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Manoeuvrability and communication requirements for safe operation when manned and unmanned vessels meet

by Ingmar Wever at Damen Shipyards,
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Summary

This research aims to help in solving the challenge of communication between manned and unmanned vessels. The communication between manned and unmanned vessels has not been touched upon in earlier projects. This report proposes two partial solutions to tackle the challenge of communication. The first solution is to avoid communication by staying well clear. The second solution is to develop a protocol based on existing systems and protocols, to facilitate communication between manned and unmanned vessels.

These partial solutions are selected by analysing the factors that influence the decision process during navigation. This decision process is also relevant to determine which situations are critical for avoiding communication by staying well clear. The decision process itself consists of the following phases: Form a mental model, identify the situation, predict future states, define strategy, execute actions, result state. The environment and communication are factors that influence the result and this process in general.

Impact of manoeuvrability on the necessity to communicate

Based on the decision process is a decision tree defined to gives insight into all different possibilities for every phase. Critical situations are determined by evaluating the branches in the decision tree using multiple criteria. This evaluation results in common critical situations, each of these situations has a favourable strategy. To ensure that a ship can avoid communication by staying well clear must all situations be evaluated to specify the manoeuvring requirements for the vessel.

This research developed a method to evaluate a common critical situation. The first situation to test this method is a perpendicular crossing situation where two ships are on a collision course. An evasive manoeuvre is the favourable strategy in this situation. The common critical evasive manoeuvre is described as a manoeuvre where the closest point of approach (CPA) and passing distance are increased as much as possible while returning to the original course. This is done in the least amount of time, and the least distance travelled forward. During the manoeuvre will the ship give maximum rudder to one side, followed by maximum rudder to the other side, until the ship has returned to its original course.

The most relevant manoeuvring characteristic in this situation is the advance distance. This distance is measured during the turning-circle test. A validated simulation tool tests the evasive manoeuvre with varying inputs which determine the advance distance and distance travelled forward. This results in the relation between the distance travelled forward, the advance distance and the resulting CPA. The distance travelled forward for this manoeuvre

is the same as the distance that is left when a ship wants to avoid a collision. This distance is also called the distance till initial CPA. The found relation can be used for both the ship design as for the design of shipping lanes, as it gives requirements for both the manoeuvring characteristics and required manoeuvring space. It shows how much distance a ship with specific advance distance needs for an evasive manoeuvre, that results in a desired CPA.

Higher advance distances will result in higher distances till initial CPA and will need even more space between traffic lanes. The advance distance can be improved by adding rudders or changing the rudder profile. An improvement of 10% on the advance distance results in a reduction of 10% on the distance required to react.

The developed method validates whether a specific ship reaches a certain level of well-clear. Testing more situations with this method will make it possible to give a set of manoeuvring requirements for a ship, related to the operational area. More research and number crunching are necessary to determine the acceptable CPA and passing distance to avoid communication and be well-clear. The results from that will also help to define what level of well-clear is necessary.

A protocol to enable communication between manned and unmanned ships

In the situations where it is not possible for a ship to get well-clear by itself, communication is necessary. Manned vessels are using VHF-radio and information exchange via AIS for this. For the communication between unmanned ships, it will be likely to develop new systems that share more information. This information is well interpretable by computers.

For the communication between manned and unmanned ships, the first steps are taken to develop a protocol. This protocol is based on existing protocols and systems, to avoid changes for manned vessels. A protocol defines the format and the order of messages exchanged between two or more communicating entities, as well as the actions taken on the transmission or receipt of a message.

The most important reasons for communication are when an operator deviates from rules, deviant behaviour is registered, or more information is necessary to decide on the right strategy. Problems that might occur with communication are an information overload of the crew or communication channels, resulting in a loss of situational awareness. In case of communication between manned and unmanned vessel can the operator both be an automated system or a human seafarer.

This research did not look into developing a full functional protocol, as more actors should be taken into account, i.e. traffic controllers and surrounding ships. This research did look into the feasibility of using existing systems and protocols to develop a new protocol. The

situated Cognitive Engineering (sCE) method is used, as the seafarers are an essential factor in developing a reliable protocol. This method helps to develop an interactive and human-centred protocol, that is built on theory and empirical research.

The core of the protocol is a conversational agent using Standard Maritime Communication Phrases (SMCP). The protocol around SMCP works with message markers and natural language variations on the SMCP phrases. Other signals are used to show that a ship is unmanned. The agent should be able to negotiate possible strategies to ensure that a seafarer has a feeling of autonomy, which is necessary for trust.

The protocol is evaluated in an experiment with 16 experienced seafarers. Measures for acceptance of the protocol in this stage are performance, trust, situation awareness and satisfaction. In the experiment will the participants get a questionnaire and have to operate a vessel in two situations. It depends on the test group in which situation they use the protocol. The experiment gave valuable feedback on the protocol which can be used in next iterations, such as the limited usage of marker words by seafarers, problems with speech recognition of non-western crews, and possible usage of text messaging via AIS or INMARSAT-C.

The main conclusion is that it is feasible to develop a protocol using SMCP and a conversational agent. The protocol is easy to use, which resulted in a good performance of participants during the experiment. The participants are confident that the system will work as expected and thus will trust the protocol. The protocol did not influence the situation awareness during the experiment, but more situations should be evaluated to ensure that this is the case. The participants liked that the protocol is based on SMCP, as this is an 'idiot proof' system.

When implementing the full protocol, more evaluations are necessary. These evaluations should consider more different situations. These will not only say if there is an impact on the performance, trust, situation awareness and satisfaction of seafarers. But the results of these evaluations should also show what this impact is, which means that it is possible to mitigate a negative impact and exploit the advantages.

The next step for developing the protocol is the mapping of situations to the possible strategies and required information. The design philosophies for uncovering the relation between manoeuvring criteria and CPA, and designing a protocol have been proven to be successful.

Preface

I did start my journey to become a shipbuilder in 2011. Delft has become my second home in the years since. In those years I have not only been introduced in the world of shipbuilding. But I have also developed myself towards a "Delftse Ingenieur". This report is the last step in this journey. And although the writing of this report has been an individual accomplishment. I could not have done it without the help of some very talented, critical, caring and enthusiastic people around me.

First of all, I would like to thank all the people I have met at Damen Shipyards, where the doors were always open to ask questions and discuss our extraordinary industry. A special thanks to Toine Cleophas, my supervisor at Damen. Besides being a supervisor, he has also been my mentor. He showed me the maritime industry and Damen from his perspective, which I could not have learned at any university. Thank you for the late afternoon discussions at the office, in the car, and with a beer in our hand.

Furthermore, I would like to thank Robert Hekkenberg as a guide in the world of academics. By questioning the steps I took and guiding the scope. He has helped me through many iterations, which have resulted in not only a good design, but also a design well sold.

Another thank you goes to Mark Neerincx, as supervisor, he has helped me to explore the world of human-computer interaction research. With his academic knowledge and practical experience did he help me to keep the balance between developing knowledge and a product.

Beside my supervisors have there been many more people involved in the steps taken, which resulted in this thesis. It is not possible to name all of you. I want and need to show my utmost gratitude to some exceptional people. My parents, pappa and mamma, I want to thank you for giving me the roots to get back to, and wings to fly beyond the horizon.

Ingmar Wever
Amsterdam, December 2018

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List of Abbreviations

AIS Automatic Identification System

AMS Alarm Management System

ARPA Automatic Radar Plotting Aid

BNWAS Bridge Navigational Watch Alarm System

CAM-HMI Central Alert Management - Human Machine Interface for presenting and handling of alerts

COLREGs Convention on the International Regulations for Preventing Collisions at Sea

CPA closest point of approach

ECDIS Electronic Chart Display Information System

ENC Electronic Navigational Chart

GNSS Global Navigation Satellite System

GPS Global Positioning System

IDPs Interaction Design Patterns

IEC International Electrotechnical Commission

IHO International Hydrographic Organization

IMO International Maritime Organization

HCI Human-Computer Interaction

Navtex Navigational text Messages

no-UI Non-visual User Interface

OoW Officer of Watch

sCE situated Cognitive Engineering

SMCP Standard Maritime Communication Phrases

SMNV Standard Marine Navigational Vocabulary

SOLAS International Convention for the Safety of Life at Sea

STCW International Convention on Standards of Training, Certification and Watchkeeping for Seafarers

TEU Twenty foot Equivalent Unit

UID User Input Device

VDES VHF Data Exchange System

VHF Very High Frequency radio

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Introduction

The Maritime industry is tapping into the world of automation and digitalisation. The automation level of vessels is increasing rapidly. Vessels are being connected to the shore by different means. Operational data is becoming available and enriched with data for weather, ship design and maintenance statistics. These technologies boost the development of autonomous and unmanned vessel designs [Blanke et al. (2017)]. At the same time the Maritime Industry faces challenges when it comes to crewing and safety [Cappelle et al. (2018)]. Also increasing competition makes it hard to realise healthy margins. These trends trigger the Maritime Industry to embrace autonomous sailing technologies to secure a healthy future.

These business developments are reflected in the significant amount of research and development projects [SMASH (2017)] [Eriksen (2017)] [MUNIN (2016)] [Sames (2017)] [Rolls-Royce (2015)] [Waterborne (2016)]. Each of these projects tackles one or more challenges in the development of autonomous sailing. However, the topic of communication between unmanned and manned vessels has not been touched upon [Saarni et al. (2018)]. In chapter 1, the challenges and related projects are discussed. Currently, no solutions are available yet, yet it is necessary to ensure the safety of all vessels: manned, unmanned, remote, automated and autonomous.

This report presents the results of the study on communication between unmanned autonomous sailing vessels and manned vessels. It presents a design philosophy which has been translated into a methodology for handling communication. Both by staying well clear to avoid communication, and the development of a protocol that is derived from current systems and protocols and that is evaluated with experts.

Context

In many situations the Convention on the International Regulations for Preventing Collisions at Sea (COLREGs) is sufficient to determine the intentions of other vessels [IMO (1972)]. These can be seen as ship separation rules, which guide all vessels to make early and correct alterations to their course. It will take more time to assess the situation when using VHF, as there is less time to act limiting the possible strategies. These rules also apply to autonomous ships, and can thus be used when manned and unmanned vessels meet. Examples of such regulations are to stay on the starboard side and to make clear manoeuvres. When these rules cannot be applied, communication is necessary. There is a much higher risk of accidents when this communication does not follow protocols. There are also situations in which regulations are contradictory, such as the accident between Artadi and St-Germain (appendix C). These contradictions occur more often in complex situations, such as a harbour approach.

The risks when COLREGs are not sufficient can be mitigated by making decisions well in advance. What well in advance means depends on the manoeuvrability and operation of a vessel. A cargo vessel will follow common paths, while a small tugboat might move around much more. These situations result in more false positives on potential collisions with other vessels when using the same safety domain and evaluation system. The impact of manoeuvrability means that it is necessary to think several minutes ahead with a large ship, while this timespan is much shorter for a small tugboat. The time-domain for decision-making depends not only on the ship characteristics but also on the waterway characteristics. Chapter 2 discusses this in more detail. Examples are the depth, traffic separation schemes and harbour entrances.

If it is not possible to make a decision well in advance, it is often due to a lack of information. Communication solves this problem. This communication between manned vessels happens with different means. Most important is communication via VHF, also is information from the AIS used to identify ships. This information can also help to determine the intentions of the vessel based on the type of vessel or destination. The used protocols for these systems are discussed in appendix A.

Design philosophy

We developed a strategy to cope with the challenge of communication between manned and unmanned vessels, without the introduction of new systems to the bridge of manned vessels. At first, we will try to avoid the need for communication, by staying well clear from other ships. Due to circumstances this might not be possible and communication is required. For the communication between manned and unmanned vessels, a new communication protocol must be developed. The strategy for developing this protocol can be used as a foundation to build a system for decision-making that ensures safe operation for both manned and unmanned vessels. Multiple steps are required to develop and implement this strategy and protocol.

First, the decision model for safe navigation has been analysed in order to deduce the relevant factors for decision-making. The next step is to study how these factors influence the decision-process. This is used to specify critical situations. In those critical situations it isn't possible to navigate without communication. Thus identifying situations where a communication protocol is necessary. Using the situated Cognitive Engineering (sCE) method, the operational demands, relevant human factors and envisioned protocol are defined. The current state of the maritime industry is thereby taken into account.

Research questions

The report covers two research domains: Maritime Technology and Computer Science. The part on maritime technology focuses on the situation where manoeuvring is just enough to avoid the need for communication. The computer science part focuses on the development of a communication protocol. Answering the following research questions:

> *How do ship manoeuvrability characteristics influence the domain for decision making, to ensure that the chosen strategy will result in a closest point of approach that does not require communication?*
>
> *Will a protocol based on existing maritime systems and communication protocols be sufficient to ensure safe navigation, while manned and unmanned vessels encounter each other?*

Report structure

This report contains four parts. Each part discusses the challenge of communication between manned and unmanned vessels. Part I describes the context of autonomous shipping. This context and a decision-model show why communication is a challenge, and how this challenge can be tackled.

Part II describes how communication can be avoided. It is important first to determine when communication is necessary. This is especially the case in critical situations, i.e. deviating from the standard safety guidelines. These situations are tested in a simulation environment. The simulations help to define the time-domain for decision-making to ensure safe operation. These situations are simulated, using a validated manoeuvring model. Thereby is evaluated whether ships need communication in fewer cases if the decision-domain is improved.

Part III will focus on critical situations where communication is a must. A communication protocol between manned and unmanned vessels has not been part of any known project. Communication is necessary when there is a lack of trust, missing information or the time-domain for decision-making becomes critical. The objective is to validate whether it is possible to design a protocol that is based on existing systems and protocols. The situated Cognitive Engineering (sCE) method is used.

In part IV is finally concluded what the results from the previous parts mean for the maritime industry and what the next steps should be to ensure safe operation of autonomous vessels, related to the challenge of communication.

Part I

The problem of communication for unmanned vessels

The most important thing in communication is hearing what isn't said.

– Peter F. Drucker [Moyers (1988)]

Safety at sea has been a relevant topic for as long as ships exist. Nowadays communication has become very important to ensure the safety of all vessels. Communication can be all forms of sharing information. Before the invention of radio communication, ships lost all connection with the shore and other ships when setting sail. Ships used flags when they were close to other ships or the coast. This form of communication was not complete as it only gave limited insight into the intentions of other vessels for example. To ensure the safety of ships, they agreed on how to act in specific situations. These agreements became the foundation of the regulations as written down in the Convention on the International Regulations for Preventing Collisions at Sea (COLREGs) [IMO (1972)].

New technologies led to new ways for communication, such as radio communication. This led subsequently to safer operations. Communication works very well between manned vessels, as a human can work well with limited unstructured information compared to computers. Communication is a challenge for unmanned ships. But autonomous ships are getting closer. Thus a solution must be found. Thereby comes that new technologies have led to more complex situations, as ships get bigger and perform more complex operations. Due to the limitations of unmanned vessels when it comes to communication, it does become even more critical to make the right decisions well in advance. To avoid critical situations and enable those ships to share the correct information at the right moment in time.

Many projects are working on unmanned autonomous ships. Chapter 1 starts to describe why steps are taken towards autonomous and unmanned shipping, including the economic and social incentives. Followed by a description of projects, showing the technological push factor. This description will give more insight into the challenges as seen relevant by others, for the introduction of unmanned vessels and the communication between manned and unmanned ships. A distinction is made between the exploratory projects, aimed to develop a vision of the future, and the applied projects intended to develop prototypes in the shorter term. Chapter 2 relates these challenges to the decision model for ships. This decision model illustrates that the need for communication depends on the steps taken in the decision process, i.e. that it might be possible to avoid communication and ensure safe operation.

1 | Steps towards safe unmanned shipping

This research focused on improving safety at sea by mitigating the risk that comes with communication between manned and unmanned vessels. This challenge has not yet been in the scope of the major projects. This chapter first discusses the reason for this transition, thus what the social or economic incentives are. Followed by the technological drivers in the form of projects that work on autonomous shipping. Additionally, is shown how these projects address the problem of communication. To evidence that the challenge of communication between manned and unmanned vessels is less explored and deserves attention.

1.1 Why autonomous and unmanned shipping

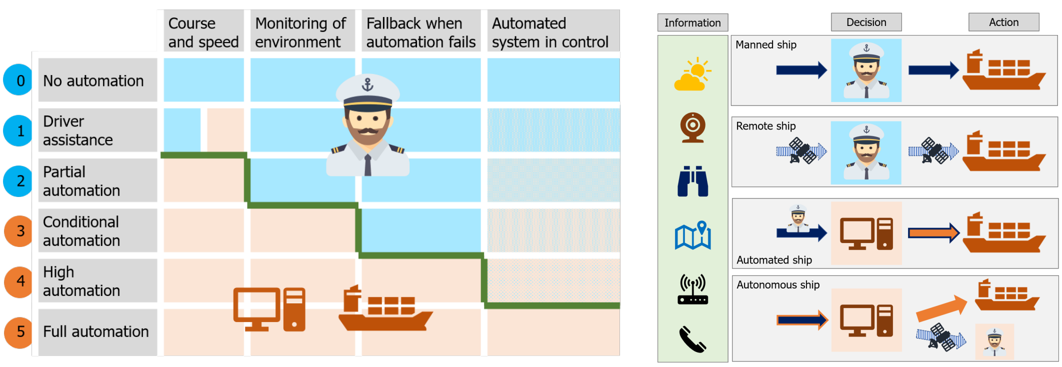
Due to digitalisation, ships will become more sophisticated. Sensors generate more data, connectivity will improve and new ways to visualise data become available. These enable ships to communicate with managers and traffic controllers continuously. Initially, this can be used to analyse data and improve advice based on expected weather, fuel consumption and arrivals at bottlenecks like ports and bridges. However, further ahead this might result in unmanned vessels, that might operate remotely. In parallel, is there the transition where people are taken out the chain of commands, which will result in automated or completely autonomous vessels. The main arguments heard for the transition towards autonomous or unmanned ships [Saarni et al. (2018)]:

- *Improved safety*, as human errors cause most accidents. Moreover, unmanned ships will result in less crew at sea. Thus less crew is at risk when an accident occurs.
- *Lower cost*, as insurance goes down due to improved safety. Thereby is manning a large portion of total cost. More automation will result in less crew, which have to be educated better.
- *Higher productivity*, as the utilisation rate of ships, can be improved, when technological developments in connectivity are used more effective. Thereby comes that computers do not have to work in shifts, go home or take breaks.
- *More comfort and attractive industry*, as people can have more regular hours to work and do not have to be away for many weeks when working remote.

The maritime trade volumes are expected to increase in the future and accordingly the numbers of ships needed to transport the freight will grow, as will the number of seafarers required to operate the vessels. At the same time, European shipping faces a lack of seafaring personnel already today [Cahoon et al. (2014)]. An often mentioned reason for this lies in the unattractiveness of seagoing professions, especially for youngsters. This unattractiveness is caused to so some extent, by seafaring's inherent problem of lacking family friendliness and the high degree of isolation from social life that comes along with working on a seagoing ship. The current trend towards slower sailing speeds justified by ecologic and economic considerations increases the length of the ship's voyage and extends the time seamen spend on sea even further [Finnsgård et al. (2018)].

Here, the unmanned autonomous vessel represents a way out of the impasse of a shortage in the supply of seafarer due to the job's perceived unattractiveness and a growing demand for seafarer caused by slow steaming and increasing transport volumes. This could reduce the expected pressure on the labour market for seafarer as it would enable, at least partly, to reduce the intensity of ship operation. Routine tasks on board will be automated and only the demanding but interesting navigational and technical jobs will be transferred from the ship to a shore-side operation centre. This will make "seafaring" jobs more attractive and family friendly than today. Furthermore, economic and environmental benefits when implementing unmanned shipping are expected. [MUNIN (2016)]

In the next sections are different projects around the world discussed, that work on the transition towards an autonomous or unmanned vessel. The projects are working on various levels of automation. These different levels are shown in figure 1.1a. This illustrates that the higher the level of automation, the automated systems become more in control. The blue boxes show when a human is in control, while the orange boxes show when automated systems are responsible for the mentioned activity. Beside these levels of automation, also different types of automation are applicable, each with its own challenges. The different types of automation are shown in 1.1b.



(a) Levels of automation (b) Types of automation on ships

Figure 1.1: Steps from manned to autonomous ships

1.2 Ongoing projects

The vision on autonomous ships is not new, as it already occurred in a book on future ship concepts in 1973. The EU-funded research project MUNIN triggered the renewed interest for autonomous shipping [Saarni et al. (2018)]. The name is an abbreviation for Maritime Unmanned Navigation through Intelligence in Networks and originated from WATERBORNE. An initiative from the EU and Maritime Industries Forum, supporting cooperation and exchange of knowledge between stakeholders within the deep and short sea shipping industry. They did initial research between 2013 and 2016. Figure 1.2 illustrates how MUNIN focussed on different elements of the autonomous shipping concept, this vision includes:

- The development of an IT architecture.
- Analysis tasks performed on today's bridge and how this will be on an autonomous bridge.
- Examining the tasks concerning a vessel's technical system and developing a concept for autonomous operation of the engine room.
- Define the processes in a shoreside operation centre, required to enable remote control of the vessel.

