cnn^2*n^2) to c =
↪  sqrt(cun*u*n + cnn*n^2)
%                        - thanks to Dr. Euan McGookin, University of
↪  Glasgow
%            2020-11-08, Edited for use in DSS for bsc thesis
% ________________________________________________________________
%
% MSS GNC is a Matlab toolbox for guidance, navigation and control.
% The toolbox is part of the Marine Systems Simulator (MSS).
%
```

```
% Copyright (C) 2008 Thor I. Fossen and Tristan Perez
%
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% it under the terms of the GNU General Public License as published by
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% (at your option) any later version.
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% along with this program.  If not, see <http://www.gnu.org/licenses/>.
%
% E-mail: contact@marinecontrol.org
% URL:    <http://www.marinecontrol.org>

% Check of input and state dimensions
x  = in(1:8);
ui = in(9:11);
tau_w = in(12:14);
nu_c = in(15:16);

% Normalization variables
L   =  295;           % length of ship (m)
g   =  9.8;             % acceleration of gravity (m/s^2)


% Dimensional states and input
delta_c = -ui(1); %minus sign to make a positive delta_c give a positive
 ↪  r.
n_c     = ui(2)/60;
h       = ui(3);

u     = x(1)-nu_c(1);
v     = x(2)-nu_c(2);
r     = x(3);
psi   = x(6);
delta = x(7);
n     = x(8)/60;
U     = sqrt(x(1)^2 + x(2)^2);

%wind forces (values from Blendermann)
tau_X = tau_w(1);
tau_Y = tau_w(2);
tau_N = tau_w(3);

tau_X = tau_X/(1*1025*g*250);
tau_Y = tau_Y/(1*1025*g*250);
tau_N = tau_N/(1*1025*g*250*L);
```

```
% Parameters, hydrodynamic derivatives and main dimensions
delta_max  = 35;        % max rudder angle      (deg)
Ddelta_max = 1.4;      % max rudder derivative (deg/s)
n_max      = 74;        % max shaft velocity    (rpm)

t   =  0.22;
Tm  =  38;
T   =  18.66;

cun =  0.605;
cnn =  29.04188948620969;

Tuu = -0.007433509;
Tun = -0.000709782;
Tnn = 0.0000304667666997686;

m11 =   1.069997082612927;          % 1 - Xudot
m22 =   1.300077829591485;          % 1 - Yvdot
m33 =   0.0500951623451746;         % kz^2 - Nrdot

d11 =  1.500000506589733;          % 1 + Xvr
d22 = -0.884020635910677;          % Yur - 1
d33 = -0.0800826820892927;          % Nur - xG

Xuu     = -0.0336857567385002;
Xvv     = 1.199999517477226;
Xvr    = 0.200000252205158;
Xccdd   = 0.093;
Xccbd   = 0.152;


YT      = 0.04;
Yvv     = -1.000236874299409;
Yuv     = -1.95226803194429;
Yurz    = 0.06563151370946;
Yccd    = 0.208;
Yccbbd = -2.16;

NT       = -0.02;
Nvr      = -0.572913891187877;
Nuv      = -0.401080504015567;
Nur     = -0.0182348035962499;
Nccd     = -0.098;
Nccbbd   = 0.688;


% Rudder saturation and dynamics
if abs(delta_c) >= delta_max*pi/180,
   delta_c = sign(delta_c)*delta_max*pi/180;
end
```

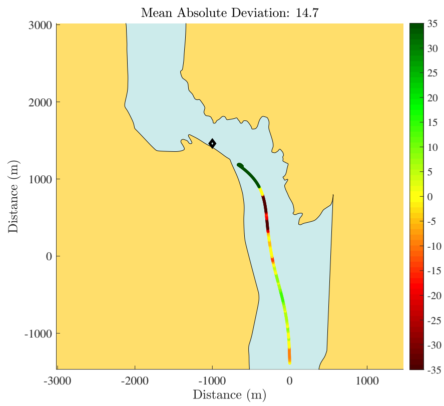
```
delta_dot = delta_c - delta;
if abs(delta_dot) >= Ddelta_max*pi/180,
   delta_dot = sign(delta_dot)*Ddelta_max*pi/180;
end

% Shaft saturation and dynamics
if abs(n_c) >= n_max/60,
   n_c = sign(n_c)*n_max/60;
end

n_dot = 1/Tm*(n_c-n)*60;

% Forces and moments
%if u<=0, error('u must be larger than zero'); end
beta = v/u;
gT   = (1/L*Tuu*u^2 + Tun*u*n + L*Tnn*abs(n)*n);
c    = sqrt(cun*u*n + cnn*n^2);

gX   = 1/L*(Xuu*u^2 + L*d11*v*r + Xvv*v^2 + Xccdd*abs(c)*c*delta^2 ...
     + Xccbd*abs(c)*c*beta*delta + L*gT*(1-t) ...
     + L*Xvr*v*r + tau_X);

gY   = 1/L*(Yuv*u*v + Yvv*abs(v)*v + Yccd*abs(c)*c*delta + L*d22*u*r ...
     + Yccbbd*abs(c)*c*abs(beta)*beta*abs(delta) + YT*gT*L ...
     + L*Yurz*u*r + tau_Y);

gLN  = Nuv*u*v + L*Nvr*abs(v)*r + Nccd*abs(c)*c*delta +L*d33*u*r ...
     + Nccbbd*abs(c)*c*abs(beta)*beta*abs(delta) + L*NT*gT ...
     + L*Nur*u*r + tau_N;

% Dimensional state derivative
xdot = [  gX/m11
          gY/m22
          gLN/(L^2*m33)
          cos(psi)*u-sin(psi)*v
          sin(psi)*u+cos(psi)*v
          r
          delta_dot
          n_dot         ];
```

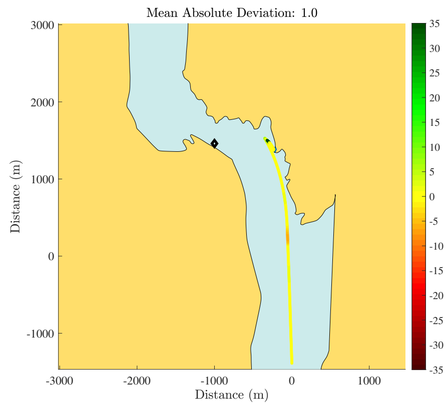
Rotation after mathematical model

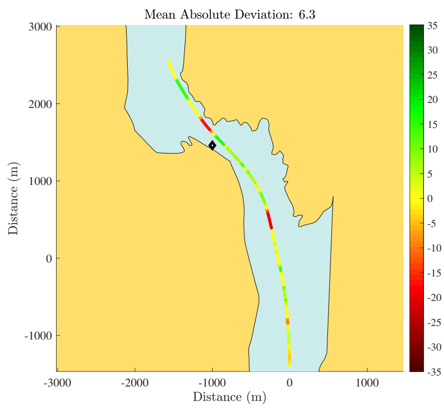
```
function [Heading,NED] = ROTATION(x,y,r)

%transformation from mathematical model output to {n}
NED = [y x];

% Wrap heading 0-360 degrees
if r < 360 & r > 0
    Heading = r;
elseif r >= 360 & r < 720
    Heading = r-360;
elseif r <= 0 & r > -360
    Heading = r+360;
elseif r <= -360
    Heading = r+720;
else Heading = r;
end