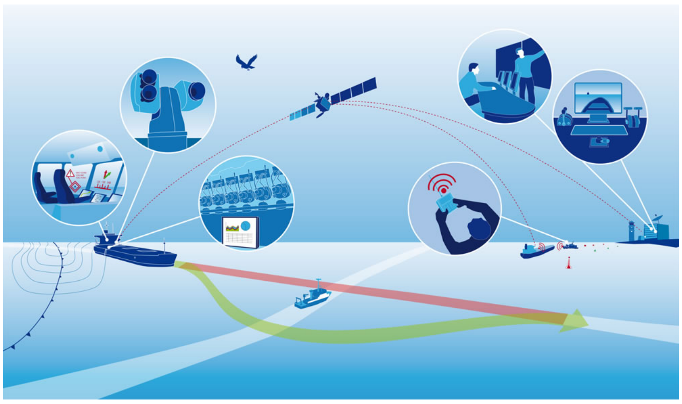


Figure 1.2: Illustration of MUNIN vision

They also considered the feasibility of the developed solution, including legal and liability barriers for unmanned vessels. They concluded that unmanned vessels could contribute to the aim of a more sustainable maritime transport industry. Especially in Europe, shipping companies must deal with a demographic change within a highly competitive industry, while at the same time the rising ecological awareness exerts additional pressure on them. The autonomous ship represents a long-term and comprehensive solution, to mitigate the challenges. It offers a potential solution to reduce operational expenses and reduce the environmental impact. A concept was developed for a bulker vessel, enabling the consortium to do a financial analysis. Showing the viability, but MUNIN admits in their results that they have had a limited scope within the project [MUNIN (2016)]. They have shown the importance of developing a method to determine the intentions of other vessels and systems that are needed. They did not yet make the step towards developing such a method, which is the scope of this report.

1.2.1 Exploratory projects

The different project worked on the vision about the future of shipping. Often these projects have different phases in which the level of automation increases with every iteration. Examples of projects currently running all over the world are:

- One Sea – Autonomous Maritime Ecosystem by DIMECC Ltd.
- Advanced Autonomous Waterborne Applications
- Unmanned Cargo Ship Development Alliance

Rolls-Royce Marine is involved in different projects, which are in some way follow-ups to the MUNIN project. The videos of the virtual bridge concept and the Electric Blue vessel have had many views, as this showed clearly their vision of how the shipping industry could look like in the future. Electric Blue is a concept ship, based on a standard 1000 TEU feeder and shown in figure 1.3. The ship is very adaptable. It can sail for example on both diesel and electricity. The modularity enables Electric Blue to adapt for specific routes and meet environmental requirements now, and in the future.

According to many projects will unmanned shipping start with a virtual bridge below the containers. The virtual bridge will utilise the opportunities for sensors during safe navigation. By using Radar, camera, IR camera, LIDAR and Automatic Identification System (AIS). This concept aims to have partial autonomy by 2020, remote operation between 2025 and 2030, starting with a reduced passive crew on board. To become fully autonomous in 2035 [Wilson (2017)]. They pinpointed the control room, as the nerve centre of remote operations. Using an interactive environment with a screen for decision support and improving situation awareness with augmented reality. With these developments does their vision look very promising. However, there have not yet been successful prototypes.

Since June 2017 is Rolls-Royce also involved in the unmanned cargo ship development alliance, which is initiated by Asian companies and classification bureaus. They aim to develop unmanned cargo ships with independent navigational capacity and make market promotion to promote the development of intelligent shipping. The alliance would not only promote changes in the ship design and operation. However, it also facilitates the establishment of technology, regulation and standard system involved in unmanned cargo ships. Combined with the accumulation of rules and standards as well as the field of an intelligent ship.

1.2.2 Industry projects

The exploratory projects work on the vision and far future of an autonomous shipping industry. Some companies are working towards prototypes, often funded by customers of shipping companies. The Yara Birkeland is one of the projects ahead of the pack, already building and testing a 120 Twenty foot Equivalent Unit (TEU) container ship (figure 1.4). This vessel will initially operate as a fully electric manned vessel, but plans are that it will sail autonomously in 2020. Operating between different Yara facilities in Norway, transporting fertilisers and raw materials. Meaning the path and quay are always the same, which reduces the number of challenges. Kongsberg is responsible for the development and delivery of all key enabling technologies. Including the sensors and integration required for remote and autonomous operations, in addition to the electric drive, battery and propulsion control systems [Sames (2017)].

Other smaller projects are the development of Norwegian ferries, which are likely to start sailing automated from 2018, just like an automated shuttle service for offshore installations. A partly Dutch project is the Roboat, where a fleet of small pontoons will be used to solve problems on urban waterways. Such as transportation of people and goods, or creating temporary dynamic floating structures like bridges and stages. Roboat is a collaboration between AMS Institute and MIT.

Most of the previous projects focussed on developing a vessel, which has to operate in the current environment. The smart shipping challenge (SMASH) focusses on combining technological developments within different parts of the inland shipping industry in the Netherlands, such as bridges and terminals. This will help to steer ships remotely, enable the intelligent exchange of information, and the optimisation of waterway maintenance. Good examples are the new vessels from Nedcargo and the Gouwenaar 3. These vessels will be able to transport more containers while reducing fuel consumption. This will not only be acquired by improving the hull shape and machinery, but also by sailing smarter. For example by optimising the speed, based on opening times for bridges and availability of the quay [SMASH (2017)].

Also in the Netherlands are different partnerships working on the challenges of autonomous and unmanned shipping. The research conducted on communication and decision making will support one of these projects via Damen Shipyards and the Technical University of Delft.

Figure 1.3: Render of Electric Blue

Figure 1.4: Render of Yara Birkeland

Where they partner with different European companies and research institutes, to develop a technology to deal with challenging environments and complex transport missions. Which is also applicable to other autonomous waterborne operations, such as inland waterways transport and coastal/inter-island short range ferry services.

Based on the projects mentioned above, are the most direct use cases: Local transport between factories and terminals and short sea shipping solutions. However, there might be more in the future, such as the usage of tugs as an additional actuator in dynamic positioning systems.

1.3 Stakeholders

When the ships mentioned in the previous section will sail, does not only dependent on the rate on which the technology can be developed. As stakeholders are there also regulatory bodies, such as International Maritime Organization (IMO) and classification societies which need to incorporate autonomous vessels into their frameworks. The exploratory projects are important, as this will help them to prioritise the codes for different ship types. These codes include information on autonomy levels and how to certify unmanned vessels.

Another group of stakeholders are the shipbuilders, system integrators and suppliers for subsystems. These are responsible for technological development. More and more shipyards try to get involved, to gain knowledge on the development process. Also are there the companies from other industries, which see opportunities for products they already developed for planes or automotive. For example using computer vision, protocols for classifying systems and connecting ships.

The last, but probably most important are the customers, as technology will only be used if they can make money with it. More and more companies are convinced this is possible. These are not only the chartering companies but also their customers, such as Heineken, Yara and BHP.

1.4 Challenges when combining unmanned and manned vessel

Based on the projects mentioned above it is clear that many projects work on different challenges. All challenges are related to the safe operation of unmanned vessels while optimising profit. For the technological challenge, is the most critical situations, when manned and unmanned vessels meet. Ship-to-ship communication is often necessary for those situations. Many of the projects so far, try to avoid these situations, as this will also result in fewer challenges for regulatory bodies. Also is technology for communication costly to develop, therefore is the aim to avoid communication where possible. The first step to accomplish this is to adjust the operational strategies for unmanned ships to avoid complex situations. This means that a strategy should be developed on how these ships can avoid communication. The easiest way is to operate only in area's where all risks are known. The best solution to enable a ship to operate everywhere is by avoiding the need for communication. This is achieved by taking decisions well in advance and making intentions clear. Still, some challenges are open, as ships cannot avoid all complex situations. For these cases, there must be a protocol which enables manned and unmanned ships to share the right information. Both of these issues have not been within the scope of the previously mentioned projects, or any other research [Kooij et al. (2018)].

In the next chapter are factors discussed which influence the decision making process. We base these factors on challenges from previously mentioned projects and current research, where the decision model is a stepping stone.

2 | Decision model for safe operation

In the previous chapter, several projects are discussed, that gave insight in the challenges towards unmanned and autonomous shipping. To gain insight into the challenge of communication is a decision model used. This model shows which factors influence the decision-making process and how relevant research support this. The steps in this decision process are the same for manned and unmanned ships. The decision process within the model is based on Boyd's OODA loop [Boyd (1987)], Endsley model for situational awareness [Endsley (2013)], and combined with models used in the projects as mentioned in chapter 1. The OODA loop has different phases: Observe, orient, decide and act. Similar to Endsley's model: Perceive, comprehend, project, decide and act.

The combined model describes how this applies to choosing the right strategy for safe operation, and relates to external factors and relevant theory. Figure 2.1 illustrates the decision model used in this research, this model shows the multiple phases in the decision process. The first step describes what can be observed, to form a mental model. The next step is to orient, which is divided into the identification of the situation and the identification of future hazards. This step will result in a set of strategies, which will be evaluated using different criteria, resulting in a decision. After this decision, the operator administers an action. This action finally results in a new situation, observed in the next iterative step. This chapter will discuss these phases in more detail and how they relate to the challenge of communication, by discussing external factors and relevant theory.

2.1 Decision process

The decision process is the core of this model. Part II will use the decision process on a less abstract level than described in this chapter. The steps taken in this decision process are similar for manned and unmanned vessels. Their way of thinking differs however when this is related to being consistent or handling exceptions.

Mental model

The first phase of the decision process is to form a mental model. A mental model is a representation of the surrounding world, including the relationships between its various parts and a person's intuitive perception about his or her acts and their consequences. Sensor data about the environment is used to make this representation. Systems interpret raw data, transforming it into information, which can be combined into knowledge.

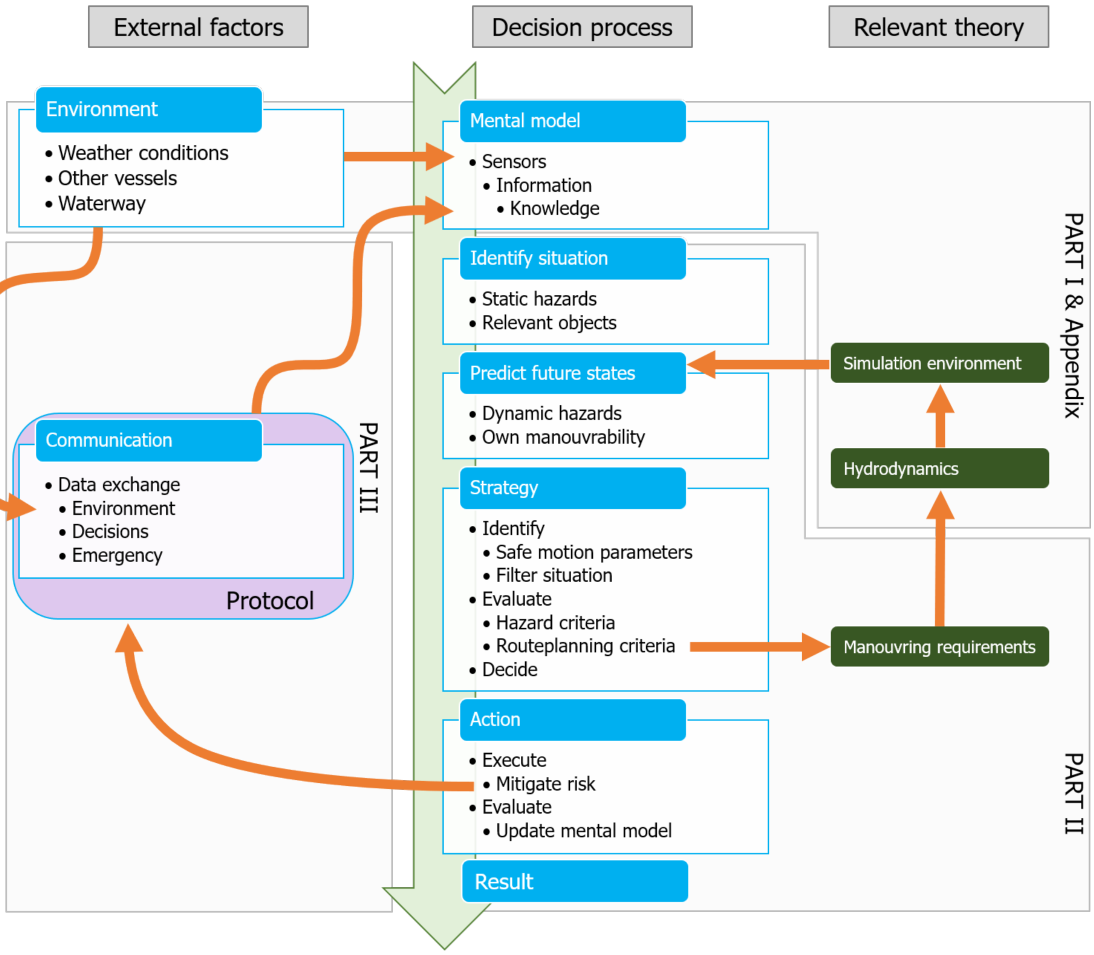


Figure 2.1: Decision model

The steps from sensor to knowledge still require much research, although large steps are taken within the domains of LIDAR [Oliver Cameron (2017)], computer vision [Bernard Marr (2017)] and sensor fusion [Hoffman (2018)]. Appendix A discusses the systems which are used at the manned vessel, to form a correct mental model. For this research, only the result of this step is relevant: Is the acquired knowledge sufficient to identify the situation correctly, or is more information needed? Future technologies and sensors are not within the scope of this research, nor how their outputs result in useful information.

Identify situation

The step from information to knowledge is in the phase where the situation, scenario, and hazards are identified. How this would go in practice is discussed in chapter 4. This step identifies critical situations during the design phase of an autonomous ship to be evaluated. This research will define a method to evaluate these critical situations. The layout of the waterway, other nearby vessels, relevant regulations, etc. determines the situation and scenario.

Predict future states and decide on strategy

Based on the situation, different strategies might be possible. A system or the operator has to evaluate these strategies. This evaluation is done by predicting how different strategies will influence the path of the various vessels. A trade-off must be made between exact calculations and computation time. For example is the closest point of approach (CPA) currently determined using linearised algorithms in common ARPA systems. Non-linearised methods using, for example, a Bézier curve will result in smaller errors. Simulations would improve this even more, however, does a simulation with correct hydrodynamic models cost much more computational time. In chapter 5, the linearised and non-linearised methods are described. Appendix B describes the simulation tool. This tool is however not optimised for such calculations. Therefore these calculations cannot be done real-time. The hydrodynamic model used in the simulation is also described in appendix B.2.3. Different manoeuvres are evaluated after this phase, that correspond to the different strategies. We will discuss this in chapter 6 for common critical strategies. This will result in manoeuvring requirements. These requirements can be used by ship designers, to ensure that the ship can operate safely with minimal need for communication. After the evaluation of these criteria is known which strategy will result in safe operation of the vessel.

2.2 External factors

How easy it is to go through the decision process and end up at the right strategy depends on the situation. Environmental factors, such as the traffic situation, will mostly influence the situation. In some cases are the static sensors not sufficient to analyse the environment properly, resulting in an incomplete mental model. This section will describe in more detail how the environment influences the forming of the mental model and how safe operation within this environment would benefit from communication.

2.2.1 Environment

The mental model is a representation of the environment in which the vessel acts. The sensors will measure this environment and provide the data. Many critical situations occurred due to weather conditions. The cause is that sight is limited during heavy rain or snow. The wind and waves might limit the manoeuvring capabilities of a vessel. These are also the reason that some vessels are not allowed to enter a port when wind or waves are too high. If such repercussions are necessary, depend on the layout of the waterway. Due to currents, operations (e.g. maintenance and fishery) or limited depth, might some area's be restricted. Operators acquire this information via communication channels, but communication channels which only allow receiving and not sending, such as Navigational text Messages (Navtex).

The same applies to standard information on other ships. They might send their location and speed via AIS, but still key is the ARPA. Due to weather conditions, these systems can be less accurate, as heavy rain results in noise at the radar. In the situations where sensors do not function as expected, communication is needed, even if the whole decision process itself is optimised to avoid communication. The same goes for communication with shore-based stations such as traffic controllers or in the future remote pilots. Sensors or current systems are not able to retrieve this information. Such as a place and time to berth or pick-up a pilot.

Both shore-based stations and ships can only share intentions and their planned path via the radio. Future unmanned will most likely be able to negotiate using other systems. But in the case with manned-manned or manned-unmanned interaction is this only possible via VHF radio for now.

2.2.2 Communication

As described there are still cases in which communication is necessary. We discuss in part III a case where communication between manned and unmanned vessel is needed. Using the situated Cognitive Engineering (sCE) method a protocol is defined, based on existing systems and protocols. Thus using AIS to send written messages, or VHF and SMCP for verbal messages. Other cases such as communication with traffic controllers and pilots could use the same protocol. Although they might need to share more information with unmanned vessels, which could be done with a new system such as VHF Data Exchange System (VDES). This will however not be part of this research.

Part II

Impact of manoeuvrability on the necessity to communicate

We rarely recognize how wonderful it is that a person can traverse an entire lifetime without making a single really serious mistake. Like putting a fork in one's eye or using a window instead of a door.

– Marvin Minsky [Minsky et al. (1991)]

The previous part describes the context of this research and showed steps towards autonomous shipping, which are relevant to this research. This part will focus on the effect of manoeuvrability on the decision-making process. The steps taken to get to the right decision are similar to steps shown in the model of chapter 2. The insights acquired from the effect of the manoeuvrability on the decision process can be used to determine manoeuvrability requirements and answer the following question:

> *How do ship manoeuvrability characteristics influence the domain for decision making, to ensure that the chosen strategy will result in a closest point of approach that does not require communication?*

The first phase of the decision process is the observation phase. This phase starts by updating the mental model and is followed by a phase where different chunks of information are connected. An operator or system uses this to identify situations and scenarios. This identification is the start of the decision making process in which different trees are used to identify potential hazards and problems that will result in strategies. These strategies are finally narrowed down to the actions. The various nodes and trees are discussed in chapter 3.

The next chapter discusses more detailed descriptions of the consecutive phases in the decision-making process. First, the identification of the situation and scenario are addressed in chapter 4. Evaluating criteria determines which branch to follow in the decision trees. These criteria define if there are hazards and which manoeuvres are feasible, that works in two ways: An operator can use these criteria during operation to determine the right strategy, while a ship designer can use these criteria to ensure a ship can navigate safely in specific situations. The criteria to evaluate what kind of problem there is, are described in chapter 5. The criteria used to assess if strategies are feasible for critical situations are described in chapter 6. In chapter 6 is also described how designers can use these manoeuvres to determine the manoeuvring requirements for safe operation. Manoeuvres are simulated to evaluate if these criteria are useful. With the tool as described in appendix B. These are also used to verify several scenarios and see how these criteria influence the decision-making process.

The result of this part is an overview, that can be used by designers to determine the effect of manoeuvring capabilities at the moment decisions have to be made, which is done for some common critical manoeuvres, showing the minimal time and distance required to make decisions to have a safe distance between vessels. This matrix depends on the manoeuvring characteristics, speed and type of manoeuvre.

3 | Decision-making process

A rule-based time-domain decision model is used, to acquire more insight into the decision-making process. By applying this model is analysed what the situation is, what problems might occur, and how to act to operate safely. A decision tree is used to analyse this in a structured way. Tags describe the nodes. This generalised model can be optimised in later stages to create a fully functional decision algorithm for autonomous and unmanned ships. The final algorithm is created using advanced modelling techniques and machine learning algorithms, as the decision algorithm becomes too complicated to draw decision trees by hand. First, the decision phases are described, followed by lists of nodes used to identify scenarios and situations. Combining this with the COLREGs will result in a functional decision model. Also, the criteria necessary to go through the steps are discussed. This decision model aims to gain insight into the decision process, and shows which situations are critical when the goal is to avoid communication.

3.1 Decision phases

The decision making process has different phases. As shown in chapter 2. A simplified version of the decision model is shown in figure 3.1. These different phases are described in table 3.1.

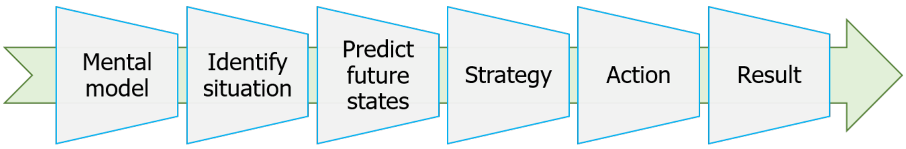


Figure 3.1: Decision process

Class	Description
Mental model	Acquire knowledge about the situation
Situation identification	Identify the encountered situation, to determine which criteria are relevant, based on waterway lay-out and other ships.
Predict future states	Predict if a problem will occur, as there is only a change in strategy needed when this is the case.
Strategy	If there is a problem, a new strategy should be chosen, this is based on the evaluation of criteria.
Action	From this strategy, different actions will follow.
Result	Finally the result is evaluated, using the same criteria to determine a problem in future states.

Table 3.1: Description of phases in decision process

3.2 Nodes in decision-making tree

Short keywords are used to describe the nodes within the decision tree. These describe in short what kind of situation, problem, strategy, action or result there is. This section gives definitions for those keywords.

Identify situations

Identification of encountered situations is the first step to limit the number of strategies which are relevant to evaluate. The nodes within the identification process are described in table 3.2, more details on how this is determined are described in section 4.1.

Tag	Description
Passing	The paths of both ships are in the opposite direction, and do not cross.
Crossing	The final direction of both ships differ, but they do cross.
Over-taking	The paths of both ships are the same but at different speeds.
Merge	The starting direction of both ships differ, but the final direction is the same.

Table 3.2: Tags for different situations

Predict future states

Different criteria are evaluated, to identify whether a problem will occur. These criteria are described in chapter 5. In table 3.3 the nodes within the decision tree are discussed to evaluate if there is a problem, and which evaluations are possible for these criteria.

Tag	Evaluation
Closest point of approach	Good; Too close
Crossing point	In front; Behind
Crossing distance	Good; Too close
Passing position	Port side; Starboard side
Relative speed	Faster; Same speed; slower

Table 3.3: Criteria and result of evaluation to identify a problem

Possible strategies

Using the identification of the situation and the prediction of future states. A limited number of strategies might be possible. The strategies will result in actions but can be categorised into groups. Table 3.4 describes this and shows the possible actions per strategy. The distance and time that is left to avoid a problem is evaluated to determine if an action is necessary and possible. These criteria are described in table 3.5.