%Output to graphics, current and wind.
NED = NED;
Heading = Heading;
```

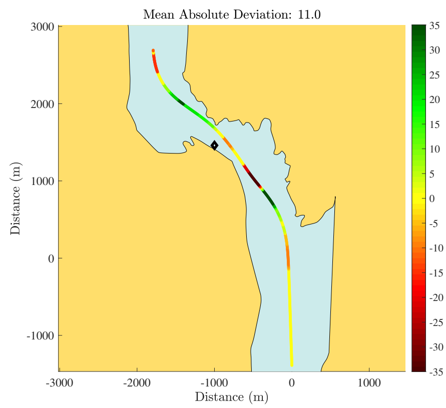
D Rudder Graphs

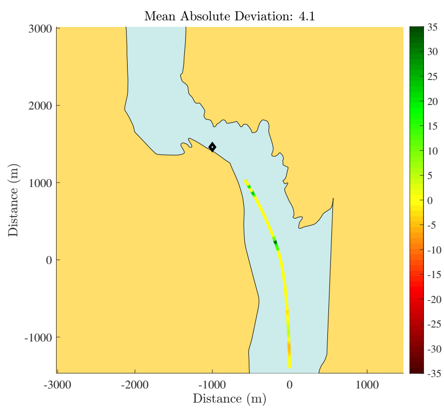
Rudder graphs for Group A without DSS

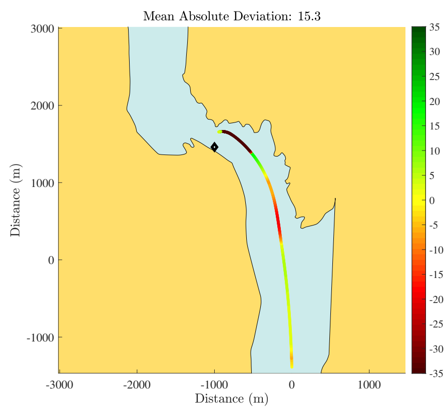




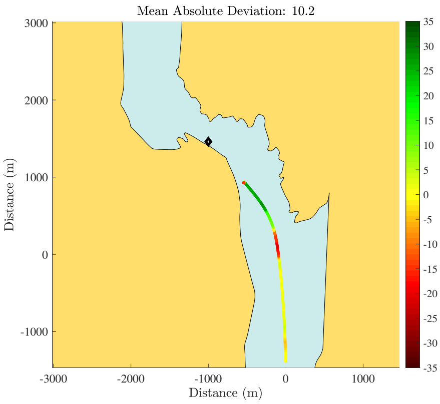


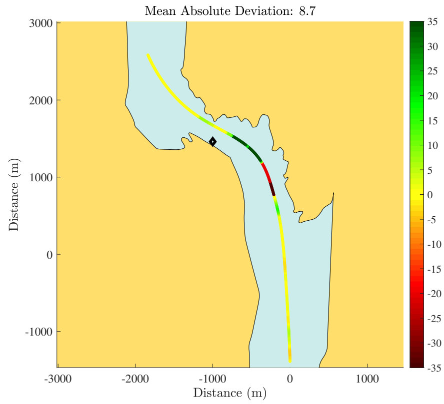




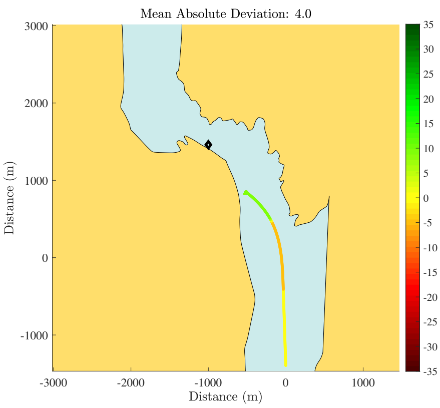


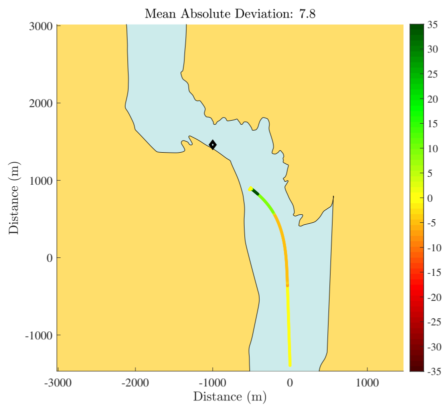
Continuation of rudder graphs for Group A without DSS

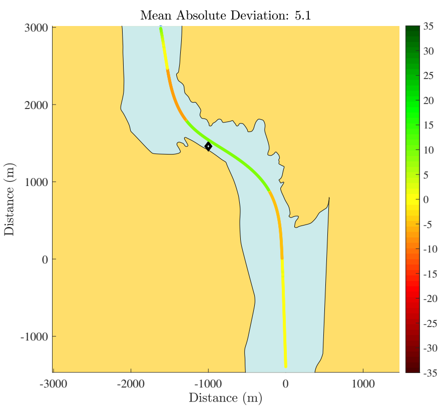


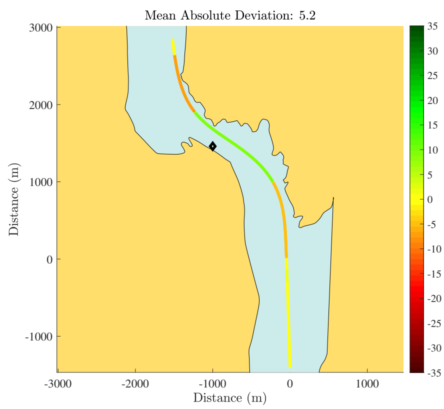


Rudder graphs for Group A with DSS

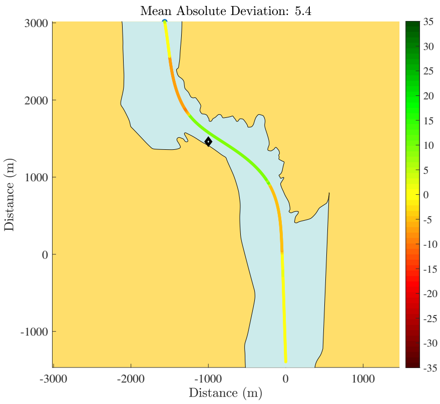


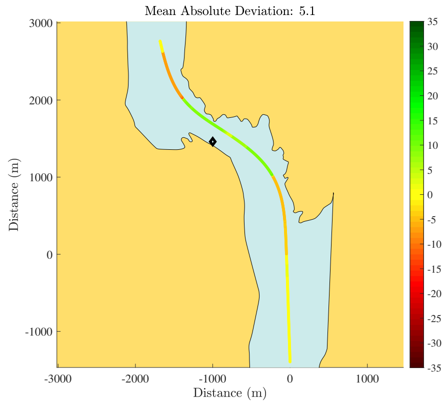


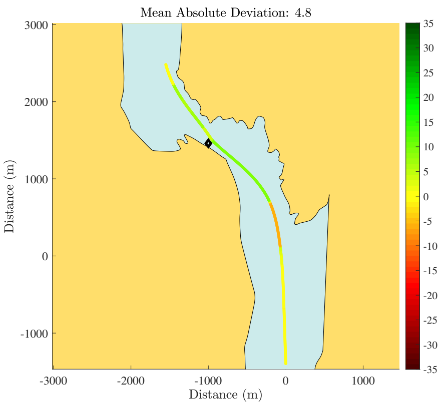


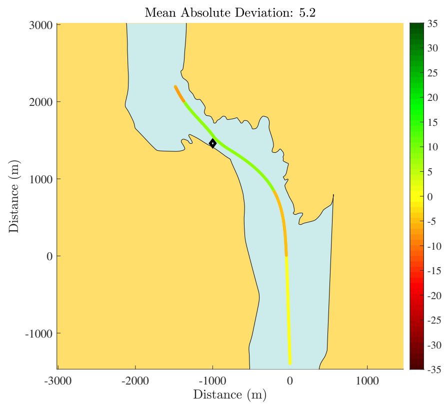


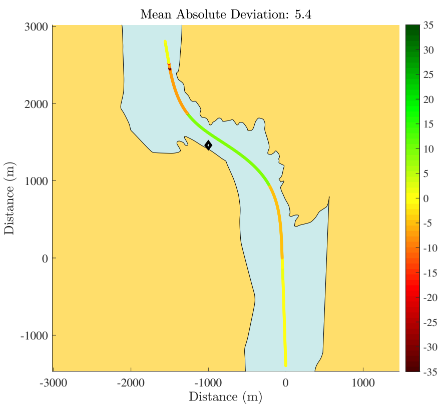
Continuation of rudder graphs for Group A with DSS



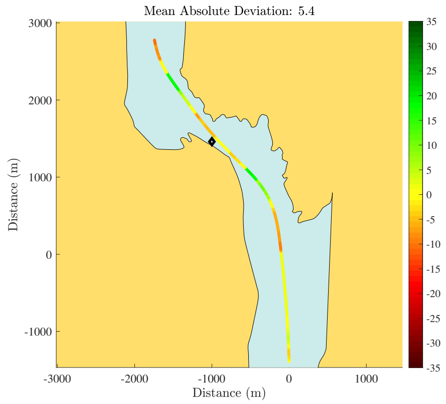


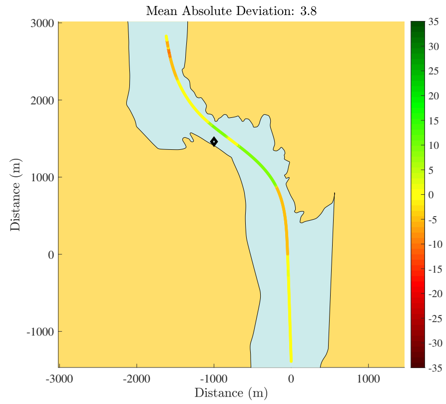


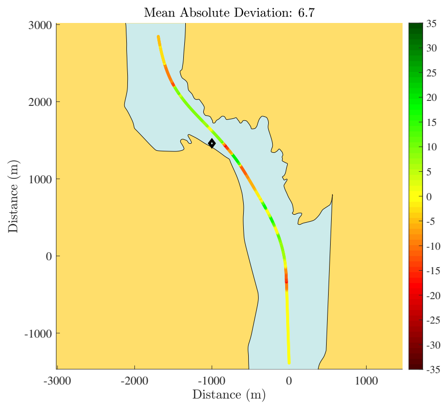


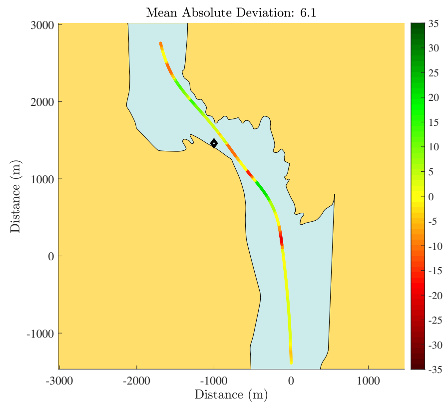


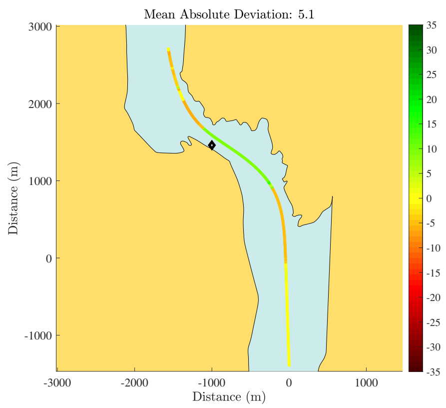
Rudder graphs for Group B without DSS

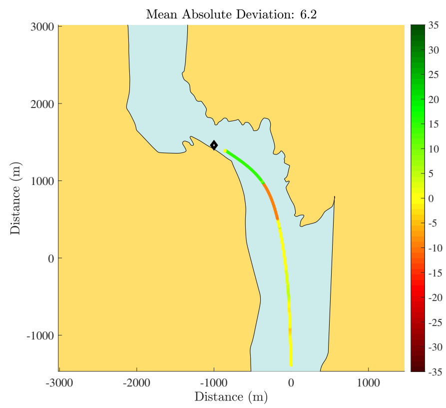




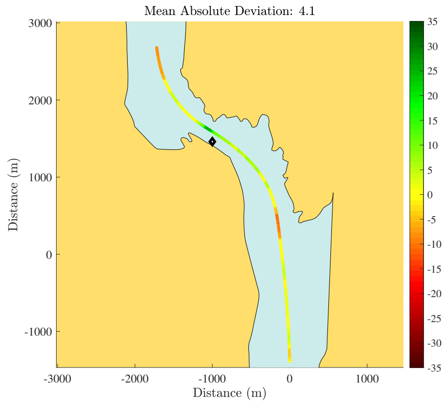


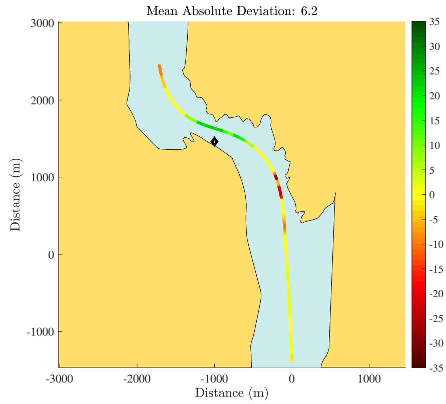


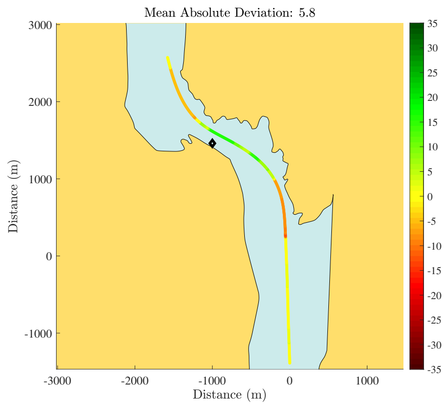


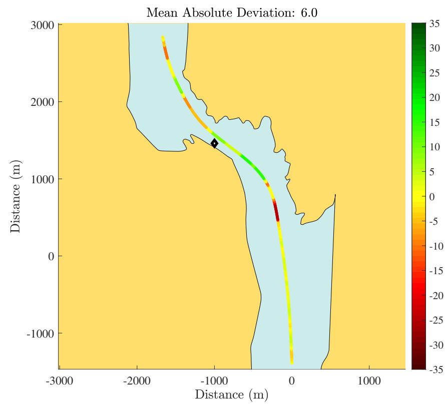


Continuation of rudder graphs for Group B without DSS

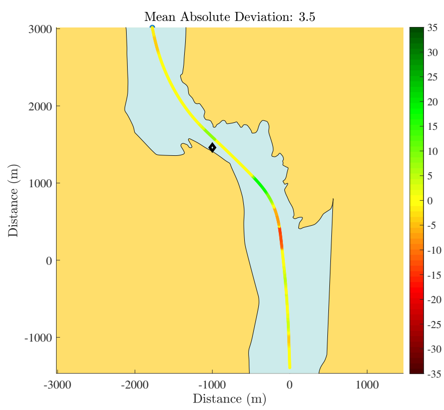


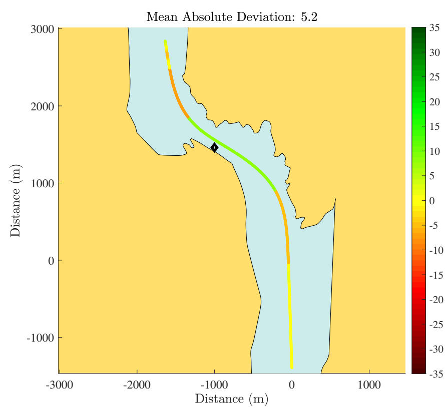




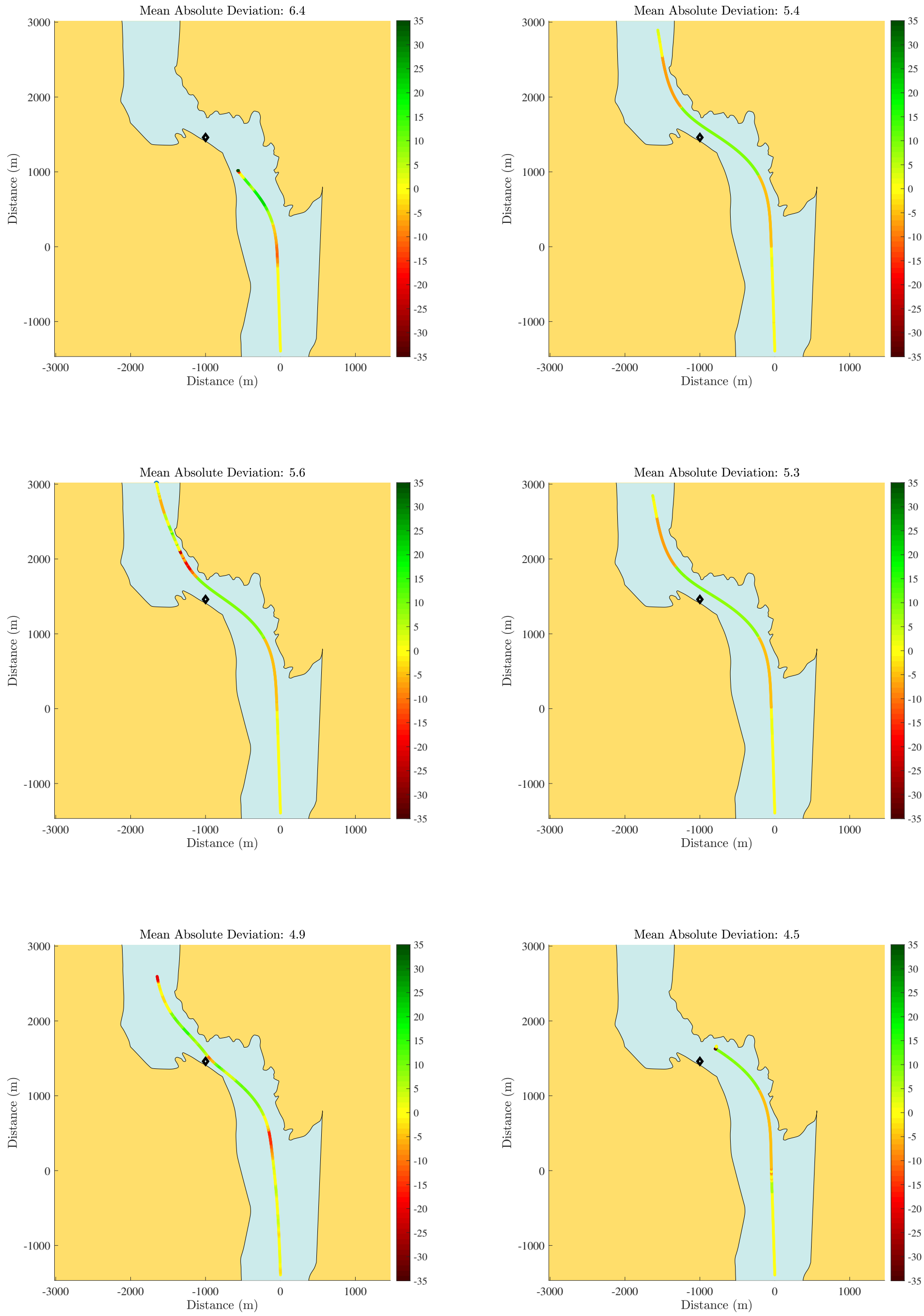


Rudder Graphs for Group B with DSS

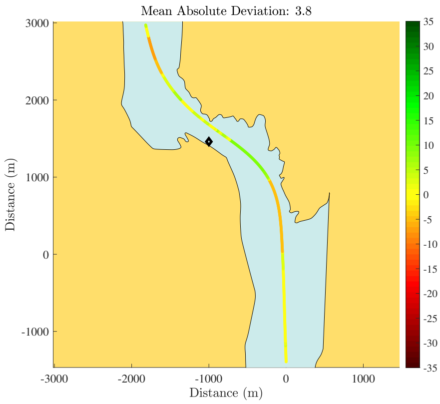


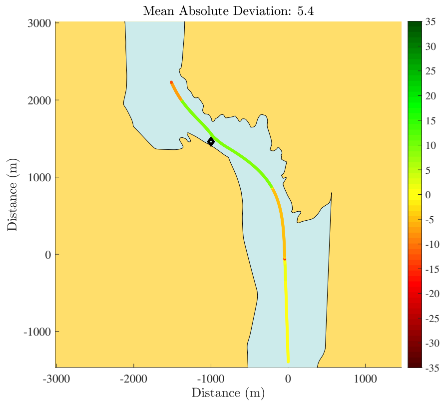


Continuation of rudder graphs for Group B with DSS



Continuation of rudder graphs for Group B with DSS





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ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/ystr20

A framework for rapid virtual prototyping: a case study with the Gunnerus research vessel

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SHIP TECHNOLOGY RESEARCH (SCHIFFSTECHNIK)
https://doi.org/10.1080/09377255.2021.1903128

A framework for rapid virtual prototyping: a case study with the Gunnerus research vessel

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ABSTRACT
Virtual prototypes (VPs) are digital models that mock-up existing or conceptual systems' behaviour. In offshore operations, VPs find usages in design, proof of concept for new equipment or method, control system testing, procedure planning, and expert crew training. Moreover, VP can be used in full mission simulators with crews of maritime and offshore engineers, in which case they integrate with control systems such as handles and dynamic positioning systems. Putting the human in the loop sets high requirements for the fidelity of the visual 3D-models and the mathematical models' validity. VPs are thus time-consuming to create and difficult to validate, even based on an existing offshore system. This paper presents an innovative framework for rapid virtual prototyping of ships for hardware and human in the loop simulations and validates the results with data gathered in a sea trial performed on a research vessel, with satisfying results for position keeping.

Abbreviations: CLI, Command line interpreter; DP, Dynamic positioning system: ship equipment used to maintain position and heading; DM, Damping matrix; Force FBK, Force Feedback Thruster1; HIL, Hardware in the loop; HITL, Human in the loop; JNI, Java native interface; LC, Loading condition; RAO, Response amplitude operator; RPM, Revolutions per minute; RPM FBK, RPM Feedback Thruster2/3 (Main/Azimuth); SCM, Source code management system; SOG, Speed over ground; VP, Virtual prototyping/prototype; VST, Virtual sea trial; sea trial performed in a simulation

ARTICLE HISTORY
Received 24 February 2021
Accepted 4 March 2021

KEYWORDS
Rapid virtual prototyping; human-in-the-loop; hardware-in-the-loop; real-time simulation; validation

Nomenclature

$\omega_{e,i}$, ω_o	Frequency of encounter, wave frequency of the ith wave component [rad/s]
g	Gravitational constant [m/s^2]
U	Ship forward speed [m/s]
ψ	Heading angle [rad]
$\boldsymbol{\eta}$	Ship motion vector [-]
$\boldsymbol{M}_{RB}$, $\boldsymbol{M}_A$	Rigid body mass and added mass matrix [-]
B, $\boldsymbol{B}_{DP}$, $\boldsymbol{B}_{MAN}$ **C**	Damping, and stiffness matrix [-]
F(t)s	External forces vector [-]
η_{ka}	kth component of the response vector [-]
$\boldsymbol{T}_{lki}$	Hydrodynamic force and moment component in the lth direction due to the excitation of the ith wave component in kth direction [-]
$\boldsymbol{A}_{lki}$, $\boldsymbol{B}_{lki}$	Added mass, damping matrix component in the lth direction due to the excitation of the ith wave component in kth direction [-]
$\boldsymbol{\nu}_r$	Ship velocity vector relative to water [-]
$\boldsymbol{\nu}_c$	Body- frame transformed current velocity vector [-]
$\boldsymbol{\nu}$	Ship velocity vector [-]
ν_l	Threshold velocity between station keeping and manoeuvring ranges [m/s]
ρ_a	Air density [kg/m^3]
$\boldsymbol{\nu}_{wr}$	Body-frame transformed wind velocity vector [-]
$\boldsymbol{C}_i$	Wind force/moment coefficients [-]
γ_{wr}	Relative wind direction [rad]
A_{FW}, A_{LW}	Frontal, lateral projected area [m^2]
$\boldsymbol{H}_{FW}$,$\boldsymbol{H}_{LW}$	Centroid of frontal, lateral projected area [-]
L_{OA}	Length overall [m]
T	Thrust [N]
t_r	Thrust reduction [-]
p_{ts}	Propulsion thrust scaling [-]
ρ_0	Water density [kg/m^3]
D	Propulsor diameter [m]
v_e	Mean entrance speed of water in the propulsor [m/s]
w_f	Wake fraction [-]
n	Propulsor revolution speed [rad/s]
PD	Propulsor pitch, angle of attach [deg]
β	Hydrodynamic pitch angle [rad]
$C_T(PD, \beta)$	Thrust coefficient [-]