Tag	Actions
Follow planned path	Continue without change
Increase CPA by yourself	Evasive manoeuvrer; Adjust speed
Increase crossing distance by yourself	Evasive manoeuvrer; Adjust speed
Work together with others	Communicate; Evasive manoeuvrer; Adjust speed
Emergency	Emergency stop; Communicate

Table 3.4: Tags for different strategies

Tag	Evaluation
Time till problem	... seconds
Distance till problem	... meter

Table 3.5: Criteria to determine if action is possible

Possible actions

From the selected strategy, actions will follow. These action are a combination of an action type, and an execution moment for the action. In table 3.6 and 3.7 these are described. These actions consist of different smaller sub-actions such as: "rudder 35 degrees to port-side".

Tag	Description
Continue without change	Do not change speed or rudder
Evasive manoeuvrer	Steer to starboard or port side first and end at same course
Adjust speed	Reduce speed or speed-up
Emergency stop	Turn ship side-ways and set propulsion in reverse
Communicate	Discuss required actions with other vessel(s)

Table 3.6: Types of actions

Tag	Description
Now	When action can be undertaken as soon as possible
In ... minutes/seconds	Wait to ensure action is necessary
After action ...	Wait with action till you or other has done another action

Table 3.7: Time-domain for action

Result

Using the criteria from the action phase, the selected action can be evaluated. Herein is the human factor on board of other vessels taken into account, in the form of perceived risk.

This perceived risk is linked to the safety domains [Szlapczynski and Szlapczynska (2017b)]. The used safety domain at open sea is described by Coldwell [Coldwell (1983)]. Figure 3.2 shows that this domain is based on an ellipse, that is not centred at the location of the vessel. This safety domain takes into account that ships rather pass on port-side and behind. In this model, the safety domain only depends on the length of the ship. In busy areas, such as harbours and coastal area's, it is not always possible to use this safety domain. Based on expert reviews for the port of Rotterdam, is a closest point of approach used in these regions of 2 cables, which is equal to 370 meters.

Evaluations and criteria are shown in table 3.8. The evaluation of these criteria determines if problems can be avoided.

Tag	Evaluation
CPA	Good; Too close
Perceived risk	Safe; Uncomfortable; Close encounter; Too close
Safe situation	Yes; Uncomfortable; No

Table 3.8: Tags for safe situation criteria

3.3 Critical paths in decision trees

When combining the nodes as described in the previous section, huge decision trees are applicable. The decision tree for specific situations and scenarios is much smaller than a tree covering all possible solutions. Based on the previously described nodes, a generalised model of the tree can be drawn. Figure 3.3 shows this model, where the orange blocks show evaluation criteria and the white blocks are choices. Thereby should be considered that the actions are similarly evaluated as the prediction of future states.

In the next chapters will the decision tree be used to identify critical paths. These paths will be evaluated for critical situations. When all possible paths are considered, this will result in a massive decision tree and many critical situations. All these paths do not result in more insight into a solution to avoid communication. Using identification and evaluation criteria several common critical paths can be identified which are used to define manoeuvrability criteria.

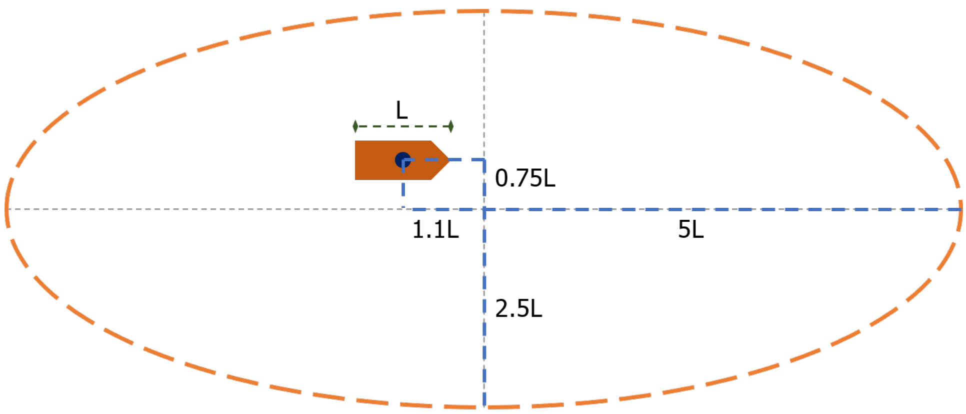


Figure 3.2: Model for safety domain by Coldwell

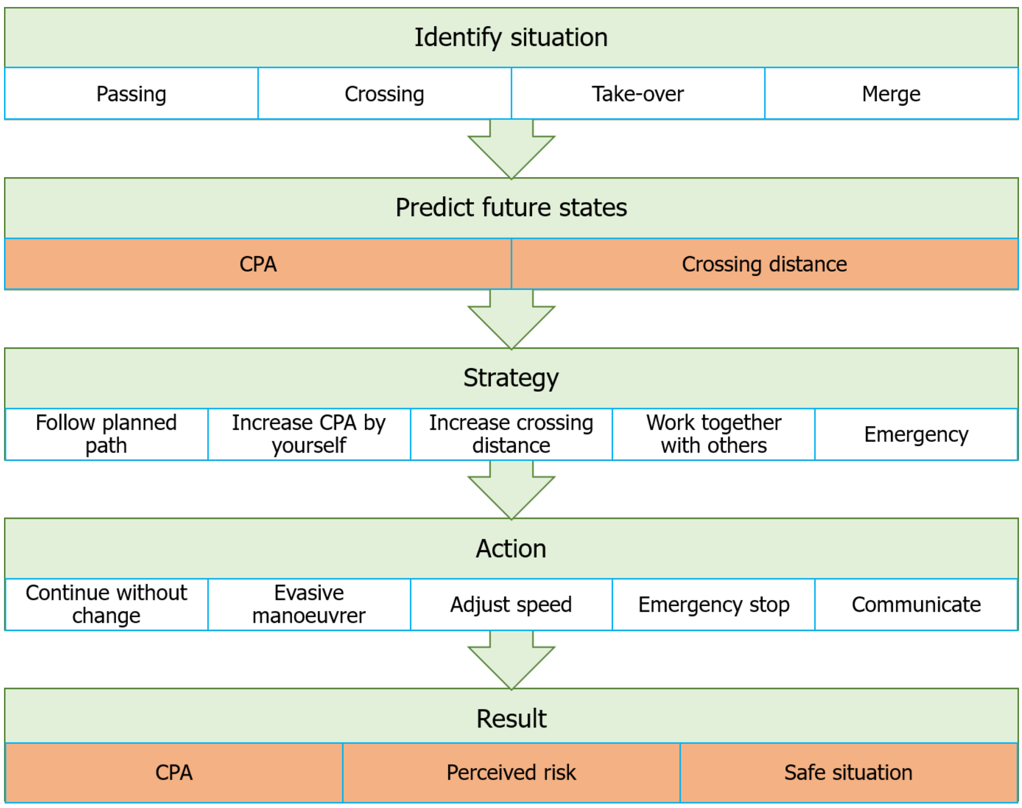


Figure 3.3: Generalized model for decision tree

4 | Identification of situation and scenarios

After forming a mental model of the situation, the decision process starts with the identification of the situation and scenario. The decision tree from chapter 3 helps to identify common critical situations. The identification of these situations aims to narrow down possible strategies in the next phases of the decision-making process. This chapter discusses the first steps of classifying the situation. Followed by the steps taken in the orientation phase to narrow down the possible strategies. This will help to determine which paths are common and critical, thus are good to be used while evaluating manoeuvring criteria.

4.1 Situation identification

Situations can be classified into four types. These are also discussed in chapter 3, as these are the same nodes as in the decision tree. Table 4.1 shows these situations:

Situations	Description
Passing	The paths of both ships are in the opposite direction, and do not cross.
Crossing	The final direction of both ships differ, but they do cross.
Over-taking	The paths of both ships are the same but at different speeds.
Merge	The starting direction of both ships differ, but the final direction is the same.

Table 4.1: Tags for different situations

It depends on the waterway lay-out which situation is likely. Traffic separation schemes, forbidden zones or land masses influence this layout. A classification of paths is used to determine the situation. Paths are based on figure 4.1 and can be written as: [current position, direction].

The paths are considered to classify a situation where two vessels encounter each other. Key is to determine the angle between those paths. This angle makes it is possible to classify the paths using table 4.2 and figure 4.1.

The boundaries to determine if the other ship comes from direction A, B, C or D are based on COLREGs [IMO (1972)]. Direction A is between 112.5 and 247.5 degrees, as shown with the dotted line in figure 4.1. While sailing this angle can be observed using the mast-head lights. These are seen as red when the vessel comes from B, green when from D and green and red from C. While from direction A the colour of the light will be white. When in doubt whether it is a head-on situation or a crossing situation. Always assume a head-on situation, as this stated in rule 14 [IMO (1972)].

Own ship	Other ships	Situation
[A,D]	[D,C] [D,B] [D,A] [C,B] [C,A] [B,A] [B,C]	Passing
[A,C]	[C,A] [C,B] [B,A]	Passing
[A,B]	[D,C] [C,D] [B,A]	Passing
[A,C]	[D,B] [D,A] [C,D] [B,D]	Crossing
[A,B]	[D,A] [C,A] [B,D] [B,D]	Crossing
[A,D]	[C,D] [B,D]	Merge
[A,C]	[D,C] [B,C]	Merge
[A,B]	[D,B] [C,B]	Merge
[A,D]	[A,D]	Over-taking
[A,C]	[A,C]	Over-taking
[A,B]	[A,B]	Over-taking

Table 4.2: Path definitions for different situations

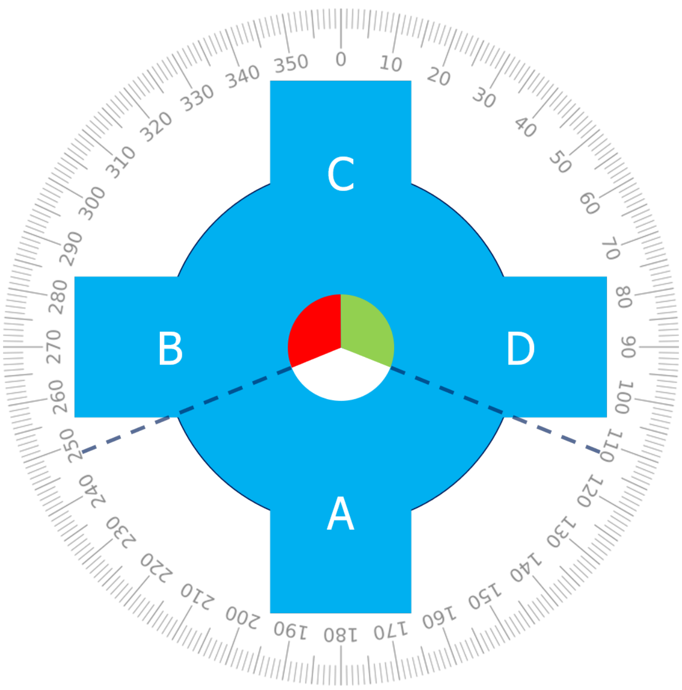


Figure 4.1: Path description for situation identification

4.2 Situations that limit possible strategies

Beside this first identification of the situation. More details must be taken into account to eventually select the right strategy, as these details might limit the possible strategies. Below the effect of the waterway and actors are discussed on possible strategies.

4.2.1 Waterway properties

To limit the strategies that have to be evaluated by a system or operator, these are filtered based on the physical properties of the waterway, as this might restrict the area where can be sailed or requires different behaviour. For example, it is common to over-take ships in open-water on the starboard side. While on restricted waterways ships will sail as far as possible to starboard already. This means that the ship that is over-taking will have to pass on the port side of the other vessel, at the centre of the waterway.

In the next step, other static hazards are considered to check whether the chosen strategy does not lead to a collision, or if there are specific regulation frameworks for this waterway. These are however not part of the first iteration of the decision model, as this will introduce much more complexity, without improving the result in most cases. Future iterations of the model should evaluate static hazards, such as buoys, forbidden zones, bridges, quays, port mouths or shallow waters. In those cases are possibilities for over-taking or evasive manoeuvres limited, which means the strategies are limited.

Another limiting factor related to waterways are the difference in regulations between waterways. Most noticeable are traffic separation schemes or other road marks such as signs which forbid to over-take or meet. But others are for example to not create wash or no turning, thus limiting the options to manoeuvre. Or more directive signs on obligated directions or speed limits. These signs are most relevant for coastal and inland waterways.

4.2.2 Dynamic objects

The second major step is the identification of dynamic objects. Those are all relevant moving objects. Most obvious are other ships, that come close. In future developments of the decision model, objects that are not under any control of a human should also be considered, such as floating containers, this is however not within the scope of this research. The major difference between static hazards is that the 'forbidden zone' around the dynamic object changes over time. This means more complex evaluation methods are needed to determine if there is no perceived risk, and thus a safe situation. The path itself is relevant for the evaluation of different criteria, as will be discussed in chapter 5 with different algorithms.

These complex evaluation methods will have to predict the path. To do this, first, the general information about the object should be acquired. Such as manoeuvrability, speed, course, type of object, under control, etc. Additionally it might be possible in future developments to take into account the human factor and further to improve the path prediction. This prediction is based today on the experience of the crew, availability of a pilot or in the future if the vessel is unmanned.

Examples of such dynamic objects that limit the possible strategies, are for instance: Fishery vessels, as they might have long nets behind them during operation. Ferries in inland waters which have priority over other shipping traffic. Ships with limited manoeuvrability or forbidden zones around them.

4.3 Scenarios

The scenario can be identified by using the information about the properties of the waterway and actors, where the situation is based on observations and describes the current state. The scenarios take into account the possible future strategies of those actors and thus describe what the future states could be. Based on the scenarios, can be determined which rules to apply and what its implications are on the possible strategies. The same is applicable for the estimated path of dynamic objects. These both might narrow down the possible strategies.

Using the information as mentioned above in the decision model, the strategies can be narrowed down. This information can be used to simplify the decision tree and select the right criteria to evaluate. Different scenarios for the same situation could be that the ship turns to port or starboard. For both scenarios does a probability exist. Using a probability index for the decision of other vessels will, in this case, improve the final decision making. This index can be taken into account by the safe motion parameters and safety domains as described by Szlapczynski [Szlapczynski and Szlapczynska (2017a)][Szlapczynski and Szlapczynska (2017b)].

In the next chapter the criteria are defined to evaluate the situations and scenarios. This evaluation shows whether a problem might occur. These criteria are eventually used to determine the most critical common situations.

5 Definition of criteria for evaluation of situation

To determine whether a problem might occur in the situations and scenarios as identified in the previous chapter, different criteria are evaluated. The current systems calculate most of these criteria, such as ECDIS and ARPA. However, they do use linearised algorithms. These do not predict the CPA and crossing distance correctly while turning, often resulting in many dismissed alarms. This chapter describes different criteria, followed by the calculation needed to evaluate these criteria. This description and calculation are given for both the linearised algorithms and proposed algorithms. Later in the process, these criteria can be used again, to ensure that the chosen strategies ensure safe operation with low perceived risk.

5.1 Calculations based on current systems

Within ARPA and ECDIS, different calculations are made, which can be used to evaluate if there is a problem in the current scenario. These calculations often use linearised algorithms, which results are not correct when turning. Humans can easily dismiss the false alarms given due to these wrong results. Computers do not handle these false positives well. The advantage, however, is that the calculations can be done very fast. Below these calculations are discussed for the closest point of approach (CPA) and crossing position.

5.1.1 Closest point of approach

The CPA refers to the positions at which two dynamically moving objects reach their closest possible distance, which is an important calculation for collision avoidance. A linearised form uses two points moving at fixed speed and fixed direction. Figure 5.1 shows an example, where P and Q are the moving points, with corresponding direction vectors u and v, which include the speed and direction.

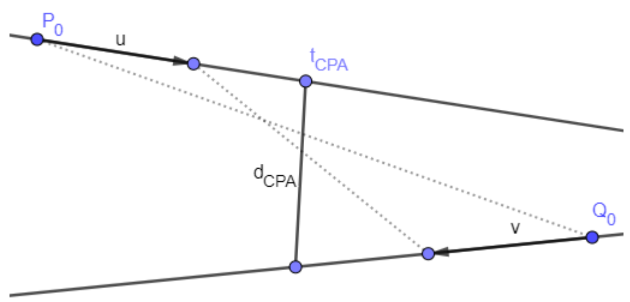


Figure 5.1: Example for closest point of approach (CPA)

A formula can be derived for the closest point of approach. With the motion equations for P and Q, the distance can be calculated. Where P_0 and Q_0 are the current positions, and u and v are the corresponding speed vectors:

$$P(t) = P_0 + t \cdot u; \quad Q(t) = Q_0 + t \cdot v \tag{5.1}$$

$$d(t) = |P(t) - Q(t)| = |P_0 - Q_0 + t(u - v)| \tag{5.2}$$

Since d(t) is a minimum when $D(t) = d(t)^2$ is a minimum, this is the case when the derivative is equal to 0:

$$D(t) = d(t)^2 = (u - v) \bullet (u - v)t^2 + 2(P_0 - Q_0) \bullet (u - v)t + (P_0 - Q_0) \bullet (P_0 - Q_0) \tag{5.3}$$

$$\frac{dD(t)}{dt} = 0 = 2t[(u - v) \bullet (u - v)] + 2(P_0 - Q_0) \bullet (u - v) \tag{5.4}$$

This equation can be solved for t, to calculate the moment where CPA is the smallest:

$$t_{CPA} = \frac{-(P_0 - Q_0) \bullet (u - v)}{|u - v|^2} \tag{5.5}$$

$$d_{CPA}(t_{CPA}) = |P_0 - Q_0 + \frac{-(P_0 - Q_0) \bullet (u - v)}{|u - v|^2} \bullet (u - v)| \tag{5.6}$$

If t_{CPA} is smaller than 0, the CPA is in the past. If t_{CPA} is equal to 0, the CPA is right now, else it is in the future. If u and v are the same, the denominator of equation 5.5 is equal to 0. This means that the CPA is constant.

5.1.2 Crossing distance

The crossing distance is the distance between two ships if they pass each others path. The position of another vessel can be both in front or behind a vessel. This distance is mostly relevant for how safe a crossing situation feels. The crew on manned ships do not want to have ships too close in front of them, as they can't do an evasive manoeuvrer in those situations. The same motion equation as for CPA can be used (equation 5.1).

In figure 5.2 the distance is calculated between two points at a certain moment in time. The first step is to calculate the crossing point (cp) of the two lines:

$$P(t_{cp,p}) = Q(t_{cp,q}) \rightarrow P_0 + t_{cp,p} \cdot u = Q_0 + t_{cp,q} \cdot v \tag{5.7}$$

$$t_{cp,P} = \frac{(Q_0 - P_0) \times v}{u \times v} \tag{5.8}$$

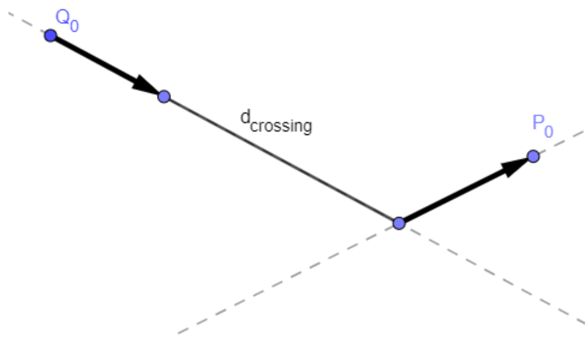


Figure 5.2: Example for crossing point and distance

$$t_{cp,Q} = \frac{(P_0 - Q_0) \times u}{v \times u} \tag{5.9}$$

$$cp = P_0 + \left[\frac{(Q_0 - P_0) \times v}{u \times v}\right] \cdot u = Q_0 + \left[\frac{(P_0 - Q_0) \times u}{v \times u}\right] \cdot v \tag{5.10}$$

The next step is to determine where each vessel is when the other vessel is at the crossing point. To determine finally what the crossing distance is:

$$P(t_{cp,Q}) = P_0 + \left[\frac{(Q_0 - P_0) \times v}{u \times v}\right] \cdot u \tag{5.11}$$

$$Q(t_{cp,P}) = Q_0 + \left[\frac{(P_0 - Q_0) \times u}{v \times u}\right] \cdot v \tag{5.12}$$

$$d(t) = |P(t) - Q(t)| \tag{5.13}$$

The crossing distance (cd) for when P crosses Q and vice versa, can be calculated using the following formulas:

$$d_{cd,PQ}(t_{cp,P}) = |P(t_{cp,P}) - Q(t_{cp,P})| \tag{5.14}$$

$$d_{cd,QP}(t_{cp,Q}) = |P(t_{cp,Q}) - Q(t_{cp,Q})| \tag{5.15}$$

5.2 Proposed algorithm based on planned path

Better non-linearised methods are necessary for the calculation of the CPA and crossing point, to improve the evaluation of criteria. By predicting the likely path of a vessel, improved estimations can be made. These use a first-order change, based on the rate of turn and course. This prediction can be extended with a combination of expected location and the probability that another ship is choosing a specific strategy.

Although it will result in better evaluations, the disadvantage is that much heavier computations are required, while also introducing uncertainty with the numerical solver. The first step will be to make a combination of both the linearised and non-linearised methods. The calculations have to be done for every combination of ships.

The Bézier curve is used to describe the paths in a non-linearised manner. This section first defines a Bézier curve. Followed by the same criteria as in the previous section: closest point of approach (CPA) and crossing distance. This time describing the algorithm using to calculate it in a non-linearised manner.

5.2.1 Bézier curve

The first iteration of the algorithm is semi-linearised, where the path of own ship is represented by a Bézier curve, based on its waypoints and strategy. Points have to be fitted along the planned path to describe the Bézier curve. This method is similar to the method as described by Taams [Taams (2018)]. The path prediction for the other ship is still linearised, new systems and protocols have to be introduced to gather enough information on the strategy and waypoints.

For the calculation does the distance function not change. This is still $d(t) = |P(t) - Q(t)|$. However is P taken as own ship and gets a new formula using the Bézier curve. This curve has a degree of n, which depends on the way-points and can be described using the following equations:

$$P(t) = \sum_{i=0}^{n} b_{i,n}(t) \cdot P_i \quad and \tag{5.16}$$

$$b_{i,n}(t) = \begin{pmatrix} n \\ i \end{pmatrix} t^i (1-t)^{n-i}, i = 0, \ldots, n \tag{5.17}$$

5.2.2 Closest point of approach

The numerical algorithm used to calculate the CPA is shown below. Herein is the path of own vessel represented by a Bézier curve. While other vessels are represented with a linearised function as described in section 5.1. This results in the following algorithm:

1. Check if situation (course, speed, other vessels) has changed since last calculation:
    (a) No, break
    (b) Yes, continue
2. Use waypoints to determine expected path for own ship (Bézier curve).
3. Use path to determine the location for each time-step.

4. Use course and speed other ships to determine their location for each time-step
5. Calculate distance between ships for each time-step:
   (a) If smaller than stored CPA, update stored CPA with calculated CPA
   (b) If larger than stored CPA, do not update stored CPA
6. Return CPA

5.2.3 Crossing distance

The algorithm to calculate the crossing distance will require much less computational power, as not all time-steps have to be calculated. Just the ones where the paths cross. The following algorithm can be used. It should be noted that some calculations from the CPA calculation can be reused.

1. Check if something has changed since last calculation:
   (a) No, break
   (b) Yes, continue
2. Use waypoints to determine expected path for own ship (Bézier curve).
3. Determine crossing point(s) between linear path and Bézier curve.
4. Check if crossing points exist:
   (a) No, break
   (b) Yes, determine location for crossing point(s)
5. Calculate time when ships are at crossing point(s).
6. Calculate distance between ships at time of crossing.
7. Return crossing distances.

The next chapter describes the criteria that depend on the manoeuvrability characteristics of a ship. Using the CPA and crossing distance can be determined whether the chosen strategy without communication will result in safe operation. Where the algorithms as discussed in this chapter, will give more exact results.

6 Manoeuvres for validation and testing

The criteria as described in chapter 5 aim to evaluate the situation to identify a problem. In case there is a problem, different actions can be taken to mitigate the risk. Other criteria are used to determine which manoeuvres are feasible. As the simulation of all possible manoeuvres can't be done in real-time, due to the endless number of possibilities and the continuously changing environment. Therefore a look-up table will be used. This look-up table has data for different manoeuvres and ship types. Every matrix shows how much the CPA can be improved at different speeds and for different decision domains (both time and distance). Simulations are performed for different ships and scenarios to gather enough data to fill these matrices. In this chapter is described which manoeuvre is most critical and will be tested in the simulation environment. These tests are a start to gather enough information. The information is also used to determine relations between different input values, which will show if an action is possible. Thus in this chapter is information gathered about the time and distance needed for a manoeuvre. Followed by an evaluation of the impact that a common critical manoeuvre has on the CPA.

6.1 Manoeuvre descriptions

Strategies often result in actions which are categorised in different types of manoeuvres. Most common to avoid critical situations are evasive manoeuvres. The time needed to do an evasive manoeuvre depends on the manoeuvring characteristics of the ship. Manoeuvres from sea-trials are used to ensure that the results from simulations are correct. These manoeuvres are used to validate if the manoeuvrability of a vessel is similar to the real-life situation. Examples of these manoeuvres are the zig-zag test and turning circle test. This section describes the manoeuvres from sea-trials and the critical evasive manoeuvre.

6.1.1 Sea-trial

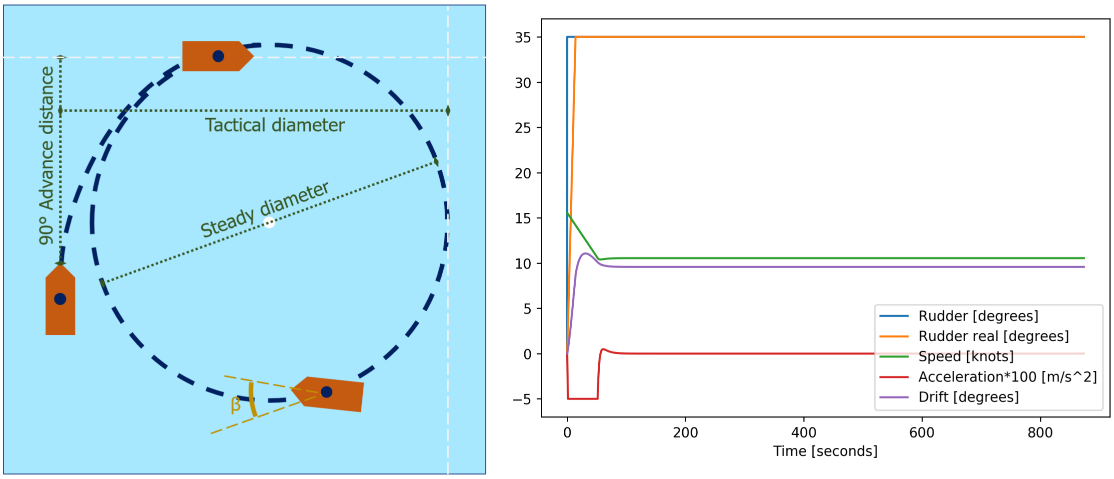
Manoeuvring capabilities of a ship are determined during the sea-trials. Using the same manoeuvring tests and metrics used by ship designers today, will ensure that the results of other tests are reliable. Multiple tests are performed to ensure the vessel complies with regulations and its contract on manoeuvring capability. The manoeuvres used to determine this, are the turning circle and zig-zag test. This section will describe these manoeuvres. Next section 6.2 will discuss the resulting metrics. These metrics are used to validate how well the manoeuvring model works, compared to existing sea-trials with the same ship. Using, for example, the trial database of Damen Shipyards.

Turning circle manoeuvre

The first test is to determine the turning circle of the vessel. The rudder is given a maximum angle of 35 degrees. The ship will start turning. After some time the ship will turn at a steady speed and course change. The results of this test are an advance distance, which is the distance from starting to give rudder until the ship has turned 90 degrees. The tactical diameter, which is the distance between the starting point and maximum distance the ship travelled to the side. And finally the steady turning diameter, which is the diameter of the turning circle when speed and course change are constant. An example is shown in figure 6.1. Showing the changes in the rudder angle, and how this affects the speed, acceleration and drift angle (β) for a 140-meter cargo-ship.

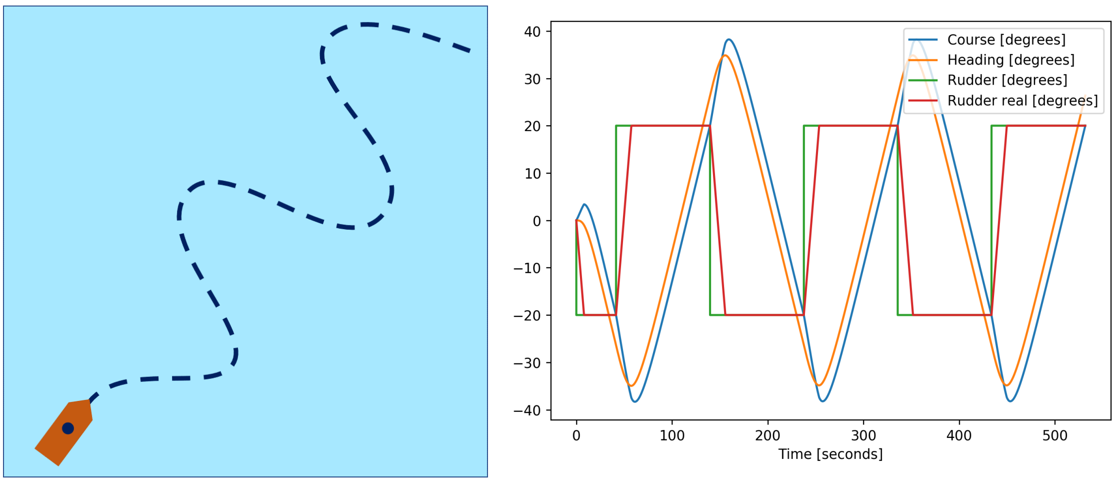
Zig-zag test

The second test is the zig-zag test. Herein is the initial turning time, yaw checking time and overshoot tested. The rudder is put at an angle of 10 or 20 degrees to the port side, till the course change is also 10 or 20 degrees, then the rudder is changed to the starboard side. These changes are repeated several times to get a good measurement of the overshoot. Measurements of the course changes determine this overshoot. In figure 6.2 the zig-zag test is shown. Figure 6.2b shows the rudder, course and heading changes during a zig-zag test. The measured overshoot is a key metric for the manoeuvrability of a vessel, as it shows how easy it is to rotate the vessel. The overshoot is the maximum course change minus the test angle. This test angle is also the maximum change of rudder (20 degrees in figure 6.2b). The larger the overshoot, the better the yaw checking ability, but this will result in a lower path changing-ability.



(a) Illustrative path (b) 15kn with 140m cargo ship

Figure 6.1: Turning circle test

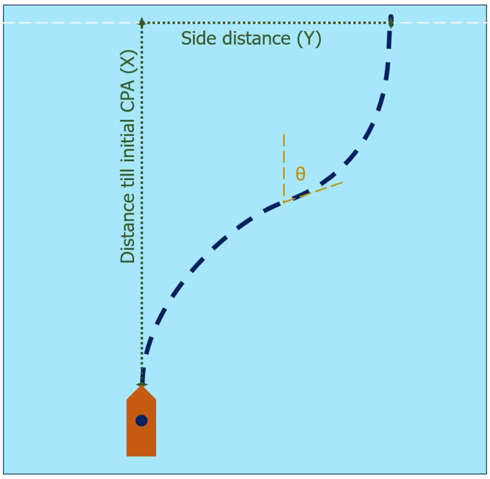


(a) Illustrative path (b) Zig-zag 20:20 test at 15kn with 140m cargo ship

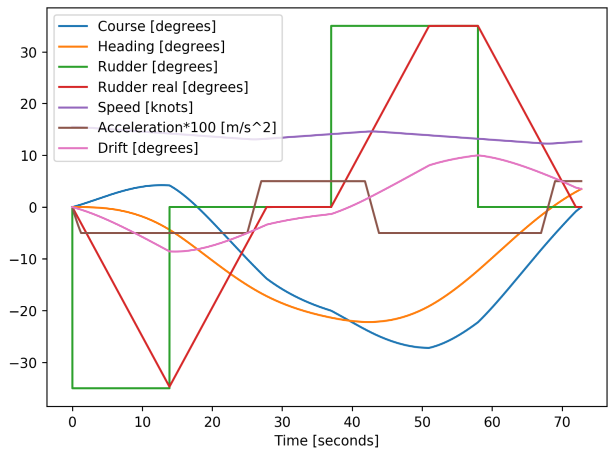
Figure 6.2: Zig-zag test

6.1.2 Critical evasive manoeuvre

The critical evasive manoeuvre aims to increase the closest point of approach (CPA) as much as possible and return to the original course. Using the least amount of time and advance distance. Based on COLREGs is there a stand-on and give-way vessel. The stand-on vessel is supposed to keep course and speed, while the give-way vessel is supposed to manoeuvre. A ship can do an evasive manoeuvre in many ways. However, the most critical situation is when the ships are on a collision course, where maximum rudder is given to avoid another vessel of which the course is perpendicular. Thereby is the aim of the give-away vessel to end the manoeuvre at its initial course. Figure 6.3 shows an example of such manoeuvre. θ is the maximum course change. X is the distance until a ship reaches the initial CPA, which is in the most critical situation, the collision point. Figure 6.3b shows how the vessel uses its rudder during the evasive manoeuvre. Also is seen that the speed reduces, mostly due to the drift angle. The manoeuvre is simulated for different start speeds and with different maximum course changes.



(a) Illustrative path



(b) 20 degrees at 15kn with 140m cargo ship

Figure 6.3: Evasive manoeuvre

6.2 Tool validation

To validate whether the results will be as expected, we use the same manoeuvres as in the sea-trials. The previous section describes these manoeuvres. This section will discuss the validation of the tool, that is presented in appendix B. The used hydrodynamic model is first validated. And then for the evasive manoeuvre that will be used to determine the dependency of the decision domain on manoeuvrability.

6.2.1 Validation of hydrodynamic model

Section B.2.3 and the paper by Artyszuk [Artyszuk (2016)] explain the used hydrodynamic model. This linear dynamic higher-order model is based on the 2^{nd} order Nomoto model [Nomoto and Taguchi (1957)], where different derivations are made to incorporate ship characteristics. The model is validated using the sea-trial database from Damen Shipyards, criteria as described by IMO resolution A751(18) [Quadvlieg and van Coevorden (2003)], similar simulator comparisons [Tjøswold (2012)] and results presented at MARSIM '96 [MARSIM (1996)]. Combining these sources gives ranges in which the metrics from the sea-trials are expected. By using the same vessels and manoeuvres as are stored in the database, the quality of the hydrodynamic model is validated. This validation is done by comparing the resulting metrics from the simulation model to expected metrics, that are based on the database and regulations.

The overshoot measured during the zig-zag test has a larger spread compared to other metrics, as it depends much more on weather conditions and human factor. But the overshoot gives insight whether the input characteristics result in behaviour that can be expected. For example, a tug should have a larger overshoot, compared to a cargo vessel, as the course keeping characteristics are very different. The results for the turning circle test give more definitive answers regarding the quality of the model. The model is accepted when the results of these tests are close to the expected results. For the simulation are not all input coefficients optimised for each ship to behave as realistic as possible, as the optimisation of these coefficients is not within the scope of this research. In table 6.1, the expected results are compared with the results from the manoeuvring model for different ship types and sizes. The overshoot is based on a 10 degrees zig-zag test, so a change of course at 10 degrees and for a rudder angle of 10 degrees. The turning circle test starts by giving the maximum amount of rudder. Both tests start when sailing at design speed. For the small tugboat, the results are not within the expected range. The overshoot and advance distance are for the other vessels within the predicted range. The tactical diameter is however relatively too large. This difference between expected results and simulation results is seen more often

[Tjøswold (2012)]. This difference has been identified as an error with non-linear damping. The critical evasive manoeuvre is much more similar to the first part of the turning circle test in which the advance distance will be determined. Therefore the inputs for the manoeuvring model will not be changed to improve the tactical diameter. Thus when testing the critical evasive manoeuvre, it should be considered that the model works better for larger cargo vessels and manoeuvres which do not go further than 90 degrees.

Ship type	Metric	Unit	Expected result	Model result
Tug	Overshoot	seconds	8 - 45	29
28 meter	Advance	meter	60 - 66	81
13 knots	Tactical diameter	meter	35 - 41	68
	Final speed	knots	6 - 7	4.4
Cargo vessel	Overshoot	seconds	4 - 10	8.6
115 meter	Advance	meter	265 - 320	315
13 knots	Tactical diameter	meter	280 - 365	362
	Final speed	knots	7.9 - 10.5	8.7
Cargo vessel	Overshoot	seconds	4 - 10	8.4
145 meter	Advance	meter	350 - 420	397
15 knots	Tactical diameter	meter	340 - 450	475
	Final speed	knots	5 - 11	9.6
Tanker	Overshoot	seconds	3 - 7	4.2
250 meter	Advance	meter	600 - 650	609
10.5 knots	Tactical diameter	meter	650 - 800	870
	Final speed	knots	7 - 9	8.9

Table 6.1: Validation of manoeuvring model

6.2.2 Input for critical evasive manoeuvre

Section 6.1.2 describes the critical evasive manoeuvre. During the manoeuvre, there are several actions: give rudder, give rudder to opposite direction, steer straight. The timing of these steps determines the overshoot. The maximum turning rate of the rudder should thereby be taken into account. During the simulation different steps are taken:

1. Start of manoeuvre. Rudder angle: 35 degrees to initial direction.
2. Few seconds before reaching desired course change. Rudder angle: 0 degrees.
3. At desired course change. Rudder angle: 35 degrees to opposite direction.
4. Few seconds before reaching original course. Rudder angle: 0 degrees.

These steps will result in a path that has a bit of overshoot but is comparable to the decision taken by an officer of watch (human or autonomous). 35 degrees is the maximum angle to which a rudder turns for most vessels. Figure 6.4 shows how the initial rudder direction should be, depending on the location and direction of the crossing vessel. To improve the CPA, you should steer away from the other's path, which means that if the other ship is in the green area, you should steer to starboard. When the other ship is in a red area, your initial direction should be to port. The orange cross represents the initial collision location in the figure. The critical evasive manoeuvre aims to increase the CPA as much as possible and return to the original course. Two factors determine the increase in CPA during the manoeuvre. The first is the distance the ship moves to the side. The second factor is the reduction in speed due to the course changes. The passing distance and closest point of approach are calculated using the algorithms from chapter 5

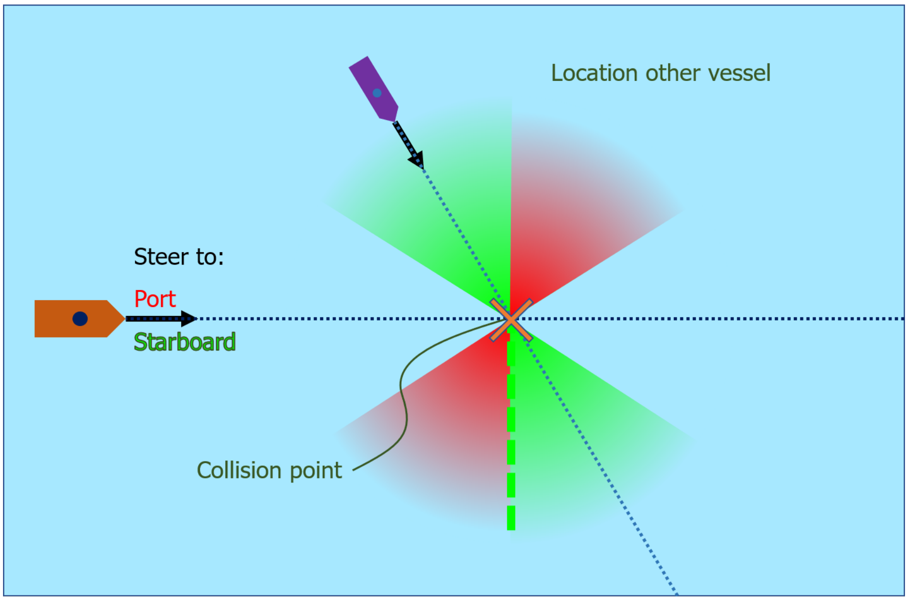


Figure 6.4: Direction for evasive manoeuvre in crossing situation

7 | Evaluation of critical evasive manoeuvre

In the previous chapters are steps taken to identify common critical situations. Enough clearance is key to avoid communication. Ships can acquire this clearance by making the right decision well in advance. This chapter will take a look at the relation between the manoeuvrability of the vessel and this clearance. Section 7.1 shows the relation between manoeuvring characteristics and criteria for safe operation. Using the simulation environment is looked into the effect of varying manoeuvring characteristics, including the advance distances from the turning circle test. These relations are used to evaluate the effect of improvements to the advance distance by increasing the manoeuvrability of a vessel on the possibility to avoid communication. This increase in manoeuvrability should result in less critical situations and hence the amount of communication. This will show how the passing distance can be improved by changing manoeuvrability characteristics, and how this should be taken into account in the design and decision process of ships. A use case is used to support this. The method to find this relation for the critical evasive manoeuvre and effect on the decision and design process can be used to give a general answer to the question whether it is possible to ensure that a chosen strategy will result in an approach distance that does not require communication.

7.1 Trial results for critical evasive manoeuvre

The first step is to find the relations between manoeuvring characteristics and criteria for the operation that do not require communication. The tests from section 6.1 are used in the simulation environment to acquire these relations. The criteria herein are the CPA and crossing distance. The primary input for the results depend on the ship manoeuvrability and starting speed of the vessel. The speed of another vessel and crossing angle should be taken into account to calculate the closest point of approach and passing distance for the most critical situation. The metrics to evaluate the above mentioned criteria are described in table 7.1 and shown in figure 6.3a.

The reason to use the evasive manoeuvre is that when two ships are parallel, the situation becomes a head-on or take-over situation. These situations are less critical and more easy to cope with than a crossing situation. A ship has to alter its course to go from a crossing situation to another situation. In case the crossing angle is 90 degrees, the ship has to alter its course the most. This is deduced from figure 6.4. Therefore is the crossing angle for the most critical evasive manoeuvre 90 degrees.