a_i,b_i	Precalculated trigonometric polynomial coefficients [-]
P_{eff}	Effective Propulsion Power [W]
m_{MDO}, m_{CO_2}	Mass of Marine Diesel consumed, and CO_2 emitted [kg]
M_{cal}	Heating Value of MDO [MJ/ kg]
ρ	Engine-heat-to-propulsion Efficiency [-]
L	Ship length [m]
B	Ship beam [m]
Δ_{sim}	Time step in the simulation [s]
Δ_{wc}	Wall clock time to perform the simulation step Δ_{sim} [s]

1. Introduction

Virtual prototypes (VPs) are 'computer simulation[s] of a physical product that can be presented, analyzed,

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and tested from concerned product life-cycle aspects such as design/engineering, manufacturing, service, and recycling as if on a real physical model' (Wang 2003). Because they often simulate a system which does not exist, VPs are generally model based. This contrasts with data-driven digital-twinning approaches, which also have unexploited potential for ship and maritime technology (Bekker et al. 2019). The VPs are used for mission planning of advanced offshore operations, for which field training is infeasible or uneconomical, but for which the physical system exists, allowing thus a comparison between the virtual model and real system. The focus of the present paper is the rapid prototyping of ship models to be used in real-time time-domain simulations with hardware in the loop (HIL) and humans in the loop (HITL) for the VP of offshore operations. In recent years, an increasing number of virtual prototyping in full mission simulators have been performed to create training scenarios (Zhang et al. 2017; Zhen et al. 2020) or to verify proof of concept of innovative offshore operations with engineering teams and operational crews (Geselschap et al. 2019; Tannuri et al. 2021).

VP are often the result of the integration of many technologies and research domains: they combine the latest advancements in hydrodynamics and propulsions with cutting-edge visuals and commercial design of ship and offshore equipment (Major et al. 2020). To this respect, mathematical models of ships are the foundation of such an enterprise. Open source libraries (Fossen and Perez 2004; Gaspar 2018; Fonseca et al. 2019) are useful toolboxes, with promising visualization, but do not focus on validating models. The current state-of-the-art for VP of maritime systems is the co-simulation Function Mockup Interface (FMI), which allows the co-simulation of loosely coupled sub-systems, thereby connecting domain-specific simulations, and load-balancing the computing intensive simulations. If the paradigm has reached the level of industrial consortium initiatives (Hassani et al. 2016; Perabo et al. 2020), little work has been performed on consistently documenting the validation of the sub-systems of the co-simulation. Finally, in spite of advances in research to validate ship models (ITTC 2014; Hassani et al. 2015; Selvik et al. 2014) or use of data-driven methods for model parameter identification (Wang et al. 2020), it is still not automated and quite time-consuming. Virtual sea trials (VSTs) offer cost benefits over expensive full-scale sea trials and model tests in towing tanks; they also offer consistent tests with reproducible environmental conditions, under the scrutiny of uncertainty assessment (Gavrilin and Steen 2017; Cheng et al. 2019). Verification, sensitivity analysis, and validation of manoeuvring models are still pending subjects to update in the International Towing Tank Conference recommendations (ITTC 2014). Such tank experiments and simulation frameworks for ship navigation are well established, they often report manoeuvrability characteristics like zigzag, full speed, turning circle, and crash stop in calm or monochromatic seas. Our research focuses on offshore operations for which station keeping characteristics, integration with DP systems, estimation of energy efficiency, investigation of multiple loading conditions, and rich wave spectrum are essential. A literature research identified a gap in frameworks for the creation and the quality assurance of rapid virtual prototypes of ship for offshore operations.

This study presents a framework for creating ship models illustrated with a case study of the NTNU owned Research Vessel Gunnerus. The next section describes the software interface and the underlying ship model theory. Section 3 describes the model-making framework. Concept proofing results based on the VST and full-scale sea trials are presented in Section 4. A discussion follows in Section 5 and Section 6 concludes by summarizing the findings and offering implications for practice.

2. Software architecture and underlying ship theory

The modularity of modern simulation and co-simulation software can be analysed in layered modules as presented in Figure 1, with an upper layer focused on photorealistic visualization and control commands, a middle layer connecting and synchronizing the modules, and the lower layer delivering the physics calculation data, such as FhSim ship simulation engine (red box in Figure 1). Figure 2 focuses on the interface between the FhSim simulation engine submodule and the middle layer. The core and physics abstraction layer communicate with the Ship Simulator FhSim Interface using simulation metadata commands, environmental commands, and actuator commands and feedbacks as detailed in Table 1. The current study exploits this architecture and builds a tuning and testing framework around it. This section describes the underlying physics model.

2.1. Basic assumptions and limitations

Vessel response calculations are based on potential flow theory and the classical strip theory (Salvesen et al. 1970). The strip theory is a computational method that allows the estimation of 3-dimensional motions and forces on floating bodies using the results of 2-dimensional potential theory. This simplification dramatically reduces the modelling and processing time. It splits the hull longitudinally into an array of 2-dimensional slices. Interaction among slices is not considered. ShipX assumes the vessel to be slender and symmetric about the centreline (Fathi 2017).

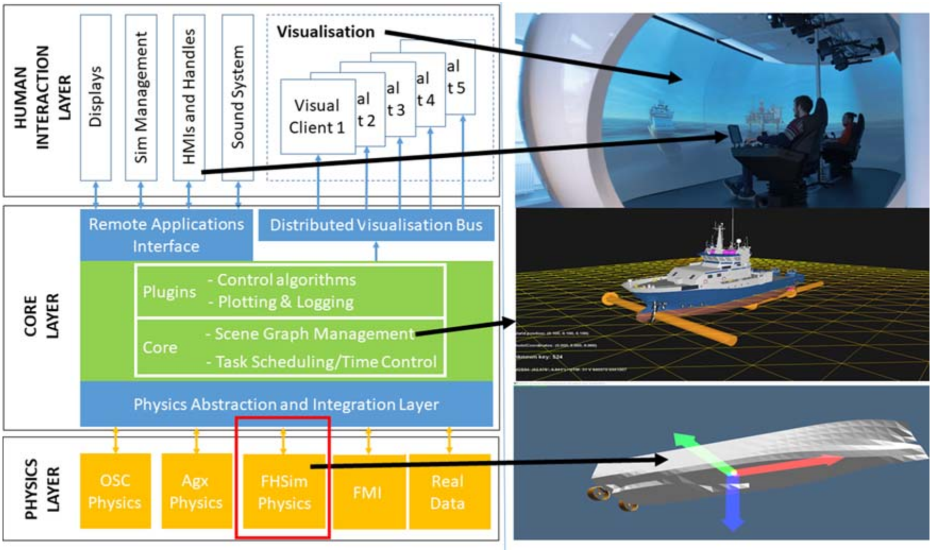


Figure 1. Software architecture for HIL, HITL virtual prototyping simulation.

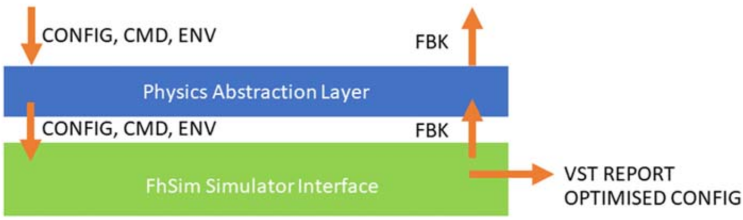


Figure 2. FhSim physics interface.

Despite this restriction, experiments show it is applicable for structures with length to breadth ratio larger than three (Journée and Massie 2001).

The potential theory is based on the assumptions that the fluid is homogeneous, non-viscous, irrotational, and incompressible. Thus, viscous effects are not accounted for. The limitations of these assumptions become significant in cases such as high-speed manoeuvres (Froude number above 0.4), shallow water manoeuvres, and proximity to other structures.

Table 1. Interface message types.

Message type	Description
Meta commands (CONFIG)	Start/stop/reset ship simulation Configuration files: placement of propulsors, hydrostatic and hydrodynamics properties of the ship Solver type (Euler, Dormand-Prince) and Time step size Ticking the simulation (advancing the simulation time)
Environment commands (ENV)	Sea bottom depth and bathymetry Wind, current, and waves properties External loads such as forces from crane, winch, fish nets etc.
Actuator feedback (FBK)	RPM/pitch/angle propeller feedback World position/orientation/velocity of the ship Forces and Moment
Actuator commands (CMD)	RPM/pitch/angle propeller commands

2.2. Equations of motion

ShipX is based on linear strip theory assuming small wave steepness and small wave amplitudes compared to ship dimensions. In such linear theory, steady-state conditions are assumed to be applicable. Therefore, ship response is considered as the sum of harmonical oscillations at wave encounter frequencies ω_{ei} (with i the index of the wave in the spectrum), as defined in Equation (1) and its six degrees of freedom equation of motion in matrix form can be written as in Equation (2), where $\mathbf{F}(t)$ includes environmental forces, the sum of wave excitation forces, and control input forces from rudders and propellers. Currents, as accounted for in the model, induce only translational forces applied at the centre of gravity of the ship; therefore, they do not induce moments. Current forces are incorporated by replacing the ship's velocity vector with a relative velocity vector from Equation (3) into Equation (4), resulting in Equation (4).

$$\omega_{ei} = \omega_{oi} + \frac{\omega_{oi}^2 U}{g} \cos\psi \tag{1}$$

$$(M_{RB} + M_A)\ \ddot{\eta} B\ \dot{\eta} + C\ \eta = F(t) \tag{2}$$

$$v_r = v - v_c \tag{3}$$

$$(M_{RB} + M_A)\dot{v}_r B v_r + C\eta = F(t) \tag{4}$$

The mass matrix elements are calculated from rigid body mass and inertia. Forced oscillations of the vessel generate outgoing waves and oscillating pressure field on the hull. Integration of this pressure over the wetted surface gives estimates for added mass forces and damping forces proportional to body acceleration and velocity, respectively. The restoring hydrostatic force behaves like a spring force and is a function of hull geometry, water density, gravitational acceleration, and mass distribution; hence, they are independent of waves or ship speed. ShipX estimates restoring coefficients in heave, roll, pitch, and coupled heave-roll degrees of freedom.

In ShipX, if the vessel is lateral-symmetric, then surge, heave, and pitch are not coupled with sway, roll, or yaw. Linearized pressure terms are integrated over the hull surface, resulting in hydrodynamic forces and moments amplitudes that can be expressed in terms of a real part (added mass effects) and an imaginary part (damping effects) such as in Equation (5). The hydrodynamic forces and moments depend on the frequency (i) and direction of encounter (k) and the hydrodynamic coefficients. In real-time simulations, they are precalculated for several frequencies, velocities, and directions (stored in the.re7 file), and, during simulation, FhSim interpolates their values at every time step of the simulation to calculate the hydrodynamic forces and moments.

$$\mathbf{T}_{lki}(\omega_{ei}) = \omega_{ei}^2 \mathbf{A}_{lki}(\omega_{ei}) + j\omega_{ei}\mathbf{B}_{lki(\omega_{ei})} \tag{5}$$

2.3. Wind forces

The wind coefficients are calculated using Blendermann's method (Blendermann 1994). The wind forces on a moving craft are calculated as presented in Equation (6):

$$F_{wind} = \frac{1}{2}\rho_a V_{rw}^2 \begin{bmatrix} C_X(\gamma_{rw})A_{Fw} \\ C_Y(\gamma_{rw})A_{Fw} \\ C_Z(\gamma_{rw})A_{Fw} \\ C_X(\gamma_{rw})A_{Fw} \\ C_K(\gamma_{rw})A_{Lw}H_{Lw} \\ C_M(\gamma_{rw})A_{Fw}H_{Fw} \\ C_N(\gamma_{rw})A_{Lw}L_{oa} \end{bmatrix} \tag{6}$$

2.4. Control input forces

The thrust delivered by each propulsor is described in Equation (7), where β is the hydrodynamic pitch angle calculated in Equation (8), and $C_T(PD, \beta)$ is the thrust coefficient of Equation (9), which depends on a series of precalculated trigonometric coefficients a_i, b_i, such that the thrust curve can match the requirements (Roddy et al. 2007). For DP operations, the propulsors must keep the position and orientation of the ship at low speed, and it is necessary to calculate the thrust in the four quadrants of the propulsor's operative mode: positive/negative mean velocity of water into the propulsor and clockwise/counterclockwise rotation of the propeller, as summarized in Table 2. When the hydrodynamic pitch angle β, is zero, the thrust is the bollard pull. Note that for the tunnel thrusters, the velocity of the water stream into the propellers tends to drop as the vessel sails at higher speeds than 5 knots, thus decreasing their contribution. v_e also decreases dramatically when the thruster ventilates, i.e. is only partially immersed. The thrust coefficients are derived from similar propellers from the Wageningen Series, with a scaling factor, wake fraction, and thrust reduction. The main propulsion of Gunnerus is based on azipods, but a similar approach is taken to calculate the drag and lift of the rudders and the torque delivered to the shaft by the engine (where applicable).