Metric	Description
Time needed for manoeuvre	Time from first rudder change, until the ship returned to its original course
Distance till initial CPA (X)	Distance travelled forward in the direction of the original course to the point where the ship had the smallest CPA
Side distance (Y)	Distance travelled perpendicular to original course
Extra time	Time needed for manoeuvre, minus the time it would have taken to travel the same distance forward
Passing distance	Adding the distance to the side to the extra time times the speed of the other vessel
CPA	Closest point of approach during the manoeuvre

Table 7.1: Metrics for evasive manoeuvre

7.1.1 Passing distance

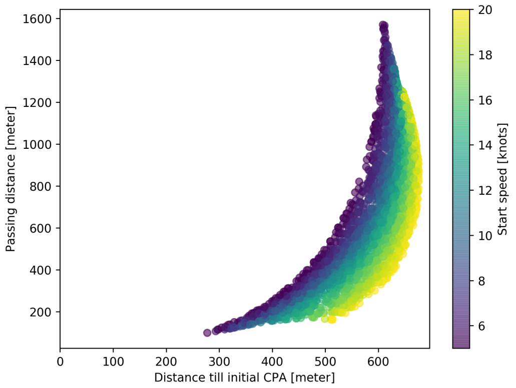
The passing distance is the first criteria that will be evaluated, as this is often used by seafarers to determine if they pass correctly. A simplified calculation for the passing distance can be used due to the perpendicular crossing situation. Figure 7.1 shows the results of trials revealing the relation between passing distance, distance till initial CPA and starting speed.

Results of simulations

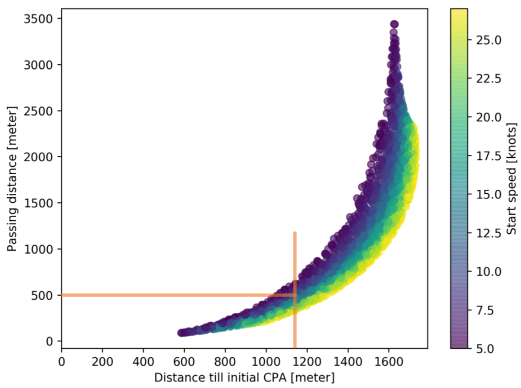
The $passing\ distance = side\ distance + speed\ other \times extra\ time$. For the simulation is the speed of the other vessel kept constant at 14 knots, as the effect of the speed of another vessel is relatively small. For the same passing distance will the distance till CPA vary with less than 50 meters. 14 knots is a typical speed for large cargo vessels at open-sea. The possible passing distance for lower speeds is smaller for the same distance till CPA.

The wedges in figure 7.1 are used to determine the distance till initial CPA. For the Gulf Valour at 13 knots, and a collision course with a vessel sailing at 14 knots, it means that the Gulf Valour has to start acting at least 860 meters before the collision point, to end up with a CPA of 500 meters. When the Emma Maersk sails 13 knots and has 1150 meter left to act before a collision. Does it mean that the passing distance can be at most 500 meters.

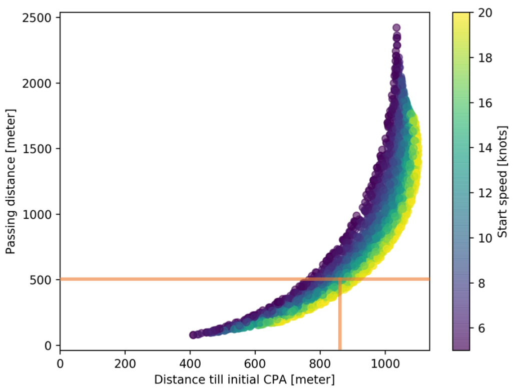
In figure 7.1d are the wedges combined, to show the relative size of these wedges. The location of the curves within the wedges depend on the start speed, that influences the advance distance. The ship becomes parallel to the other vessel when the course changes 90 degrees, as it means that it is not a crossing situation anymore. The point where this happens is the maximum passing distance for each advance distance.



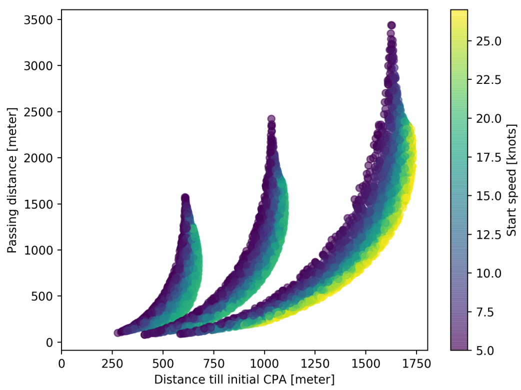
(a) Astrorunner (140m - 9500 ton - General cargo)



(b) Emma Maersk (400m - 157000 ton - Containers)



(c) Gulf Valour (250m - 115000 ton - Tanker)



(d) Combined relations for vessels

Figure 7.1: Relation between passing distance, distance till CPA and start speed

Relation between the passing distance and advance distance

The results in figure 7.1 make it clear that there is a relation between start speed and the results of the critical evasive manoeuvre. This start speed influences the key manoeuvrability characteristic relevant to the critical evasive manoeuvre: Advance distance. This is measured during the turning circle test. To show the relation between the advance distance, distance till initial CPA and passing distance, trial results are as shown in figure 7.1 combined. Many more ships are however needed to create a continuous graph that can be used to show relations over a wider range. More ships are created using a mocking strategy, where besides the start speed and course change, also the input for the manoeuvring model is varied. This creates artificial ships that do not exist in reality. With these ships it is possible to test more advance distances. The empirical amplification factor of the rudder force is varied, that means that the rudder is more or less effective. Vessels acquire this change by changing the size of the rudder or adding rudders. Due to non-linearities no conclusion can be made that a doubling of this factor is the same as adding an extra rudder. However, it will give a requirement for the advance distance.

Figure 7.2 shows how the relation between distance till CPA and the final passing distance depends on the advance distance. Where the advance distance depends on three factors, the ship (140m cargo ship, 250m tanker or 400m container ship), the start-speed and the empirical rudder amplification factor. Combining the results of these simulation will result in a continuous graph. The curves deducted from this graph can be used during the design process or while operating a vessel to determine the required advance distance for a specific situation. This can be used on its turn to define vessel dependent speed limits or manoeuvrability requirements for specific areas and situations.

Generalised relation for passing distance

Figure 7.3 shows the generalised form for the relation between distance till initial CPA and passing distance. Going left or right on this general curve, relates to the maximum course change (θ). The position of the curve depends on two factors, the advance distance and speed of another vessel. Where the speed of another vessel has a relatively small impact, as the bandwidth of these curves is small. By comparing different curves, is seen that an increase of 1 knot, will result in a maximum change of 1% of the distance till CPA when the passing distance is kept constant. This change means for a 400-meter container ship with the desired passing distance of 1000 meter that the distance till initial CPA varies between 960 and 1070 meters when the speed of the other vessel varies between 0 and 18 knots.

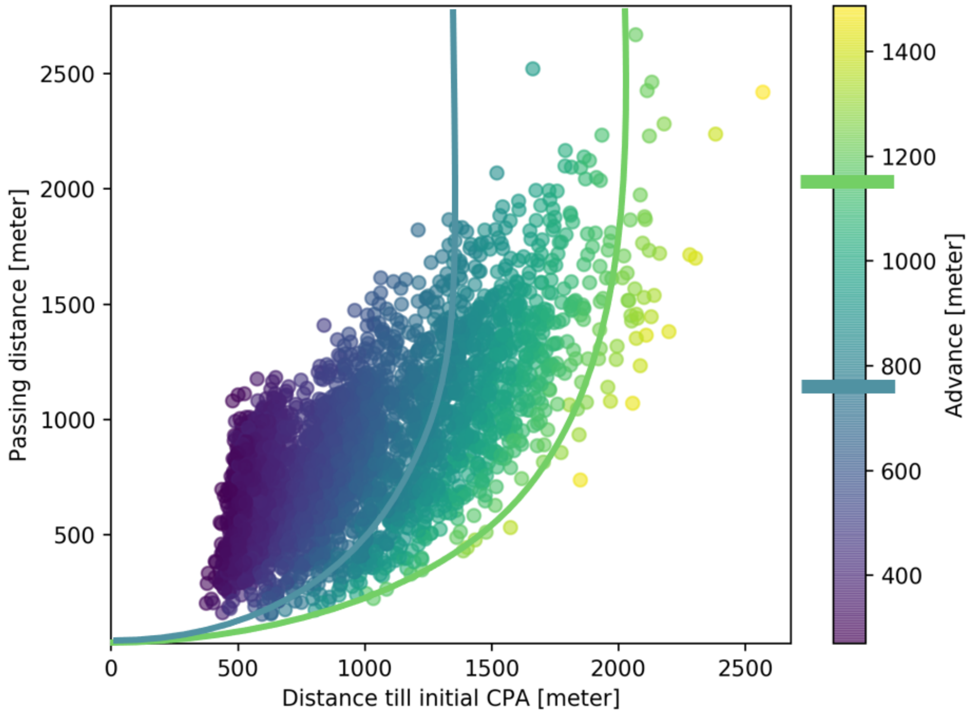


Figure 7.2: Combined plots for different advance distances, showing the relation between distance till CPA, passing distance and advance distance by varying start speed and rudder amplification factor. Including example advance distance iso-curves

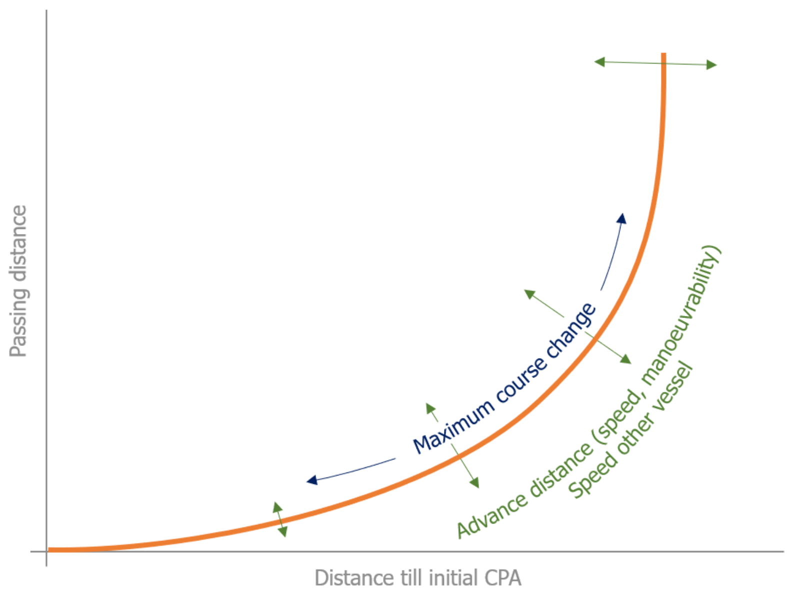


Figure 7.3: General curve for relation between distance till initial CPA and passing distance

The advance distance is however much more relevant for increasing the ability of unmanned vessels to ensure safe operation in critical situations. In case of an evasive manoeuvre does a reduction of 1% of the advance distance, result in a 1% reduction of the distance till initial CPA. Liu [Liu et al. (2015)] has shown that a reduction of 10 % in advance distance can already be acquired by using different rudder profiles, compared to commonly used profiles. Similar results are acquired by using a high-lift rudder [Zaky et al. (2018)]. For a 250 meter tanker at 12 knots, with the desired passing distance of 1000 meter. This would mean a reduction of 100 meters on the distance till initial CPA. This reduction will on its turn mean that 100 meters less is required to ensure that the chosen strategy will result in a passing distance that does not require communication.

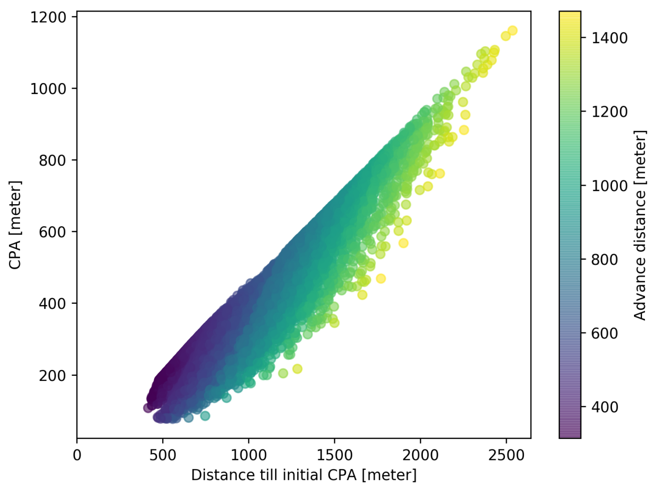
7.1.2 Closest point of approach

The more critical measure is the CPA, as this defines the minimal distance between two vessels. For this criteria is a more complex calculation required. The algorithm specified in section 5.2.2 is used to calculate the CPA. In case of the critical evasive manoeuvre is the CPA smaller than the passing distance. The moment of the CPA is often earlier than the initial CPA, as the first step in a crossing situation is to steer towards the other vessel. Using the knowledge from the passing distance is again looked at the influence of the advance distance on the CPA.

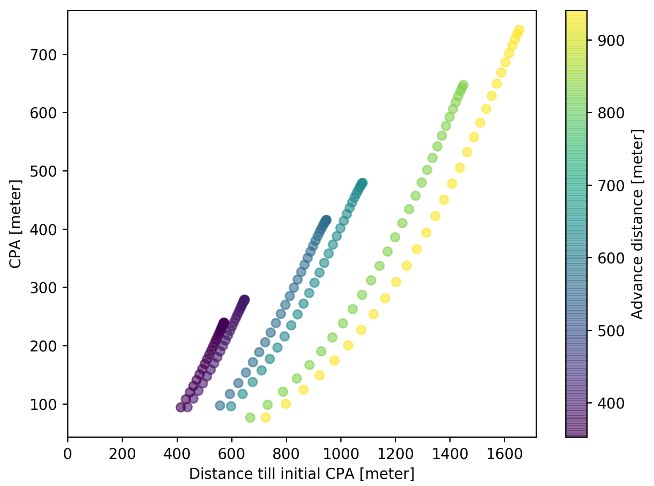
Results of simulations of the relation between the CPA and advance distance

The minimum for the distance between another ship and own ship at every timestep is the CPA. The different inputs are varied again to find the general relations for this simulation. Varying these inputs will give insight into how these affect the decision and design process. Inputs which are also varied to find the general relation for the passing distance are the ships, the maximum course change, the start speed, and the rudder amplification factor. The speed of the other vessel is 14 knots again for the same reasons as described in the previous section.

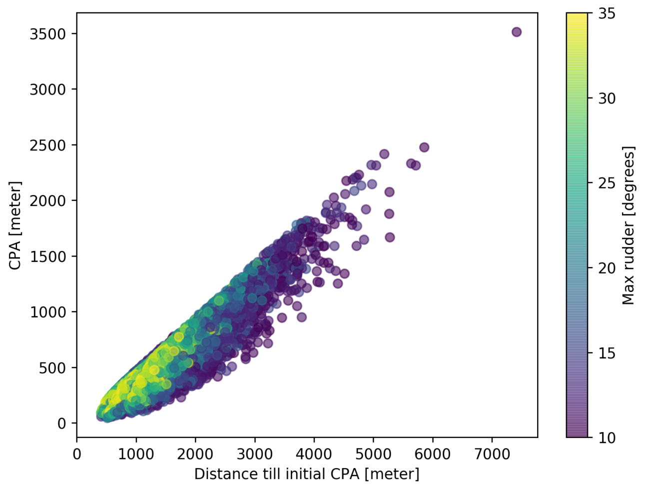
Figure 7.4a shows a clear maximum for the CPA at every distance till the initial CPA. Thereby can be seen that this depends on the advance distance. This relation has a different generalised curve than figure 7.3. Figure 7.4b shows the generalised curve for the CPA, where the advance distance is constant for each of the different curves. The advance distance for these curves is 397, 609 and 1140 meter.



(a) Combined plot for the resulting CPA at different advance distances



(b) Example iso-curves for different speeds and manoeuvring characteristics, as used in use case



(c) For different maximum rudder angles

Figure 7.4: Relation between distance till CPA and CPA

The maximum rudder angle during the evasive manoeuvre is an extra factor influenced to find the relation between CPA and advance distance. For calculating the CPA is the shape of the curve during the evasive manoeuvre relevant, as the CPA takes often place somewhere in this bend. Varying this input will give results for a larger range of CPAs. Figure 7.4c shows how this changes the relation between distance till initial CPA, CPA and the advance distance.

General relation for CPA

In the previous section are results shown for the impact of the advance distance. The manoeuvring characteristics and start speed of the vessel determine the advance distance, thereby is shown how these affect the CPA in a critical evasive manoeuvre. Conclusions can be drawn on the effect of the manoeuvring characteristics on the decision process, by taking the general curves for these relations. These are also taken into account during the design process of a ship or traffic schemes.

One of the most interesting characteristics from the results, is the maximum value for CPA at different distances till initial CPA. Thus the almost linear line showing the maximum CPA reachable for each distance till a collision would occur. This line can be explained by the trajectories of the ships and the shape of the safety domain. The exact trajectory of the ship depends on the manoeuvrability characteristics, such as overshoot and turning ability. But the most important factor for the shape is the advance distance.

The point where the CPA is reached is at a similar location in the manoeuvre when normalized by the advance distance and time for the situation where the maximum course change is 90 degrees. This point is exactly where the ship has turned 90 degrees. This point is exactly the same as the point where the advance distance in the turning circle test is measured. This means there is a direct correlation between the advance distance and the point where the CPA is reached. As the speed of the other vessel is kept the same due to its limited impact, will this result in a linear line for the relation between CPA and distance till initial CPA.

7.2 Use case

Examples are given to show how the found relations for the common critical evasive manoeuvre can be used. These show how the relations are used to define vessel dependent speed limits and manoeuvrability requirements. The used situation is the crossing of a traffic lane. This is similar to the situation as used in part III. The situation is described first, next the manoeuvrability characteristics are varied to show how this influences the decision process. This is concluded by a discussion on the requirements for different vessels in such a situation.

The crossing situation is at the North-Sea and also described in section 11.1.2. The situation is based on the accident between MV ARTADI and MV ST-GERMAIN (appendix C.2). Three vessels are included in this use case: a 250-meter tanker (GULF VALOUR), a 140-meter cargo vessel (ASTRORUNNER) and a 400-meter container vessel (EMMA MAERSK). Different screenshots of the situation are shown in figure 7.5 and 7.6 over time, on page 62 at the end of this chapter. The relevant information about the ships is given in table 7.2.

	GULF VALOUR	ASTRORUNNER	EMMA MAERSK	
Length	249.0	141.6	397.7	m
Width	48.0	20.6	56.4	m
Draft	13.2	6.5	12.6	m
Deadweight	114900	9543	156907	ton
Type	Oil tanker	General cargo vessel	Container vessel	
Colour	Green	Orange	Blue	
Start position	[-100, -100]	[3250, 0]	[2800, 3400]	m
Speed	15.0	14.7	12.0	knots
Course	45	315	225	degrees
Advance distance	633	393	940	m

Table 7.2: Relevant information for crossing situation at North-Sea

The ASTRORUNNER sails perpendicular to the courses of both GULF VALOUR and EMMA MAERSK. The first interaction is between GULF VALOUR and ASTRORUNNER. The GULF VALOUR has to give-way in this situation. Based on the results from the previous section and considering a minimal CPA of 370 meters (two cables). The experts from the experiment in chapter 11 confirmed that this a realistic CPA in busy areas. This CPA forces the GULF VALOUR to start the evasive manoeuvre 968 meter before the initial collision point.

As the ASTRORUNNER is the stand-on vessel, it has to hold course and speed till the GULF VALOUR has passed. But also considering the results from the previous section and a minimal CPA of 370 meters, this does mean that the ASTRORUNNER has to change its course 739 meters before colliding with the EMMA MAERSK. The GULF VALOUR has passed the ASTRORUNNER 1060 meter before the initial collision point with the EMMA MAERSK, which means that the ASTRORUNNER has plenty of time to avoid a collision with the EMMA MAERSK

If the GULF VALOUR would be in the same situation as the ASTRORUNNER, it would be still be possible to manoeuvre in time. As the CPA of 370 meters can be reached by changing its course 968 meter in advance. This is less than the 1060 meter that is left after becoming the give-way vessel. The EMMA MAERSK faces a problem, as she has to start the evasive manoeuvre 1285 meters before the collision, while the distance at which the vessels changes from stand-on to give-way vessel is only 1060 meters from the collision point. In that case is it for the EMMA MAERSK only possible to increase the CPA to 218 meters.

Small adoptions are for vessels with the size of the EMMA MAERSK not sufficient, such as an improvement of the rudder properties or reducing speed. These changes will result in a maximum decrease for the distance till initial CPA to 1180 meters. For the GULF VALOUR will changing the rudder profile reduce the advance distance with 10% as described before in section 7.1.1. This reduction will result in an distance till initial CPA of 897 meters, instead of 968 meters for the same desired CPA of 370 meters.

Tables 7.3 and 7.4 show the results of substituting the ASTRORUNNER by the EMMA MAERSK or GULF VALOUR in the use case. This shows that the EMMA MAERSK can't act in this situation, the GULF VALOUR is limited by its manoeuvrability characteristics to improve the CPA, while the ASTRORUNNER would not benefit due to it's high manoeuvrability.

7.3 Effect of advance distance on decision and design process

In this research the critical evasive manoeuvre is evaluated. By evaluating more different manoeuvres and situations, it will be possible to create many more common use cases, that can subsequently be used to define more requirements for the advance distance in those situations. This advance distance is an input for the design process of a ship. On the other hand is it possible to use these results to make vessel and situation dependent speed limits. This will ensure that ships can operate safely without communication.

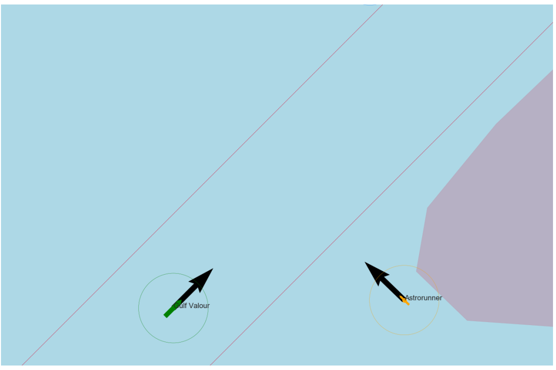
For the critical evasive manoeuvre three results are possible. The first result is when insufficient distance is left until the initial CPA to improve the CPA to a satisfying distance. For the EMMA MAERSK this is true in the use case. In those situations it is necessary to communicate. The second result is when the manoeuvrability characteristics are limiting the possible CPA. In that case is a ship not able to turn 90 degrees, but has enough distance left till the collision to improve the CPA to the desired CPA. This is the case for the GULF VALOUR when no adaptions are made. The last possible result is that sufficient distance is available to go from a crossing situation to a situation where the courses of both ships are parallel. The maximum possible CPA can exceed in those cases the required CPA. For every extra meter distance till initial CPA, does the CPA also increase one meter. This is the case for the improved GULF VALOUR and the ASTRORUNNER.

	GULF VALOUR	ASTRORUNNER	EMMA MAERSK	
Advance distance	633	393	940	m
Distance till initial CPA	1060	1060	1060	m
Possible CPA	462	691	218	m
Accepted CPA (370 m)	✓	✓	✗	
Advance distance	633	393	940	m
Distance till initial CPA	968	739	1285	m
Possible CPA	370	370	370	m
Sufficient distance (1060 m)	✓	✓	✗	

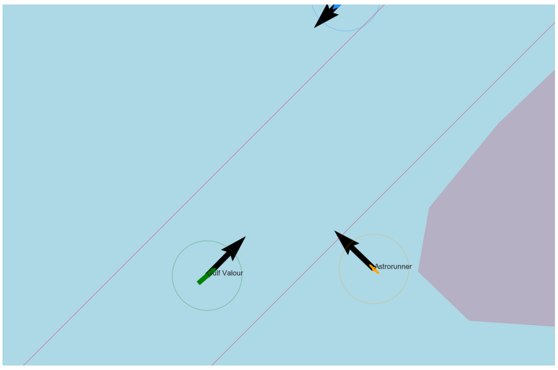
Table 7.3: Results for double crossing situation with original advance distance

	GULF VALOUR	ASTRORUNNER	EMMA MAERSK	
Advance distance	570	354	846	m
Distance till initial CPA	1060	1060	1060	m
Possible CPA	527	762	274	m
Accepted CPA (370 m)	✓	✓	✗	
Advance distance	570	354	846	m
Distance till initial CPA	897	704	1180	m
Possible CPA	370	370	370	m
Sufficient distance (1060 m)	✓	✓	✗	

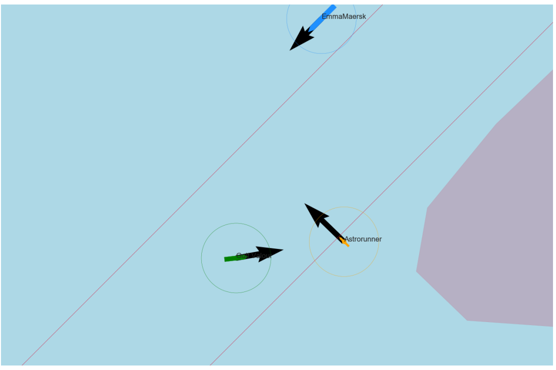
Table 7.4: Results for double crossing situation with improved advance distance



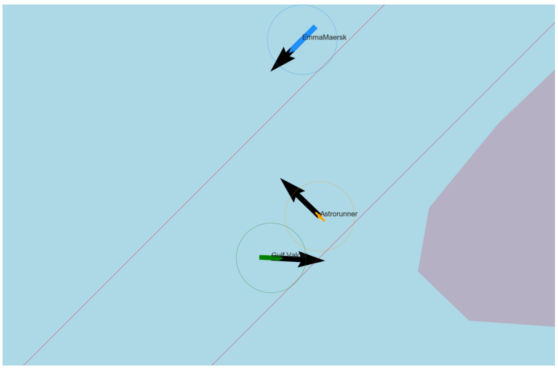
(a) Time: 0



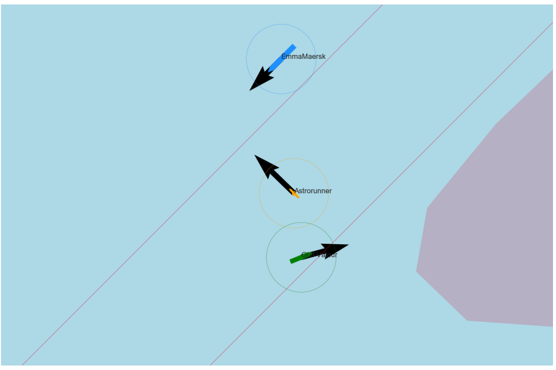
(b) Time: 65



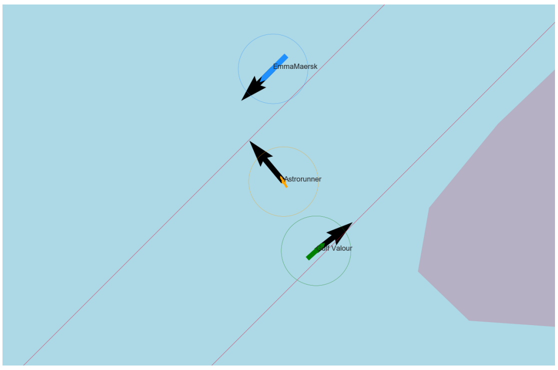
(c) Time: 120



(d) Time: 170

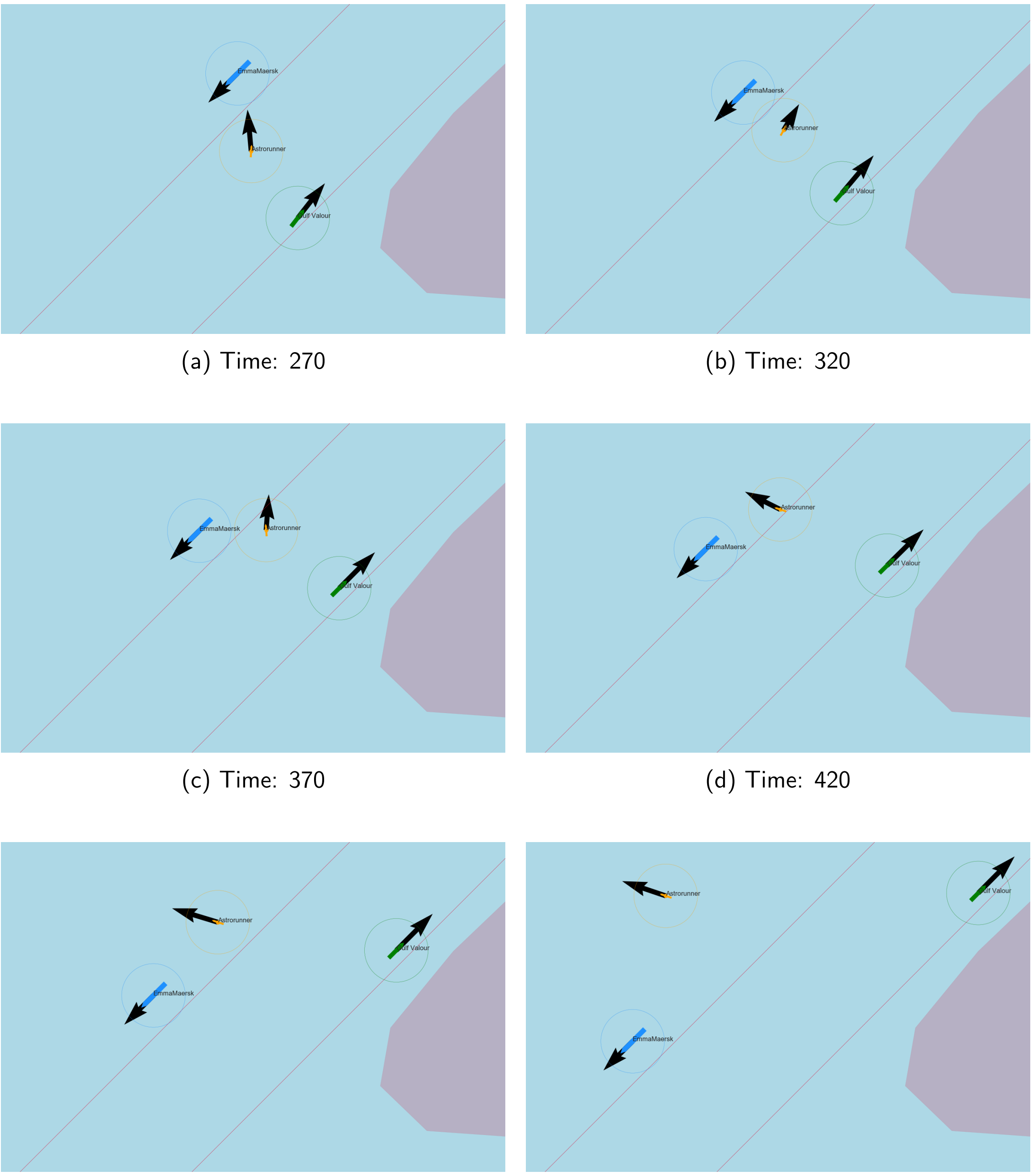


(e) Time: 220



(f) Time: 240

Figure 7.5: Situation sketch for crossing situation at North-Sea part 1



(a) Time: 270

(b) Time: 320

(c) Time: 370

(d) Time: 420

(e) Time: 500

(f) Time: 620

Figure 7.6: Situation sketch for crossing situation at North-Sea part 2

8 | Conclusion

This part describes the steps to show the impact of manoeuvrability on the necessity to communicate. The first was an analysis of the decision making process. This analysis made the selection of critical situations and relevant criteria possible. A decision tree is defined to determine the favourable strategy in those critical situations. The crossing situation is one of the most critical situations. The favourable strategy in this situation is an evasive manoeuvre. The method to determine the relation between manoeuvring characteristics and criteria is evaluated with the evasive manoeuvre. This is used to answer the following question:

> *How do ship manoeuvrability characteristics influence the domain for decision making, to ensure that the chosen strategy will result in a closest point of approach that does not require communication?*

For a specific situation which requires an evasive manoeuvre is determined that the key manoeuvring characteristics is the advance distance, which is tested during the turning circle test. A relation is found between this advance distance and decision criteria. The relevant decision criteria during a common critical evasive manoeuvre are the closest point of approach (CPA) and passing distance. When these criteria are met, no communication is needed.

The discovered relations show that in case the required CPA is 370 meter, the distance till initial CPA should be at least 835 meter. One of the conclusions that can be drawn from this is that the distance between two traffic lanes should be at least 806 meters to ensure that crossing ships have enough space to react, and can avoid communication. The maximum advance distance is in this case is 400 meter. Longer advance distances will result in longer distances till initial CPA and thus will need even more space between traffic lanes. The advance distance can be improved by adding rudders or changing the rudder profile. One of these changes could already result in an improvement of 10% on the advance distance, which results in a reduction of 10% on the distance required to react. But this distance cannot be smaller than the mentioned 806 meters, when only using the evasive manoeuvre. By sailing parallel this distance can be increased, but this means it is no crossing situation anymore.

The method used to validate if a ship with certain manoeuvring characteristics is able to act safely and avoid communication, can also be used for other situations. More situations are required to define manoeuvring requirements for any ship in any situation. This will ensure that the chosen strategy will result in a closest point of approach which does not require communication.

Part III

A protocol to enable communication between manned and unmanned ships

Meant is not said, said is not heard, heard is not understood, understood is not done.

– Marcus Rall [Rall and Dieckman (2005)]

It is not always possible to operate without communication, as is tried to accomplish in part II. This is often the case due to missing information, or a lack of understanding about the intentions of other vessels. With manned ships, verbal communication via VHF radio is used to acquire the missing information or discuss strategies with other ships. This communication is likely to be also necessary when unmanned vessel operate between manned vessel. This part discusses the development process of such a protocol. The relevance of such a protocol is proved using an experiment. This part will answer the following question:

> *Will a protocol based on existing maritime systems and communication protocols be sufficient to ensure safe navigation, while manned and unmanned vessels encounter each other?*

A protocol defines the format and the order of messages exchanged between two or more communicating entities, as well as the actions taken on the transmission or receipt of a message. It mostly is verbal communication, but it will not be limited to this. As it might result in better situational awareness for both the manned and unmanned to use other means, such as visible signals or text messaging.

The communication which happens today between vessels is most often when COLREGs do not result in clear strategies, or when intentions are not clear. Communication which will not be within the scope of this research, is the communication with traffic controllers and how other vessels interpret conversations. Thus this research is a starting point to develop a full protocol needed for the acceptance of unmanned vessels.

This protocol is developed using an iterative process based on the situated Cognitive Engineering (sCE) method. Where reviews and prototype evaluations continuously refine a requirement baseline. How to apply sCE is described by Neerincx and Linderberg [Neerincx and Lindenberg (2012)].

The first step is to create a foundation. The current situation of the problem is addressed. Thereby considering existing knowledge which might be relevant to solve the problem, which results in the envisioned technology. The next step is to define the system design specification. In which scenarios are described that show how the problem is solved. From this can be extracted what should be designed and why this is done. Using this, a design is made that is being evaluated to make improvements in next iterative steps.

9 | Foundation

The foundation segment in the situated Cognitive Engineering (sCE) methodology describes the design rationale in terms of operational demands, relevant human factors knowledge, and envisioned technologies. Together, these three constituents describe the problem to be solved, the existing knowledge on ways to solve the problem, and the technology needed to implement that solution.

9.1 Operational demands

The operational demands describe the current practice as it is, i.e. without the envisioned technology. For the operational demands, the sCE method prescribes as main components the stakeholders with their characteristics and the problem description with an analysis thereof.

9.1.1 Problem scenario

Convention on the International Regulations for Preventing Collisions at Sea (COLREGs) have been developed long before bridge-to-bridge voice communication became available. These are supposed to be unambiguous. It is the responsibility of all bridge watchkeepers to know how to apply these instinctively, from observation by sight and radar. The regulations work effectively when ships in an interaction obey these; the regulations also specifically address circumstances where one ship does not.

However, as shown in the previous parts, COLREGs are not always sufficient to decide on the right strategy, for example, due to missing information. Problems with COLREGs happen already more often due to larger ships, more complex manoeuvers and more traffic. In those cases, operators can use the VHF radio for verbal bridge-to-bridge communication. Leading here are the Standard Maritime Communication Phrases (SMCP). The primary task of these phrases and surrounding protocol is to diminish misunderstanding in safety-related verbal communications. Beside this verbal communication, non-verbal communication might be used, such as light signals, sound signals and text messaging.

Three reasons for safety-related verbal communication are: As the operator you will deviate from the rules, you register deviant behaviour at other ships, or more information is needed to decide on the right strategy. Communication is often necessary due to the lack of visual information. For example, due to bad weather, obstacles like bridges and terminals, or the information received via AIS is not reliable. Besides the impact on the information you get by looking out of the window, is also the quality of the Electronic Chart Display Information System (ECDIS) and Automatic Radar Plotting Aid (ARPA) worse.

The different ways for communication are not developed to be used by unmanned vessels. On the other hand, it is not feasible to require all manned vessels to install new systems for communication, before introducing unmanned vessels. As this will require many more new regulations, development time and time to train seafarers.

Misunderstanding and problems with communication can be the result of changing the usage of systems over time, due to the evolving demands for operators. These changes can result in an information overload of the crew and communication channels, caused by the more frequent use of VHF. As it is a receiver or a transmitter, but can't be both at the same time, which means that in case two messages are sent at the same time, both senders will not receive the others message.

9.1.2 Problem analysis

To avoid misunderstanding that could result in hazardous situations, it is important that manned and unmanned vessels are able to communicate. A more extensive analysis is made to solve this problem. Describing the values of the different actors and discussing their related problems.

Primary actors

The focus of this research will be on bridge-to-bridge communication. For this communication are the most important actors for unmanned and manned vessels:

- Manned vessel
  - *Officer of watch*. He is the responsible person. He might work together with a helmsman and a lookout. He must ensure proper functioning of all available systems. He does discuss with other crew members if there are any unusual activities. He is responsible for following a proper navigation plan while having his safe passage plan, to avoid collisions. He will use sight, Automatic Radar Plotting Aid (ARPA) and Electronic Chart Display Information System (ECDIS). Thereby he is aware of the ship's speed, turning circle and other handling characteristics to decide on the right strategy. He will monitor the VHF radio all the time while underway, to assist in emergencies if necessary, to hear Coast Guard alerts for weather and hazards or restrictions to navigation, and to hear another vessel hailing you.

He wants to avoid information overload while being aware of the situation, which is only possible when he stays concentrated. This happens when the tasks are challenging, and he needs to have a form of autonomy [Porathe et al. (2014)].

  - *Helmsman and lookout*. Both monitor the situation and execute commands from the officer of watch. A risk for them is information overload or underload [Neerincx et al. (2008)].

- Unmanned vessel
  - *Controller agent*. This agent is responsible for situational awareness. Thus getting safely from A to B. It will decide on the navigational strategy, it will do this based on the information acquired via all different means. Including newly developed communication protocols, computer vision and algorithms to transform sensor data into useful information. His duties are similar to the duties of the officer of watch as described for the manned vessel.

- Other vessels
  - *Crew and pilots on nearby vessels*. They might want to know the intentions of other vessels to base their strategy on, without receiving all discussions, as this might result in information overload.

Secondary actors

Beside the first group of actors, the new protocol could also influence others, besides the first groups of actors mentioned above. Although they are not within the scope of this first design cycle, they should be considered to avoid problems such as information overload on current communication channels or confusion.

- Only recipients
  - Crew on vessels which are not travelling.
  - Shipowners of unmanned vessels, monitoring vessel from a remote location.

- Not within the scope of the research
  - Vessel traffic controllers
  - Crew which are in distress and require assistance

Goals

The main goal is to ensure reliable sharing of information, without the risk for information overload or misunderstanding, so that manned ships will trust unmanned ships to choose the right strategy, as manned ships can be informed, using natural language describing the reasoning of unmanned vessels. During communication manned vessels should only be updated when requested or in case of an unusual activity that could affect their strategy. Manned vessels should thereby be aware when unmanned vessels desire more information to decide on the right strategy. It might be possible to develop a protocol for communication with traffic controllers in later iterations, using the same philosophy. This communication becomes more critical when the development of a new system for traffic controllers will take too much time to develop or implement.

Infeasible solutions

A logical solution for unmanned ships would be to install a new system on every vessel. To implement this, it would mean that all ships that could encounter an unmanned ship will have to install this. It might be possible to make it obligatory via regulations, which will cost much time and money. This might delay the introduction of unmanned ships significantly. Time and money are also the reason to use a Non-visual User Interface (no-UI), as a GUI will require new screens or changes to the ECDIS which is only possible when regulations are changed.

9.2 Human factors

When designing technology, two driving questions are crucial to be well-thought out: (1) What tasks and/or values is the user trying to accomplish and how can the technology support the user in doing so?, and (2) How can the technology be designed such that the user can work with the technology?

The Human Factors segment of the sCE method describes the available relevant knowledge about, for instance, human cognition, performance, task support, learning, human-machine interaction, ergonomics, etc. Note that we emphasise that this knowledge should be relevant for the problem and its design solution: the knowledge described here should lead to a better understanding of either (1) or (2). The three elements relevant to the human factors analysis are the human factors knowledge, measures, and interaction design patterns.

Human factor knowledge

Human factors knowledge describes available knowledge coming from previous research about solving the problems that have been identified during the problem analysis. The key problems relevant for human factors are information overload, situational awareness, autonomy, and learning a new protocol. The following questions should be answered:

- When does information overload occur?
  - In case of divided attention, there is a high risk for information overload and distraction by low priority messages. Therefore, the developed system should be context-aware so it can limit this risk by adapting the message to the situation [Lenneman and Backs (2007)].
  - Overload might appear due to a competition for the operator's attention that is going on between multiple information items. If automated systems handle many tasks, the operator can deal with high workload circumstances but will suffer from severe underload during quiet periods, probably losing his or her situational awareness [Neerincx et al. (2008)].
  - The information acquired at one specific moment does not necessarily serve for high-level situation awareness, for the user needs to recall the previous related information to understand the situation thoroughly. But constantly providing information might not be the solution because there will be a huge risk for information overload. It is plausible to deliver the desired information for a future task, by detecting what future tasks should be. The user might still fail to keep pace in case of multi-threaded tasks[Porathe et al. (2014)].
- Which information do operators need for situational awareness?
  - Understanding the current status of the system is not enough for full situational awareness. Expert decision makers must be able to project their understanding into the future. This projection enables experts to make the decision which results in the best options in the future. Projection requires good mental models of the dynamic relationships between the relevant parts of the environment over time. Experts focus a lot on creating their futures via present decisions. In turn, experts do form these decisions out of their comprehension of the likely interactions of all the elements they deem both relevant and important [Gregory and Shanahan (2010)].
  - Situational awareness can be enhanced by feedback, perceived information from the environment, information from other agents, as well as remote sensors. [Carver and Turoff (2007)]
- How is information perceived when acquiring it passively or actively?
  - Attention profoundly modulates the activity of sensory systems, and this can take place at many levels of processing. Especially, imaging studies have revealed the greater activation of auditory areas and areas outside of sensory processing areas when attending to a stimulus [Palmer et al. (2007)].

  - Good teamwork involves anticipating the needs of teammates, and that means pushing information before operators request it. Therefore, if things are going well, there should be little need for pulling information. In this study task, participants were instructed to push information to others, and over time master the specific timing of information sharing to the intended recipient. Findings indicate that pushing information was positively associated with team situation awareness and team performance, and human-autonomy teams had lower levels of both pushing and pulling information than all-human teams [Demir et al. (2017)].