$$T = t_r \cdot p_{ts} \cdot \frac{1}{2} \cdot \rho_0 \cdot \frac{\pi}{4} D^2 C_T(PD, \beta) \Big) \times ((v_e.w_f)^2 + (n\pi 0.7D)^2 \tag{7}$$

$$\beta = \tan^{-1}\left(\frac{v_e}{n\pi 0.7D}\right) \tag{8}$$

$$C_T(PD, \beta) = \sum_{i=0}^{N} a_i(PD)\ .\cos(i\ .\ \beta) + b_i(PD).\ \sin(i.\beta) \tag{9}$$

2.5. Fuel consumption and CO_2 emission

To evaluate the energy profile of offshore operations, the fuel consumption is calculated by integrating over time the sum of effective powers of the thrusters, with T calculated in Equation (7), divided by the

Table 2. Four quadrants.

β	Propeller movement though water	Propeller thrust direction
$0 \le \beta \le 90$	Forward	Forward
$90 \le \beta \le 180$	Forward	Backward
$180 \le \beta \le 270$	Backward	Backward
$270 \le \beta \le 360$	Backward	Forward

heating value of Marine Diesel Oil (MDO) and by the engine heat-to-propeller efficiency factor, as detailed in Equations (10) and (11).

$$P_{eff} = \sum T.v_e \tag{10}$$

$$m_{MDO} = \frac{1}{\rho\, M_{cal}} {}^{P}_{eff}\, dt \tag{11}$$

To calculate the emitted mass of CO_2 from MDO combustion, the latter is assumed to be composed of long carbon chain hydrocarbons of the form C_nH_{2n+x} with $2n + x \approx 2n$. Other compounds such as NO_x and SO_x are ignored. MDO combustion can thus be formulated according to Equation (12):

$$C_nH_{2n} + \frac{3}{2} n\ O_2 \rightarrow n\ CO_2 + n\ H_2O \tag{12}$$

Furthermore, from the Mendeleev Atomic Classification Table, H having an atomic mass of 1, C of 12, and O of 16, the quotient of masses can be expressed as in Equations (13) and (14). The mass of CO_2 emitted is around three times the mass of MDO burned, a figure consistent with recent studies (Spoof-Tuomi and Niemi 2020).

$$\frac{m_{CO_2}}{m_{MDO}} = \frac{n\ CO_2}{C_nH_{2n}} \approx \frac{44n}{14n} \approx 3.14 \tag{13}$$

$$m_{CO_2} \approx\ 3.14\ m_{MDO} \tag{14}$$

This section briefly presented the underlying theory for the simulation and energy estimation, the next section addresses the tuning and reporting framework.

3. Framework for rapid virtual prototyping of ships

This section describes the innovative processes underlying the rapid prototyping framework involved as illustrated in Figure 3. Rapid VP has been achieved by automating the process over many VP projects, by structuring the data and creating a Java-based object-oriented library framework for parameter fine-tuning and the reuse of previous virtual model tests.

Firstly, a wide variety of model data must be collected (Step 1 in Figure 3). This involves gathering commercial and confidential data, listed inThe model quality is documented in an automated VST report at Step. Sea trials are manoeuvring experiments commonly performed before ship delivery, for which LC, ship behaviour, and weather conditions are documented in a poster hanging in the wheelhouse. Performing a sea trial of a ship model in a full mission simulator normally involves experienced, authoritative, but hard-to-find bridge officers, and the trials are time-consuming. To contravene these problems, Step 4 performs a VST, using an automatic reporting framework, and produces a quality assurance report encompassing all the metrics related to the vessel in Table 4. The object-oriented VST framework uses the class inheritance pattern: a ship 'child' class inherits the methods from its 'parent' class, where generic procedures are implemented, and itself implements its ship-specific procedures, such as configuring the ship and its thrusters or manoeuvres which are hard to generalize. Figure 4 (left) shows a generic pseudo code of the sea trial implemented in the framework. For each trial, before the simulation starts, the ship is initialized according to configuration and environment variables such as the wave settings, the current, and the wind settings, are set from the test configuration. Then the trial starts, and the thruster commands are adjusted at each step; the physics is ticked a time step forward, the data are collected from the solver, the iteration step is repeated until the test finishes. Then the data, gathered as timeseries, are presented in a visual format.

This section described the many steps necessary to create a functional and realistic ship model, each step having a relative degree of automation. Making ship models is a collaborative and multi-disciplinary process, involving competence from software programming, hydrodynamics, 3D modelling. Thus, there is a strong need to build an open library of propellers and hulls, knowledge accumulation, and sharing. The next section describes the model concept proofing and comparison with full scale experiments.

Table 4, from various ship and equipment designers. The data being often confidential, encapsulation methods to hide the model IP are necessary. If information about physical properties is missing, educated guesses often provide realistic values. When planning for offshore or maritime operations, specific

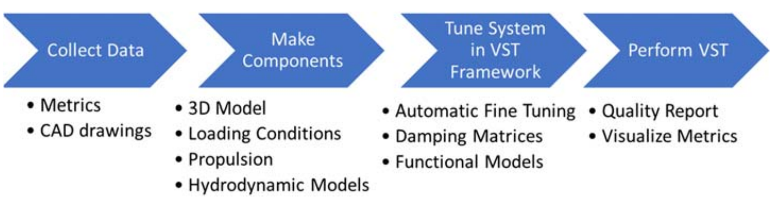


Figure 3. Ship modelling process.