- What is needed for successful teamwork between human and a computer?
  - People need to understand what is happening and why when a teammate tends to respond in a certain way. They need to be able to control the actions of an agent even when it does not always wait for the human's input before it makes a move, and they need to be able to reliably predict what will happen, even though the agent may alter its responses over time [Bradshaw et al. (2003)].
  - Effective team communication, a fundamental part of team coordination, is crucial for both effective team situation awareness and team performance [Demir et al. (2017)].

- Do people trust automated systems?
  - When using automation, the role of the human changes from operator to supervisor. For effective operation, the human must appropriately calibrate trust in the automated system. Improper trust leads to misuse and disuse of the system. [Walliser (2011)].

Human factor measures

Measures describe how to operationalise the quality of the intended behaviour or performance, i.e. how well is a user working with the design able to reach his/her objectives and what is the quality of the collaboration between the human worker and the technology?

- Is the system used correctly?
- Will the protocol solve the problem of missing information?
- Does the protocol act as expected?
- What is the impact on attitude towards unmanned ships?

Interaction design patterns

Interaction Design Patterns (IDPs) focus on the Human-Computer Interaction (HCI), such as usable interface design and control options. IDPs offer generic solutions to recurring HCI design problems that have been proven to be effective. Relevant IDPs are given in table 9.1. Keywords are often seen as the new buttons to interact. For the new protocol are message markers the keywords. These make it easier to train the conversational agent and clarify the available options for operators on manned vessels. Whereas the conversational skills of the agent are the core of general communication, the usage of other methods of communication will improve redundancy and effectiveness. A multimodal conversational agent also includes visible signals such as masthead light signals, flags and AIS messages. These will enable operators to see immediately if the vessel is unmanned. The last two methods are for extreme situations: audible and distress signals. The agent for the unmanned vessel should understand what these mean and how to use them before manned vessels trust them.

Radio communication	Usage of message markers and conversational agent
Visible signals	Mast head signals, flags and AIS information
Audible signals	Horn and speakers
Distress, urgency and safety signals	Flares and smoke

Table 9.1: Interaction design patterns

9.3 Envisioned technology

The envisioned technology describes the available options of using existing technology and the need to develop novel technology to come to a system solution. The sCE method asks to specify what devices (hardware) and software the designers could use in the system design. In addition, for each type of technology, an argument should be provided as to why this technology might be of use and what the possible downsides might be of that specific type of technology.

The envisioned technology will use only existing systems to develop a no-UI. Different systems that are currently used, are described in appendix A. Below different systems and protocols are mentioned that can be used in the new protocol. Using these already existing systems will shorten the development, learning and implementation time. Table 9.2 gives the used systems, equipment and protocols.

Using already existing protocols makes it easier to learn, such as Standard Maritime Communication Phrases (SMCP) and COLREGs. These systems make it also recognisable, which means that users will understand the benefits quicker. Show that it is useful and easy to use, as this is key to the acceptance of technology [Davis (1989)].

The type and amount of information presented to users must be tailored to the unique situation in which users use the information. Prior research on trust in automation found that providing human operators with information related to the reliability of an automated tool promoted more optimal reliance strategies on the tool. Further, information related to the limitations of an automated tool aids in trust recovery following errors of the automation. This added information appears to be useful in deciphering the boundary conditions under which the tools are more or less capable. Thus, providing human operators with information related to the performance of an automated tool appears to be beneficial [Lyons and Havig (2014)]. Therefore it is beneficial for the cooperation between manned and unmanned vessels to show if it is an unmanned vessel, which will first be done using visible signals, and also at the start of radio communication. Telling the user that you are unmanned or automated also happens in industry projects, such as Google Duplex [Nieva (2018)].

Radio communication	Conversational agent Negotiating agent Usage of message markers Availability on VHF Natural language variations on SMCP NATO phonetic alphabet and numbing Addressed AIS message to exchange information or interrogate
Visible signals	Light signals Mast head signals Flags Heading, position and movements
Audible signals	Horn Speakers

Table 9.2: Envisioned technology

In the next chapter the system design specification will be presented for the envisioned technology. Most important will be the definition of the usage of radio communication and how this should be supported by other ways of communication, such as visible and audible signals.

10 | System design specification

The system design specification describes the solution to the problem in the form of a system design that makes use of the identified relevant human factors knowledge, and the envisioned technology. The system specification consists of design scenarios, use cases, requirements, claims, and ontology. This chapter will answer the question: How a protocol should look like to ensure safe navigation when manned and unmanned vessels meet.

10.1 Design scenarios

The sCE method prescribes the specification of design scenarios. Design scenarios are short stories that provide a clear description of how the user will work with the technology thereby enjoying the solution offered to one of the problem scenarios. Together, the problem and design scenarios provide a context view on:

1. The problem the design aims to solve.
2. The people that are currently affected by this problem.
3. The way the current system design aims to solve this problem.
4. How people will use the system.

Manned ships can understand intentions for unmanned vessels, resulting in good situational awareness. In cases they desire more information, they can acquire this by using existing systems. Without the risk for information overload. Thereby are the additions to existing protocols for those systems easy to understand, as they use the same philosophy as current protocols.

Trust in autonomous ships is formed, as the information is reliable, the interaction is equal to the interaction with other manned ships. The risk of collisions and perceived risk is reduced or at least does not increase. This results in improved acceptance of unmanned ships on the general waterways.

Information extraction from problem scenario

The previous chapter describes the problem that will be solved by the envisioned technology. The following issues have to be tackled to solve the problem:

1. Different actors are afraid of information overload.
2. Officer of watch is afraid to lose situational awareness.

3. Officer of watch is afraid to lose autonomy.
4. Current systems are not designed to be used by unmanned vessels.
5. Manned ships want to ask for support or information.
6. Unmanned ships want to ask for support or information.

Envisioned effect of system implementation

How the problems as mentioned above are tackled is discussed below. This shows what the result is after implementing the envisioned technology:

1. The system will send only on demand or when it has tried any other solution, as this will reduce the probability for information overload. As a threshold to check if the system is successful in solving the problem of information overload, the current amount of communication is used as the criterium.

2. The protocols currently used by the officer of watch are the same. The purpose is to enable officers to get information easier. This means that the situational awareness will minimally be affected by the system on board of the manned vessel. Again the current level of situational awareness can be used as a threshold.

3. The introduction of a negotiating agent, which uses the same decision tree as used by manned vessel. Will ensure that a logical strategy is chosen. But the officer of watch at a manned ship still has a feeling of autonomy, as it is possible to divert from these strategies.

4. Significant developments to conversational agents happen in the last few years due to new applications for a broader public and market. This makes voice communication is easier to develop, especially when considering that training the systems is easy, as most VHF conversations are recorded today.

5. By using addressed AIS messages and a conversational agent at unmanned vessels, manned ships will be able to ask for support or information at all time. It is even likely they will receive the information faster compared to manned-manned ship communication.

6. The conversational agent is most relevant for unmanned ships when they want to ask for support or information, as operators do not use addressed messages often at the moment. They will use the SMCP in a similar way to how they use it right now. So not much will change compared to the current situation for manned ships.

10.2 Functional requirements and claims

The functional requirements and claims, describe specific functionalities the technology should provide to its users, this is followed by the system's objectives, and the hypotheses to be tested during system evaluations. All functional requirements are annotated with their underlying objectives (called claims).

This explicit linking of requirements to claims enables designers to formulate hypotheses that need to be tested in system evaluations to justify the adoption of the functional requirement. If the claim cannot be proven to be valid through system evaluations, the designers need to refine their system design, for instance, by trying to improve the functionality, replacing the functionality with a different one, or dropping the functionality and the claim altogether (i.e. by deciding that the objective is not reachable at this point). Either way, there is no use of including functionality that does not achieve its underlying claims. User stories are used to do this, these are usually in a form: "As an $\langle actor \rangle$, I want to $\langle what? \rangle$, so that $\langle why? \rangle$". Followed by acceptance criteria, to determine when this part is correctly implemented. The primary actors who will be considered in this first iteration are Officer of Watch (OoW), unmanned vessels, and nearby vessels.

User stories

- As an officer of watch, I want to know if there are unmanned ships in the area, so that I know what to expect from the communication. AIS shows if the ship is unmanned, and what its status is.
- As an officer of watch, I want to validate if the information received via AIS is correct, so that I can base my decision on accurate information. When an officer of watch asks unmanned ship via VHF, the answer should be reliable and based on the live information.
- As an officer of watch, I want to make my intentions clear towards all other ships, so that they can anticipate this. The agent should incorporate the shared intentions into the decision-making process.
- As an officer of watch, I want to be able to make small mistakes when following a protocol, so that I can still act fast when I do not know the exact SMCP sentence. The unmanned vessel should understand natural variations in a message, compared to the SMCP sentence.

- As an officer of watch, I want to use existing protocols, so that the extra effort to communicate with unmanned vessels will be kept to a minimum. Current seafarers should be able to understand what they should be doing without an explanation on the protocol.
- As an officer of watch, I want to receive only information which is relevant to me, so that the risk for information overload is limited. By ensuring that information which is shared is relevant to current or future tasks.
- As an unmanned vessel, I want to initiate communication, so that I can exchange information or ask questions to another specific ship. The unmanned ship needs situational awareness based on a digital model of the reality to know which vessel sails where and what the interactions could be to make the right decision.
- As an unmanned vessel, I want to validate if acquired information is accurate, so that I can base my decision on accurate information. Check via communication if the digital representation is accurate.
- As an unmanned vessel, I want to be able to check if they understand my intentions when other ships do not act as expected, so that I know if I should change my strategy. The communication should be incorporated in the decision-making process and unexpected actions by others ships should be registered.
- As a nearby vessel, I want to receive only information which is relevant to me, so that the risk for information overload is limited. By switching VHF channels for full conversations, this is similar to the current way of working.

10.3 Use case

Scenarios are used to create more specific descriptions of step-by-step interactions between the technology and its users (i.e. use cases). Use cases include actors, to specify which stakeholders/agents are interacting in specific sequences. Use cases make the design scenario more concrete by describing exactly how technology makes sure that the problem is solved. Use cases are informed by human factors theories as described in the previous chapter.

The purpose of the use case, as described in this section is to give insight in all interactions during a common critical situation at sea. Tags are used to relate these to the situations and scenarios as described in chapter 3. By making it very specific, better insight is acquired in factors that should considered when defining functional requirements.

Autonomous fast crew supplier crossing shipping lane in front of cargo ship

Tags: Crossing, Move away from other, Evasive manoeuvre now, Crossing distance, CPA, Intention, Messaging

A 26-meter autonomous fast crew supplier (FCS2610) is heading towards a wind farm at the North Sea with a speed of 22 knots. To get there, she has to cross a busy traffic lane. She will pass a 150-meter container ship (Reefer), sailing at 14 knots. The FCS2610 has noticed the Reefer late and has to make an evasive manoeuvre, to pass in front of the Reefer with a passing distance of 900 meters or 0.5 Nautical miles, which is just accepted according to the safety domains [Szlapczynski and Szlapczynska (2017b)], using criteria from chapter 5. Communication is necessary to ensure the Reefer understands the intentions of the FCS2610. This will take place in the following manner:

- The AIS, masthead and flags are showing the vessel is sailing autonomously, which means there is no crew, but the autonomous systems listen to the VHF.
- A conversation is started by the FCS2610, calling the station on board of the Reefer and updating status in AIS to communicate intention.

  Reefer, C-6-Z-G-7
  Reefer, C-6-Z-G-7
  This is unmanned FCS2610, 2-F-F-P-4
  Unmanned FCS2610, 2-F-F-P-4
  Switch to VHF channel seven-two
  over.

- The FCS2610 waits for a response from

  Unmanned FCS2610, 2-F-F-P-4
  This is Reefer
  Agree VHF channel seven-two
  over.

- At VHF channel 72, FCS2610 communicates her intentions.

  Reefer, C-6-Z-G-7
  This is unmanned FCS2610, 2-F-F-P-4
  Intention. I intend to pass in front with a distance of 0.5 Nautical mile.
  over.

- At VHF channel 72, Reefer confirms intention.

  Unmanned FCS2610, 2-F-F-P-4
  This is Reefer, C-6-Z-G-7
  Intention received. You intend to pass in front. Distance is 0.5 Nautical mile.
  over.

- Close communication and pass in front.

  Reefer, C-6-Z-G-7
  This is unmanned FCS2610, 2-F-F-P-4
  Nothing more. Have a good watch.
  Over.

  Unmanned FCS2610
  This is Reefer
  Thank you.
  Over and out.

- Update AIS status of FCS2610 to show it has no questions, and is listening.

10.4 Specification of terms used in protocol

Lastly, the sCE method prescribes the construction of an ontology, i.e. a vocabulary describing a common language to be used throughout the system specification to avoid miscommunication, misunderstanding, and inconsistencies. Furthermore, the ontology can serve as the basis for the technology's data structure. By specifying important concepts in the ontology and also choosing to use only one word instead of various ambiguous synonyms, communication becomes clearer, and misunderstandings can be reduced to a minimum. The terms specified in the ontology are consistently used throughout the entire project. For this project, these are categorised in status, messages and situations.

10.4.1 Status

The system will know which functions and protocols it should execute, by defining different states for the system. The list below describes the different states:

Listening Listening to the radio without taking action.

Waiting Waiting for a response by other ship.

Negotiating Deciding on the right strategy by discussing this with other ship(s).

Messaging Sending a message. While sending it is not possible to receive a message.

Updating Adjusting the information stored within the system, which will consecutively be sent to others ships via AIS.

Unavailable There is a problem with the system, which makes it unable to communicate.

These states will also be communicated via AIS, to ensure transparency between different agents and avoid confusion.

10.4.2 Types of messages

Both in the messaging and negotiation states messages are sent. These messages form the conversation. The agent will send different messages, during the phases of the conversation. The types of messages are described below:

Call Start of conversation, in which a ship only requests contact with another ship.

Acknowledge Accept the invitation for conversation.

Message Starts with "marker word" to clarify communication purpose, followed by the actual message and ended by a request for confirmation. The SMCP use the following marker words: *advice, information, warning, intention, question, instruction* and *request*.

Response Response to the previous message in the conversation.

Close End conversation with a greeting.

The Standard Maritime Communication Phrases (SMCP) will be used, as this is a known protocol for seafarers. This protocol has its ontology. This is described by IMO in the regulations [International Maritime Organization (2000)]. A summary of the SMCP can be found in appendix A.1.4.

10.4.3 Speech acts

The use case in section 10.3 describes a conversation containing several steps that relate to the different message types. Every message within the conversation ends with *"over"*, and the other vessel should answer with a response.

The speech act theory of Austin [Austin (1975)] is used to validate that each message and conversation are useful. As communication should be kept to a minimum, which means that every message sent, should have a locutionary, illocutionary and perlocutionary speech act.

Where the locutionary part is the sound, the illocutionary part is the intrinsic message, and the perlocutionary speech act aims to trigger an action. In case of the locutionary act, *"What are your intentions?"*. The illocutionary message is: *"I want you to tell me that your intentions are"*, while the perlocutionary aim is that the other vessel will say what its intentions are. Below the different **perlocutionary**, illocutionary, and (locutionary) acts in a conversation are shown. It should be considered that the MESSAGE itself also has these various acts.

Other ship pays attention I want other ship to listen to me.
(${<}\,name\ \&\ call\ sign\ other\ vessel\,{>}$, ${<}\,name\ \&\ call\ sign\ other\ vessel\,{>}$. This is ${<}\,name\ \&\ call\ sign\ own\ vessel\,{>}$)

Other ship switches to right VHF-channel I want to communicate via specific VHF-channel.
(Switch to VHF channel ${<}\,channel\,{>}$)

Other ship takes action or shares information I want other ship to understand the message.
(${<}\,marker\ word\,{>}$, *MESSAGE*)

Other ship closes message too I want other ship to know, the conversation has ended.
(over and out)

The SMCP define seven marker words to clarify the illocutionary act. These marker words introduce the content and purpose of the communication. The marker word is placed in a message after calling the other vessel and introducing yourself but before the real message. Examples of messages with different marker words are shown below:

- *Advice*. Stand by on channel 6 - 8.
- *Information*. The fairway entrance is: position: bearing 1-3-7 degrees true from North Point Lighthouse, distance: 2 decimal 3 miles.
- *Warning*. Buoy number: one - five unlit.
- *Intention*. I intend to reduce speed, new speed: eight knots.
- *Question*. What are your intentions?
- *Instruction*. You must alter course to starboard.
- *Request*. Immediate tug assistance.

11 | Design evaluation

The last part of the sCE method is the design evaluation. The design evaluation aims to test and validate the system's design to improve the current design in incremental development cycles. The evaluation method will be an experiment, where participants have to decide on the actions in a simulation environment, together with a questionnaire related to the experiment and communication in general. The participants are experienced seafarers. The interviews aim to answer the following question:

> *Will the described protocol ensure safe navigation and more situational awareness, when manned and unmanned vessels encounter each other?*

Different measures are used for validation and verification. The four key variables are performance, trust, situation awareness and satisfaction. This chapter describes these in more detail. This chapter aims to test the effect of the designed protocol on these measures. Four sub-research questions are answered.

Research questions

The performance variable measures if the protocol does not influence the decision-making negatively, thus do the participants follow COLREGs and use SMCP correctly. This is validated by looking at the CPA and questioning the participants about their reasoning. The main question is: *Does the protocol influence the performance of seafarers? (1)*

The trust variable is about the confidence of seafarers in the system. The protocol will only work effectively when seafarers trust the protocol. The aim of this first iteration is to find out what worries the participants, and if they want to cooperate. Based on this can be answered: *Are seafarers confident that the protocol will act as they expect? (2)*

The third variable is situation awareness, as this should not be influenced negatively by the protocol. This means that seafarers predict future states correctly and are aware of everything happening around them. This is rated by the participants themselves using an observer rating system, and by questioning them on their awareness of key characteristics of other vessels (e.g relative speed, colour, course changes). This answers the question: *Has the protocol a negative impact on the situation awareness? (3)*

The last variable is satisfaction, seafarers should like to use the protocol, as this is necessary to ensure that seafarers indeed use the protocol. Thus answering the question: *Do seafarers like to use the designed protocol? (4)*

Experiment

Two situations will be simulated to get relevant feedback and answer the above mentioned questions. The situations are based on the accident reports as described in appendix C, everyday situations around the port of Rotterdam and cases used in literature. The situations are simulated and visualised using the tool as described in appendix B. This visualisation will enable the experts to gain situational awareness and give useful feedback on the protocol. The protocol itself is mostly knowledge-based and not automated during the evaluation. Thus the interviewer has to know the Standard Maritime Communication Phrases (SMCP) relevant to the experiment, and usage of systems like Automatic Identification System (AIS) and Automatic Radar Plotting Aid (ARPA).

11.1 Evaluation method

The evaluation method is a so-called Wizard of Oz evaluation. This technique enables unimplemented technology to be evaluated, by using a human to simulate the response of an automated system. As the technology itself has not yet been implemented. The "wizard" simulates the system responses in real-time. Using seafarers and the Wizard of Oz method, an expert evaluation can be acquired on the proposed protocol without implementing it.

11.1.1 Experiment set-up

A participant acts as an Officer of Watch (OoW). During the experiment, different variables will be tested answering the research questions as mentioned at the start of this chapter. The description of the participants, tools and experiment are given in this section. The independent variable in this experiment is the possibility to use the designed communication protocol.

Participants

The 16 participants in this experiment are classified, based on their experience and expectations for autonomous shipping. All participants are Dutch, but their experience differs in certification, types of vessels they have operated, and their years of experience at the bridge.

Officer in charge This category has the lowest ranked officers at the bridge. In this case, they were trained to be officers of watch but only had limited sailing experience. Therefore they are not yet allowed to be chief mate or master. They are currently studying at STC-Rotterdam. The advantage of this group is that they studied SMCP and COLREGs and worked as an officer of watch, within the last year.

Chief mate is head of the deck department of a merchant ship. He is responsible for the deck crew and cargo. He reports to the master or captain. The officer directs the helmsman to carry out a course or speed change.

Master is the highest ranked officer. He is ultimately responsible for the safety and security of the ship. The master ensures that the ship complies with company policies, local regulations and international laws. The captain is ultimately responsible for aspects of the operation, including the safe navigation of the ship.

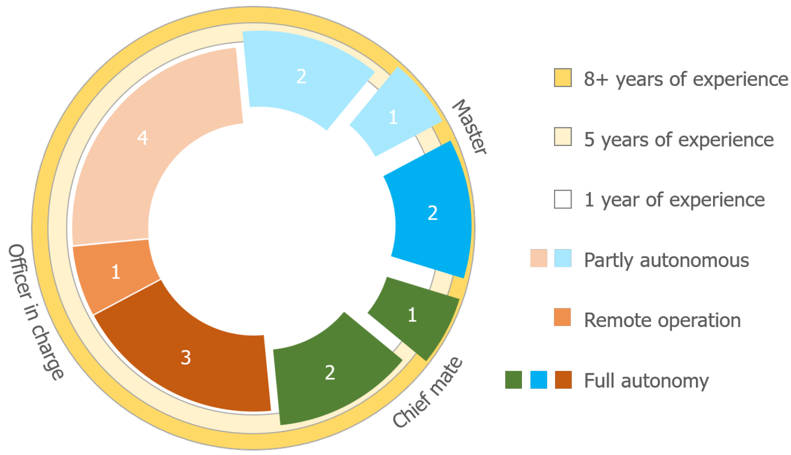


Figure 11.1: Classification of participants based on highest rank

The classification of participants is shown in figure 11.1. The different colours indicate the participants highest rank according to their certification. The maximum radius corresponds to their years of experience, while the shading the autonomy participants think ships will eventually have. The lightest colour is for participants who expect vessels to be partly autonomous, which means that they expect there will always be crew on board. Remote operation means that they expect ships to sail without a crew, but that every ship will be monitored 24/7 from a remote location, where the operator can intervene at any time. The darkest colours show the participants who think ships will eventually be able to operate fully autonomous, even in the busiest regions, such as the Dover and Malacca Strait.