```
Algorithm 1: RunTrial
Purpose: Perform a sea trial (crabbing, pirouette, full speed, zigzag
etc.)
Input: shipConfiguration, test
Output: timeSeries
# Initialisation:
  ship.configure(shipConfiguration)
  environment.setState(testConfiguration.getEnvironment()
  TimeSeries[] timeSeries
# Run Test:
   While (test is not Finished)
     state = ship.getState()
     # Generate trial specific control commands
     commands=ship.getCommands(state, test.getConfiguration())
     ship.setCommands(commands)
     # Physics engine has to calculate/integrate forces
     test.calculateNextStep()
     ship.calculateNextStep()
     timeSeries.add(state)
     timeSeries.add(commands)
Return timeSeries
```

```
Algorithm 2: TuneConfiguration
Purpose: Tuning of ship configuration to match a set of metrics
Input: initialShipConfiguration, testList[], metricsList[], numberOfGenerations
Output: optimizedShipConfiguration
# Initialisation:
  Dictionnary<Configuration,Metrics[]> configs
  tunedShipConfig = initialShipConfiguration
# Find Optimal Configuration:
For generation in 1:NumberOfGenerations:
   Dictionnary<Test,TimeSeries>  testResults
    # Run the trials (Algorithm 1) for the given configuration, assign the time series to each trial
    # the trials include.
    For test in testList:
      testResults.add(test, RunTrial(tuneShipConfig, test.getConfiguration()))
    # Compute metrics for each trial:
    # e.g. for DP Crab, the metrics is the max sway in the time series for the given thruster command
    # and store it in a dictionnary of configurations and metrics
    configs.add(tunedShipConfig, getMetricsFromTestResults(testResults)
    # Find the configuration that minimises the cost function for the whole metrics set
    tunedShipConfig = getOptimizedConfig(configs)
Return tunedShipConfig
```

Figure 4. Pseudo-code for generic trial (left) and for fine tuning the ship configuration (right).

loading conditions (LCs), i.e. waterline of the ship and load distribution in the vessel impacting the inertia matrix of the ship, must be established (Step 2). These are documented in the stability booklet, a hydrostatic stability calculation document delivered by the ship designer for the delivery of new builds and retrofits. ShipX imports hull shapes in the *.mgf format, which can be produced manually or automatically with Blender subroutines, based on the ship's 3D model.

Detailed in Section 2, the ShipX modelling tool provides a hydrodynamics frequency domain analysis of the hull for various wave directions. Table 3 presents the required configuration files, which should contain enough directions and frequencies to avoid too coarse interpolation between wave directions. This step is manual; as it is not possible to automate for multiple loading conditions in the current version of ShipX (Fathi 2017).

Step 2 also includes the modelling of the thruster by creating the trigonometric polynomial coefficients. A set of (a_i, b_i) coefficients are calculated to fit the thrust curve CT(PD,β) (Pivano et al. 2009) using a Forward Feed Neural Network algorithm (Roddy et al. 2007), requiring some manual inputs for specific meta-information about the thrusters, propellers, and rudders. Propellers and actuators simulation data are then packaged in an SCM-managed file structure that can be read by FhSim at simulation initialization.

Once thrust and torque curves and ship responses are modelled, the DP damping matrix (DM) is tuned in time-domain simulation, as the quadratic damping cannot be modelled in frequency domain. The main goal of the iterative automated routines of Step 3 framework, also shown in Figure 4 (right), is to find the DM that creates the desired behaviour in station keeping manoeuvres called DP crabbing and DP pirouette. The secondary goal is to tune damping coefficients for the manoeuvring range. To provide a unified model, FhSim phases in and out the ranges in an exponential manner, as shown in Equation (15). The result of this step is a fully functional, fine-tuned FhSim configuration.

Table 3. ShipX export files.

Extension	Description
*.hyd	Ship and loading condition data
*.re2	Added resistance
*.re7	Hydrodynamic coefficients
*.re8	Wave excitation forces
*.mgf	Ship strip model

$$\mathbf{B} \;=\; e^{-\nu_r/\nu_l}\mathbf{B}_{DP} \;+\; (1 - e^{-\nu_r/\nu_l})\, \boldsymbol{B}_{MAN} \qquad (15)$$

The model quality is documented in an automated VST report at Step. Sea trials are manoeuvring experiments commonly performed before ship delivery, for which LC, ship behaviour, and weather conditions are documented in a poster hanging in the wheelhouse. Performing a sea trial of a ship model in a full mission simulator normally involves experienced, authoritative, but hard-to-find bridge officers, and the trials are time-consuming. To contravene these problems, Step 4 performs a VST, using an automatic reporting framework, and produces a quality assurance report encompassing all the metrics related to the vessel in Table 4. The object-oriented VST framework uses the class inheritance pattern: a ship 'child' class inherits the methods from its 'parent' class, where generic procedures are implemented, and itself implements its ship-specific procedures, such as configuring the ship and its thrusters or manoeuvres which are hard to generalize. Figure 4 (left) shows a generic pseudo code of the sea trial implemented in the framework. For each trial, before the simulation starts, the ship is initialized according to configuration and environment variables such as the wave settings, the current, and the wind settings, are set from the test configuration. Then the trial starts, and the thruster commands are adjusted at each step; the physics is ticked a time step forward, the data are collected from the solver, the iteration step is repeated until the test finishes. Then the data, gathered as timeseries, are presented in a visual format.

Table 4. Model documentation: Model Input Data and Metrics for Tuning.

Purpose	Document
Hull	• General arrangement of vessel • 3D Hull shape • Design Water Line • Stability booklet with draft/trim + position of centre of gravity • Wind area: lateral and frontal area above water [m^2] • Response Amplitude Operator (RAO) documentation • Mass and Added Mass Matrix • Bilge keels dimensions and positions
Vessel (Metrics)	• Full speed ahead [kt], thrust allocation [kN], power used [MW] • Wheelhouse poster • DP capability report: DP envelopes for various weather conditions and thruster failures • Crab manoeuvre: maximum sideways speed by using thrusters [kN], thrust allocation, power used • Pirouette manoeuvre: maximum yaw speed [deg/min], thrust allocation • Heel decay: roll eigen period and oscillations • Surge decay (to 5% of initial value 2.5 kt) • Sway decay (to 5% of initial value from max sway in kt) • Yaw decay (to 5% of initial value 2.5 kt)
Propulsors	• Propulsor positions and mounting angle • Direction of rotation (clockwise/counterclockwise) • Nominal thrust of main propeller (Bollard Pull) [kN] • Max/min RPM/pitch/angle • Thrust curves: power (RPM /pitch) and thrust (RPM, pitch) for each thruster • Thruster loss thruster-thruster and thruster-hull
Actuators	• Effect: maximum effect to propeller [kw] • Gear: gear rate propeller/motor • Ramping times for pitch, RPM, rudder and azimuth angles

This section described the many steps necessary to create a functional and realistic ship model, each step having a relative degree of automation. Making ship models is a collaborative and multi-disciplinary process, involving competence from software programming, hydrodynamics, 3D modelling. Thus, there is a strong need to build an open library of propellers and hulls, knowledge accumulation, and sharing. The next section describes the model concept proofing and comparison with full scale experiments.

4. Concept proofing and comparison with full-scale trials

Model validation requires an inquiry of its real time performance under rich environment and of its fidelity to the real-life systems. A VST report for the R/V Gunnerus is accessible in (Major and Zghyer 2020). The following subsection addresses the performance of the engine, followed by proof of concepts of the different aspects of the model and a deeper analysis of DP crab manoeuvre.

4.1. Validation of the real-time performance

Dense wave spectra are necessary to ensure realistic human experience during simulations for offshore operation design and planning. However, the number of wave components in the spectrum negatively impacts the real-time performance of the simulation engine, which is measured by the real time index (RTI). As formulated in Equation (16), the RTI is the quotient of the simulated time step over the wall clock time necessary to calculate the step.

$$RTI = \frac{\Delta_{sim}}{\Delta_{wc}} \tag{16}$$

Figure 5 shows a scalability test of FhSim Interface relative to the number of wave components in the spectrum. A DP crabbing manoeuvre is performed for 100 s simulated time, with a synthetic wave spectrum containing a variable number of wave components, repeated multiple times to mitigate the possible jitters caused by the multi-tasking of the operating system. The tests are performed using the following solvers: Euler and Dormand-Prince with time steps of 100 and 10 ms, respectively, denoted in Figure 5 as E100, E10, DP100, and DP10. Bigger time steps scale relatively well for 200 wave components: DP100 starts around 25 and finished at 5. E100 starts with RTI at around 30 for one wave component and ends at 10 for 200 ones. The shorter the time step, the more calculations the engine must perform for a given end simulation time, impacting negatively on performance but positively on stability and precision. DP10 and E10 begin to be slower than real time ($RTI < 1$; $\log_{10}(RTI) < 0$) and are not fast enough for HIL/HITL from 130 and 180 wave components, respectively. Figure 5 thus illustrates the limit of the algorithms but shows acceptable performance of the simulation engine.

4.2. Comparison of virtual sea trials for DP operations

Figure 6 is taken from the VST report and documents various trials such as the DP crabbing trial velocity and

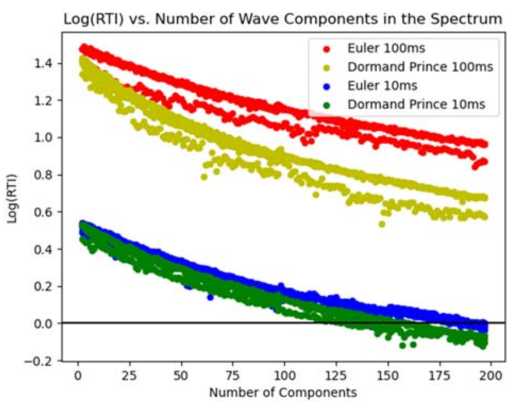


Figure 5. FhSim $\log_{10}$ (RTI) as function of the number of wave components and solver method.

Full speed forward: 11.26 Knots			
Name	RPM	Pitch [deg]	Azimuth [deg]
conMainPort	204	25	0
conMainStarboard	204	25	0
Crash stop distance/time: 88.24 m / 0.37 min			
Name	RPM	Pitch [deg]	Azimuth [deg]
conMainPort	204	25	180
conMainStarboard	204	25	-180
DP Crab maneuver sideways speed: 3.39 Knots			
Name	RPM	Pitch [deg]	Azimuth [deg]
conMainPort	81	25	90
conTunnel	275	30	0
conMainStarboard	0	25	0
DP Pirouette maneuver yaw speed: 293 deg/min			
Name	RPM	Pitch [deg]	Azimuth [deg]
conMainPort	102.0	25	-90
conTunnel	275.0	30	0
conMainStarboard	0.0	25	0
Decay time to 5% of initial value from:	Surge 2.5 Knots	Sway 2.50 Knots	Yaw 60 deg/min
	23.6 seconds	165.8 seconds	5.0 seconds
MDO Consumed and CO2 emitted			
Full speed MDO [kg]	9	Full speed CO2 [kg]	29
DP Crab MDO [kg]	1	DP Crab CO2 [kg]	4
DP Pirouette MDO [kg]	15	DP Pirouette CO2 [kg]	48

Figure 6. VST trials for DP operations.

thrust allocation for a pure sway translation; the thrust allocation is based on a simple moment balancing algorithm between the fore and stern thrusters. During the DP pirouette, the vessel rotates around its centre of gravity in yaw, with minimal surge and sway velocity. The constructed decay tests in surge, sway, and yaw from an initial small velocity, without any applied thrust, are representative values of the damping in the respective dimensions. Some damping is not modelled by ShipX and the tests show the effect of the added damping on the ship's behaviour.

The VST results presented in Figure 6 are consistent with the sea trials performed on the research vessel on 21st of November 2019. The DP pirouette manoeuvre of the VST has a maximum rotational yaw speed of 293 degrees per minute, this shows good concordance with the 270 degrees per minute measured during the full-scale sea trials, as seen in Figure 10 (right). The DP Crab test is analysed deeper in Section 4.6. Fuel and CO_2 estimations are presented at the end of the table.

4.3. Visualization of thruster parameters

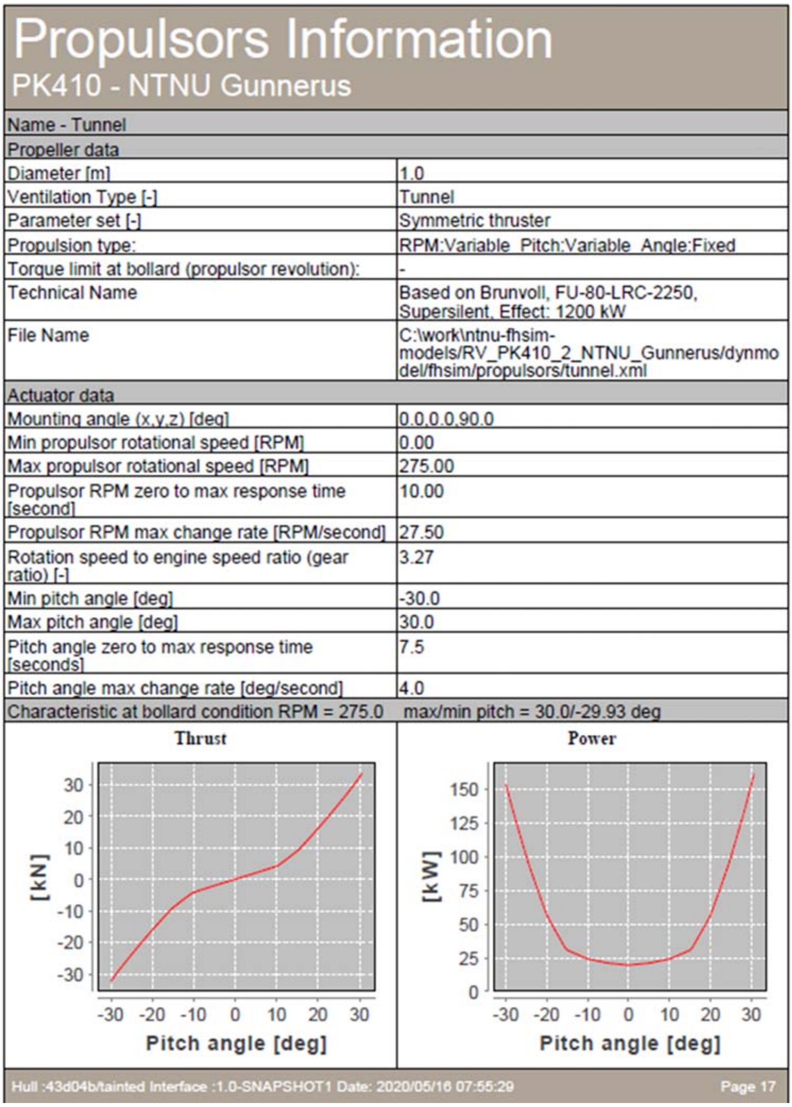
Figure 7 shows VST thruster information for the tunnel thruster. Some design data could be gathered but thrust curves were not provided. The thruster models are thus validated by their performance in virtual sea trials.

4.4. Comparison of full-speed trials

Full speed tests might not be deemed important for offshore operations but having a navigation model with realistic behaviour including correct maximum speed and time to maximum speed is a requirement for maritime personnel. If the full-scale trial started with a non-zero velocity, Figure 8 shows a good consistency between virtual and real test in top speed and time to reach it.

4.5. Visualization of roll damping in free heel decay

Figure 9 shows two virtual heel decay sea trials where the ship starts at 5 degrees roll and is left to retrieve equilibrium. Modelling the correct roll eigen period and damping is important for crane operations and is still the subject of current research. The roll properties depend on the LCs and it is challenging to measure them accurately in full-scale experiments. Furthermore, roll can be measured from onboard motion sensors, but the measurements must be completed by wave spectrum analysis to identify the eigenfrequencies via the ship response and the measured wave spectrum. This requires wave radar, which is still expensive and not installed on every ship, leaving the modeler with assumptions of correct values. Finally, to prevent sea sickness during virtual prototyping sessions in full mission simulator, it is sometimes necessary to dampen the roll. This is possible without affecting the realistic behaviour of the model, as in the station keeping model, the low-speed roll damping parameters have no impact on the DP capability of the ship. With both a linear and quadratic additional damping term in roll, the decay shown in Figure 9 (right) is shorter than the undampened decay in presented (left), but it has the same roll period.



Propulsors Information
PK410 - NTNU Gunnerus

Name - Tunnel	
Propeller data	
Diameter [m]	1.0
Ventilation Type [-]	Tunnel
Parameter set [-]	Symmetric thruster
Propulsion type:	RPM:Variable Pitch:Variable Angle:Fixed
Torque limit at bollard (propulsor revolution):	-
Technical Name	Based on Brunvoll, FU-80-LRC-2250, Supersilent, Effect: 1200 kW
File Name	C:\work\ntnu-fhsim-models/RV_PK410_2_NTNU_Gunnerus/dynmodel/fhsim/propulsors/tunnel.xml
Actuator data	
Mounting angle (x,y,z) [deg]	0.0,0.0,90.0
Min propulsor rotational speed [RPM]	0.00
Max propulsor rotational speed [RPM]	275.00
Propulsor RPM zero to max response time [second]	10.00
Propulsor RPM max change rate [RPM/second]	27.50
Rotation speed to engine speed ratio (gear ratio) [-]	3.27
Min pitch angle [deg]	-30.0
Max pitch angle [deg]	30.0
Pitch angle zero to max response time [seconds]	7.5
Pitch angle max change rate [deg/second]	4.0
Characteristic at bollard condition RPM = 275.0	max/min pitch = 30.0/-29.93 deg

Figure 7. Thruster characteristics and bollard pull performance.

4.6. Comparison of DP Crab manoeuvres

A DP Crab manoeuvre experiment was performed during the full-scale sea trials on R/V Gunnerus as seen in Figure 10 (left). Tables 5 and 6 display the mean and standard values of the variables of interest. The analysis of the standard deviation in the experimental data indicates that the heading was relatively constant; the DP system kept a steady heading by dynamically allocating thrust by changing the direction of Thrusters 2 and 3 (main propulsion) and keeping the thrust of the bow thruster constant at around 100%. The ship velocity relative to water, $\boldsymbol{v}_r$, is 3.64 kt. The VST value matches the experimental data well, with a crabbing speed of 3.39 kt, though the respective thruster allocations differ. The thrust allocation in VST is generic, with one of the stern azipods constantly compensating the momentum of the thrust of the less powerful bow propulsion. Furthermore, the VST DP crab test is performed without environmental perturbations due to wind, waves, and current. During the experimental DP crab manoeuvre, both the azimuth thrusters were activated, in an almost anti-parallel orientation, to neutralize each other and to compensate the effect of the wind and the current in the surge direction, while balancing the thrust of the bow thruster.

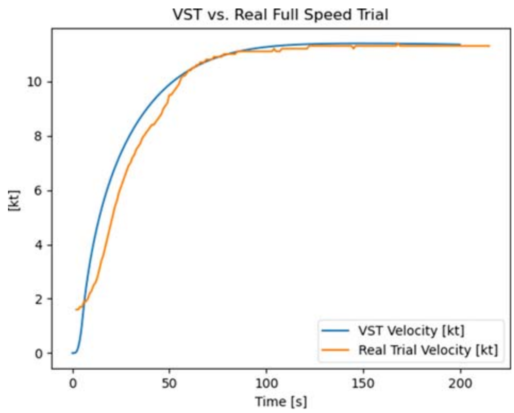


Figure 8. Full speed trial: VST (blue) vs real trial (amber).

4.7. Comparison of zigzag tests

The virtual and real zigzag tests are performed according to IMO Standards for Ship Manoeuvrability. The simulated results presented in Figure 11 (left) are acceptable, as they show a realistic behaviour but fail to precisely replicate the full-scale experiment Figure 11 (right): the overshoot angles and the speed drop are too extreme.

5. Discussion

Tuning a model with orthogonal output dimensions is relatively straightforward. But when the outputs are not independent, it is necessary to automate the task and structure the problem in such a way it is possible to optimize with algorithms such as genetic algorithm or gradient descent. The VST framework aims at being a transparent depiction of the model's quality and a clear indication of where the time-domain behaviour is plausible and where it is not. Comparisons between full-scale sea trials and VST show acceptable correspondence for the DP crab and pirouette tests.

The number of wave components plays a major role both in the realism of the sea in the visuals and in the relevance of the physics effects on the submerged items and on the hull. Modular simulation framework must transmit environmental parameters to all relevant physics modules, this has an impact on the performance of physics engines themselves as shown in Figure 5, but also on the performance on the interprocess or network-based coordination between the co-simulation modules as seen in Figure 2.

The VST report on the Gunnerus indicates that the simulated model behaves realistically and in accordance with measured values for the trials in question. There are many sources of human and programmatic error: ShipX configuration files, propeller configuration, fine-tuning, software errors in the simulator itself (FhSim, VST), testing procedures with wrong setup and test dataset, control command algorithm, system time synchronization, direction convention for the sensors ('wind comes from', 'waves go to'), and procedures presenting the data. That is, basically any step depicted in Figures 3 and 4 could be a source of error. There are so many input parameters in VP models that quality assurance and the use of modern source version control (e.g. git) are essential, especially when working in teams of experts. The many trials

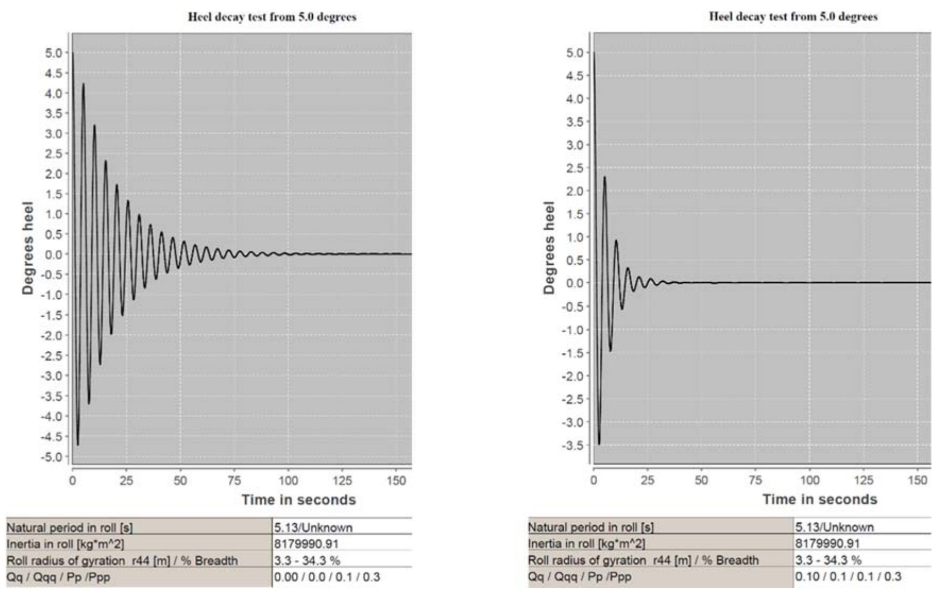


Figure 9. VST tuning the roll damping: No damping (left) aggressive artificial damping (right).

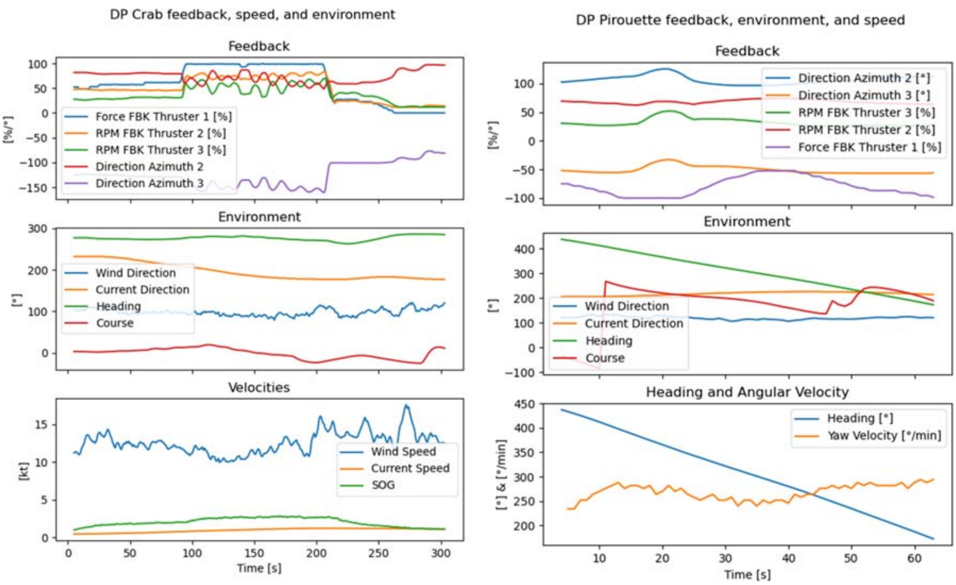


Figure 10. Full-scale Crab (left) and Pirouette (right) sea trials.

Table 5. Thruster allocation values from the Crab Test of the Sea Trials on Gunnerus 21.11.2019.

	Force FBK Thruster 1 [%]	Direction Azimuth 2 [deg]	RPM FBK Thruster 2 [%]	Direction Azimuth 3 [deg]	RPM FBK Thruster3 [%]
Mean	98.4	67.2	74.3	−148.3	53.4
Standard Deviation	1.31	9.91	4.21	7.54	9.42

Table 6. Experimental values from the Crab and Pirouette Test of the Sea Trials on Gunnerus 21.11.2019.

	Wind Speed	Wind Direction	Current Speed	Current Direction	Course	Heading	SOG
	[kt]	[deg]	[kt]	[deg]	[deg]	[deg]	[kt]
Mean	11.51	92.6	1.03	188.4	1.3	277.0	2.62
Standard Deviation	1.14	5.84	0.13	9.92	13.38	3.35	0.12

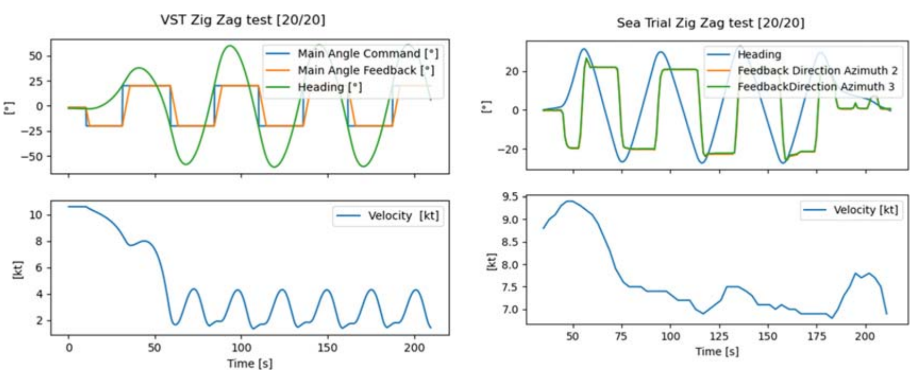


Figure 11. Zig zag tests: Virtual sea trial (left) and full-scale sea trials (right).

documented in the VST report do not show major shortcomings such as failing manoeuvres or crashing simulation; the report is accessible online (Major and Zghyer 2020).

6. Conclusion

A framework for virtual prototyping of ship for offshore operations was presented, demonstrating station keeping capability specific to such operations. Furthermore, an automatic tuning and report tool chain was illustrated, together with a documentation of operation energy profile. The real-time performance of the physics module was assessed in terms of wave spectrum density.

Making VPs of maritime and offshore systems is a challenging and time-consuming task which requires multi-disciplinary competence. It demands the gathering information from IP design, exporting the various files to required formats and coordinate systems in the toolchain, and testing the model in an efficient and valid way. Completing this efficiently requires automation. This paper presented an iterative and systematic method and framework to build VPs in a rapid and robust manner, using modern software engineering methods. We argue that there should not be virtual prototypes and co-simulation without trackability of information nor without model quality reporting.

The VST framework is useful to automate the testing and quality-assurance procedures and to meet the needs of commercial documentation and academic research. Furthermore, VST is an inexpensive alternative or complement to towing tanks and field experiments. A core property of the framework is its reusability: the object-oriented code is general enough to run generic tests, yet specific enough for each vessel. The framework is under continuous improvement of the tuning and test procedures and subroutines, making them more robust and generic, as well as adding new virtual trials for each project. It is necessary to build a library of assets: hulls and propulsors which can be reused in various subsequent projects, often with sisterships. The fast solvers could be used for other applications such as ship motion prediction in real-world situations: giving warnings during manoeuvring, predicting collision during berthing, and training generations of autonomous systems in an efficient, controlled, and risk-managed manner.

Acknowledgements

This work was supported by the NRC 'Data-driven ship models for rapid virtual prototyping', industrial PhD. under Grant Number 285949 and regional structural fund of Mid Norway Grant Number 298399, the IKTPLUSS Project 'Remote Control Centre for Autonomous Ship Support', Grant Number: 309323, and by Offshore Simulator Centre. Many thanks to our colleagues from NTNU for gathering the data, performing the sea trials on Gunnerus, making the 3D models, and creating the hydrodynamics model and to our colleagues from SINTEF for their excellent comments and help. We appreciate Brunvoll and Kongsberg Maritime's contribution and are grateful for the data about the thrusters.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by Norges Forskningsråd [grant numbers 309323; 285949].

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ISBN 978-82-326-5946-3 (printed ver.)
ISBN 978-82-326-5441-3 (electronic ver.)
ISSN 1503-8181 (printed ver.)
ISSN 2703-8084 (online ver.)

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