The number of operators and their role per ship-type is shown in figure 11.2, some participants sailed on different ship types. Tugs and fast crew suppliers are under small vessels. Complex workboats are crane barges and dredgers. Coasters and general cargo vessels are most common. Ro-Ro and Ferries are more complex than the coasters and often also a bit longer. Cruise ships bring much more responsibility due to the number of passengers, resulting in larger safety domains. Tankers are the least manoeuvrable vessels operated by one of the participants.

Tools

Beside the participants, tools are needed to do the experiment. The tools needed are:

- Screen to show the simulation environment
- Questionnaire to be used before, during and after the experiment
- Room without distractions to do the experiment
- Possibility to store and later process actions during the experiment

The simulation environment is discussed in more detail in appendix B. Figure 11.3 shows the simulation environment. The environment has the map on the left, the side-bar or arrow-keys can be used to control the selected vessel. The status bar at the bottom of the screen gives information on possible actions, errors and status of simulation.

Experiment design

The experiment will consist of an interview and two test with two possible conditions. In only one of the two tests is the participant allowed to use the protocol. This set-up means that the experiment is a within-subject design. The most significant benefits of this type of experimental design are that it does not require a large pool of participants. A within-subject design can also help to reduce errors associated with individual differences. A major drawback which should be taken into account during the experiment is that the result of the first test may influence the result of the second test. A problem which is known as the carryover effect. This effect is mitigated by counter-balancing the participants. Thus some are allowed to communicate using the protocol during the first test, others during the second.

Thereby are variables measured on different levels. The same set of questions is used both times. The questionnaire uses both questions with a linear scale and open questions. The linear scale questions are on an ordinal level, it is not possible to do calculations, but making a histogram of the results will show the tendency of the participants. The level of measurement for the open questions is at a nominal level. Conclusions are drawn based on the grouping of questions and answers per subject.

11.1.2 Experiment task

The participant will act as an Officer of Watch (OoW) in two situations. The duties of the OoW are to keep watch and navigate the vessel. He is the representative of the ship's master while keeping watch on the bridge, and has the total responsibility for safe navigation. This responsibility means that he has to follow a proper navigation plan to avoid any collision according to COLREGs. He is thereby aware of ship's speed, turning circles, and ship handling characteristics. He also communicates with other vessels when that is necessary.

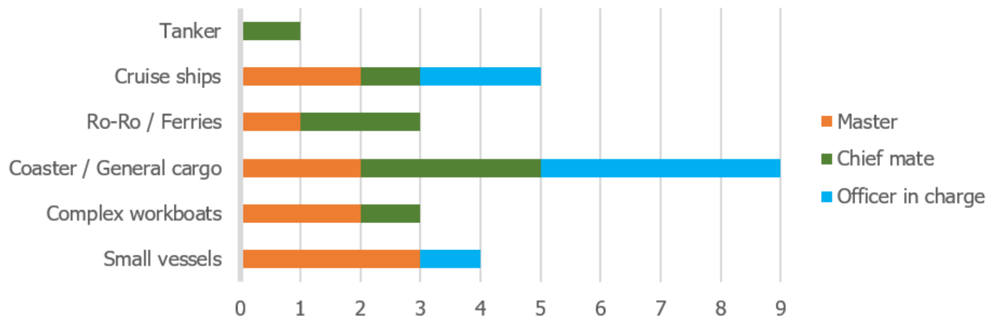


Figure 11.2: Ship-types operated by participants

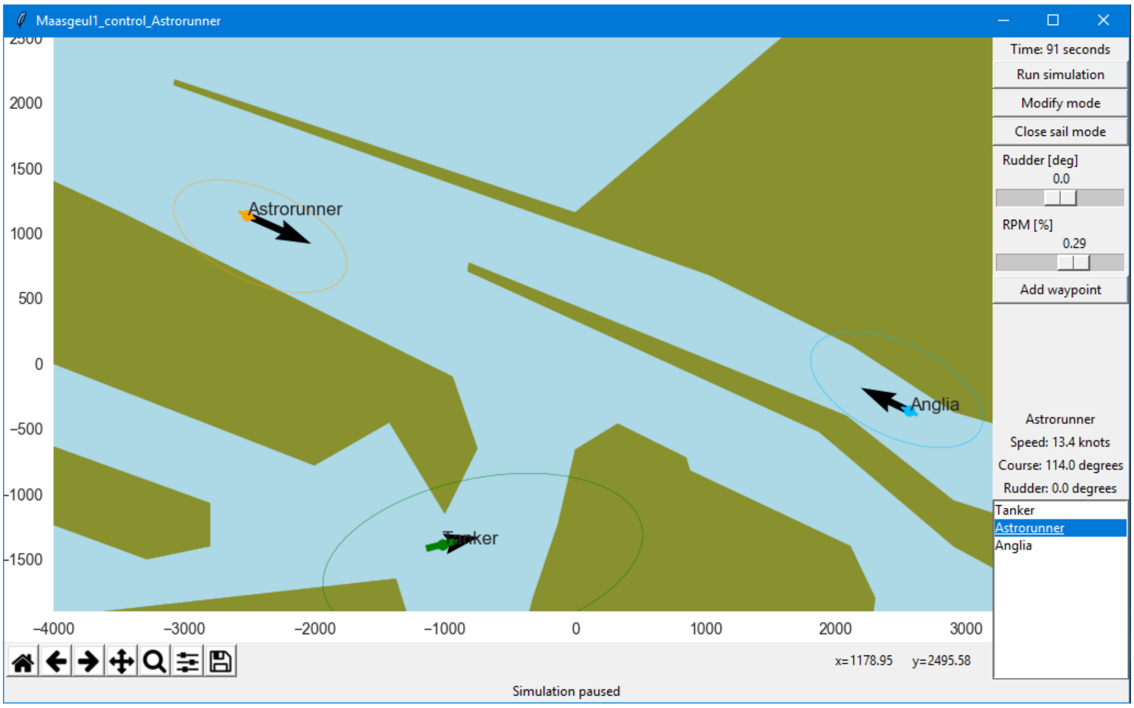


Figure 11.3: Simulation environment

More specific will he sail a vessel in different scenario's. To answer the research question for this chapter, two cases are applicable. One in which the participant can communicate using the designed protocol, in the other scenario he is not able to communicate. During each scenario will he direct a vessel on a 2D-map, as shown in the simulation environment. Within the experiment, tests will be done for different situations and scenarios. Each participant is thus able to communicate in either situation 1 or situation 2. The resulting strategies are listed below. The situations are described in more detail on the following pages.

1. Crossing situation at North-Sea
   - (A) Follow COLREGs strictly
   - (B) Cross in front
   - (C) Cross at the back
2. Entering Maasgeul from Maasvlakte
   - (A) Cross in front
   - (B) Cross at the back
   - (C) Pass without crossing

Crossing situation at North-Sea

The first situation for the experiment is a crossing situation based on the accident between MV ARTADI and MV ST-GERMAIN (appendix C.2). Where both ships followed COLREGs, but due to a lack of communication and wrong presumptions on the intentions, did the accident occur. The traffic in this simulation consists of three ships: a 250-meter tanker (GULF VALOUR), a 140-meter cargo vessel (ASTRORUNNER) and a 400-meter container vessel (EMMA MAERSK). Figure 11.4 shows the situation. The relevant information for these ships is given in table 11.1. An example is given below for the communication in the situation when operating the ASTRORUNNER while crossing the GULF VALOUR at the North-Sea:

- Call

  Gulf valour, Gulf valour. This is Astrorunner. Over.

- Acknowledge

  Astrorunner. This is Gulf Valour. Over.

- Message

  Gulf Valour. This is Astrorunner.
  Question. Is your intention to alter course to Starboard?. Over.

- Response

  Astrorunner. This is Gulf Valour
  Question received. We will alter course to give way and pass one nautical mile astern. Over.

- Close communication.

  Gulf Valour. This is Astrorunner. Understood. Have a good watch. Over.

  Astrorunner. This is Gulf Valour. Over and out.

	GULF VALOUR	ASTRORUNNER	EMMA MAERSK	
Length	249.0	141.6	397.7	m
Width	48.0	20.6	56.4	m
Draft	13.2	6.5	12.6	m
Deadweight	114900	9543	156907	ton
Type	Oil tanker	General cargo vessel	Container vessel	
Position	[-1400, -1400]	[3250, 0]	[400, 2400]	m
Speed	16.0	15.2	12.0	knots
Course	45	278	225	degrees
Previous port	Singapore	Zeebrugge	Rotterdam	
Next port	Rotterdam	Dover	Hongkong	
Direction	North-east	West	South-west	

Table 11.1: Relevant information for crossing situation at North-Sea

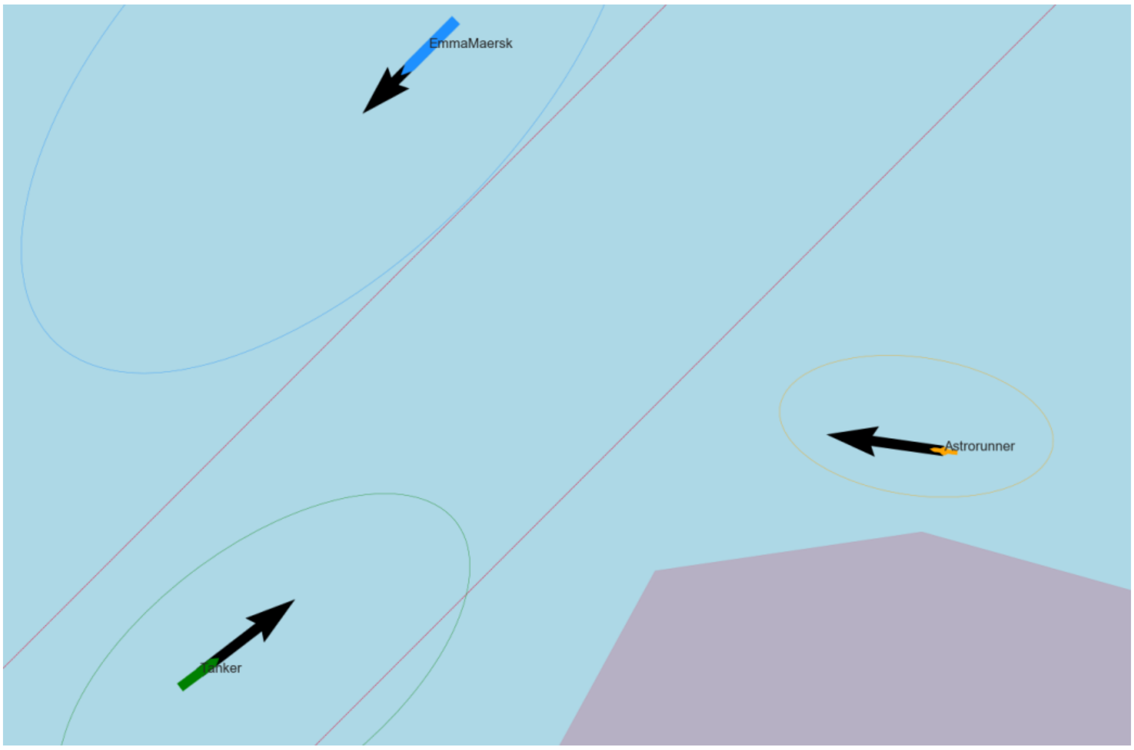


Figure 11.4: Situation sketch for crossing situation North-Sea

Entering Maasgeul from Maasvlakte

The second situation is a common situation at the port of Rotterdam. The situation is based on the description by Pilots from 'Nederlands Loodswezen'. The big challenge here is that ships are accelerating and decelerating. Therefore do traffic controllers notify ships about others intentions. But in the case as presented does this not always happen, or too late.

The traffic in this simulation consists of three ships: a 250-meter tanker (GULF VALOUR), a 140-meter cargo vessel (ASTRORUNNER) and a 140-meter Ro-Ro vessel (ANGLIA SEAWAYS). Figure 11.5 shows the situation. The relevant information for these ships is given in table 11.2.

The following conversation is likely for the situation where the GULF VALOUR is leaving the port of Rotterdam and has to cross or pass the ASTRORUNNER:

- Call

  Astrorunner, Astrorunner. This is Gulf Valour. Over.

- Acknowledge

  Gulf Valour. This is Astrorunner. Over.

- Message

  Astrorunner. This is Gulf Valour.
  Question. What is your port of destination? Over.

- Response

  Gulf Valour. This is Astrorunner.
  Question received. My port of destination is the Vulcaanhaven. Over.

- Message

  Astrorunner. This is Gulf Valour.
  Instruction. You are the stand-on vessel and should keep course and speed.
  Over.

- Response

  Gulf Valour. This is Astrorunner.
  Instruction received. We will stand on. Over.

- Close communication.

  Astrorunner. This is Gulf Valour. Nothing more. Have a good watch. Over.

  Gulf Valour. This is Astrorunner. Over and out.

	GULF VALOUR	ASTRORUNNER	ANGLIA SEAWAYS	
Length	249.0	141.6	142.4	m
Width	48.0	20.6	23.0	m
Draft	13.2	6.5	5.0	m
Deadweight	114900	9543	4650	ton
Type	Oil tanker	General cargo vessel	Container vessel	
Position	[-1372, -1377]	[-3090, 1395]	[3000, -550]	m
Speed	7.8	13.4	10.3	knots
Course	98	114	291	degrees
Origin	Princess Arianehaven	North-Sea	Vulcaanhaven	
Destination	North-Sea	Beneluxhaven	North-Sea	
Direction	Leaving	Entering	Leaving	

Table 11.2: Relevant information entering Maasgeul

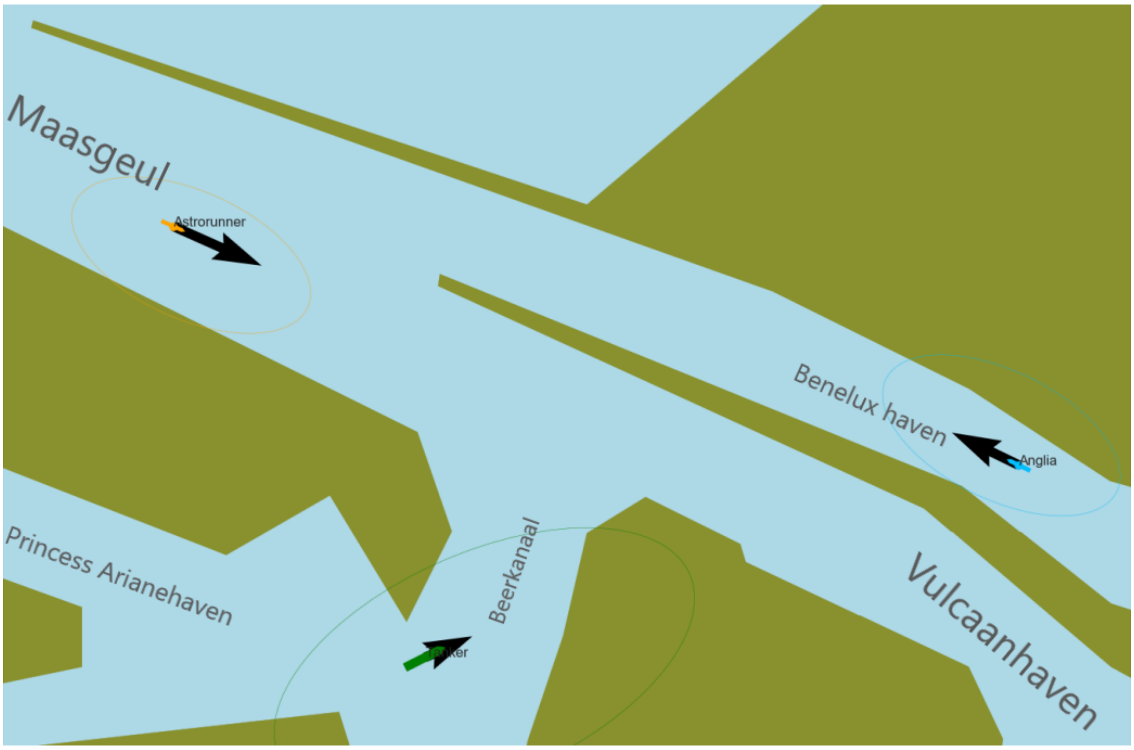


Figure 11.5: Situation sketch port of Rotterdam

11.1.3 Dependent variables

The variables evaluated during the experiment are based on the human factor measures, as described in section 9.2. The results of the experiment answer the research questions as described at the start of this chapter. Each dependent variable answers one of the four research questions:

1. Does the protocol influence the performance of seafarers?
2. Are seafarers confident that the protocol will act as they expect?
3. Has the protocol a negative impact on the situation awareness?
4. Do seafarers like to use the designed protocol?

A combination of both quantitative and qualitative measurements is used. By combining numerical values with non-numerical arguments. The measurements are done during the experiment via an interview and observations. With the variables can be concluded if the system acts as expected and will result in safe navigation when the designed protocol is used.

The next subsection maps the variables to the questions asked during the experiment, the symbols as shown behind the variable names are used for this mapping. This shows which "raw data" is relevant for each dependent variable and research questions. Some of the questions mentioned below are asked directly to the participants. Other answers are based on the behaviour of the participants. The level of measurement is discussed after the experiment procedure at the end of this section.

1. Performance ♣Evaluation if the participant operated safely. Thus did he safely navigate the vessel by making the right decisions, which means that the participant followed the applicable COLREGs and showed good seamanship. The resulting closest point of approach (CPA) is a good measure for this. Also, the reasoning and situation recognition which results in choosing the right strategy is a measure. Questions which will be answered are:

   1. Does the participant follow COLREGs?
   2. Does the participant stay well clear of other ships?
   3. Does the participant communicate using SMCP?

2. Trust ♢The system does not act only out of self-interest but to acquire a pareto-optimal solution. The participants must have a feeling of confidence that unmanned vessels operate as they expect. Therefore, they must be confident that the system works as it is supposed to do. In later stages, this will also be supported by evaluations of reputable institutions. [Ozawa and Sripad (2013)]. For now, the survey is leading here, where questions will be asked on the participant's trust in autonomous systems, their trust in SMCP, and their opinion on the communication during the experiment. Questions which will be answered are:

1. Is the participant confident that the system works?
2. What worries a participant when using the system?
3. How well trusts a participant unmanned vessels compared to manned vessels?

3. Situation awareness ♠The perception of environmental elements and events with respect to time or space, the comprehension of their meaning, and the projection of their status [Naderpour et al. (2016)]. The situational awareness is measured using an observer rating system, showing if participants have noticed changes in course, the colour of different vessels and relative speed. Questions which will be answered are:

1. Does the participant predict future states correctly?
2. Is the participant aware of other vessels (e.g. speed)?
3. Has the participant free cognitive capacity (e.g. colour)?

4. Satisfaction ♡The participant should like to use the protocol. This is measured by questioning them on the effectiveness of SMCP, observe their usage of the protocol during the experiment and their reaction to vessels using the protocol. Questions which will be answered are:

1. Does the participant enjoy using SMCP?
2. Does the protocol change the behaviour of participants?

11.1.4 Experiment procedure

The experiment is executed with the Officer of Watch (OoW) by taking the following steps:

1. Explain how the OoW can take actions, such as steering, change speed, set way-points or engage in communication.
2. Ask general questions on attitude and basic information.
3. Explain the situation to OoW in a similar way, to a usual watch hand-over. Only discussing relevant issues for navigational duties.r
4. Start simulation.
5. Operate vessels

6. End simulation.
7. Question OoW why he made decisions.
8. Evaluate the simulation.
9. Repeat step 3-8 for more situations.
10. Question OoW about advantages and challenges of the protocol.

The answers to the questions are collected using a Google form. This form includes the same questions as described below. These questions are yes/no, a yes to no scale of four steps or answers can be selected in a list. Often followed by an open question to explain the answers in more detail. All questions aim to gather information for one of the dependent variables, get to know the participant or gather expert opinions and feedback on the designed protocol. Using symbols behind each question shows what this aim is.

♣ Performance	♠ Situation awareness
♢ Trust	♡ Satisfaction
⊙ Get to know the participant	⋆ Protocol

Explanation and basic information (1, 2)

The participant is not explicitly informed about the exact purpose of the research before the experiment. The participant will, however, get a short introduction on how to use the simulation environment. This introduction includes the commands it can give as an officer of watch. The environment is easy to use, as action are similar to actions at the bridge today. Some information about the participant is acquired first, followed by general questions relevant to the protocol, such as there knowledge of Standard Maritime Communication Phrases (SMCP).

- Which certificates do you have? ⊙
- What is your experience as captain and mate? ⊙
- Which type of vessels did you operate? ⊙
- What do you expect from the developments towards autonomous shipping? ⊙⋆
- What do you see as the biggest challenge for introducing autonomous and unmanned vessels? ⊙⋆
- Do you expect to trust autonomous ships more? ⊙♢
- Do you want to know if a ship is unmanned? ♢
- Are ship's horns still used to communicate intended manoeuvers? ⋆
- What are the most important forms of communication? ⋆

- Do you still use SMCP consciously? ⊙
- How does a standard conversation look like, according to the SMCP? ⊙⋆
- Is the protocol around SMCP easy to use? ⋆

Situations and scenarios (3, 4, 5, 6)

The next steps are repeated two time for the different situations. The communication in that situations should be about the intentions of the other vessel. When using the designed protocol, the conversation should be similar to the examples given in section 11.1.2. It depends on the experiment order, in which situation it is possible to communicate:

1. Crossing situation at North-Sea
2. Leaving port of Rotterdam via Maasgeul

During these simulation are all actions logged together with the CPA. Thereby are notes made on the way decision are made, these are verified with the participants when filling in the questionnaire in the next steps. This includes feedback on the risk taken.

Relevant questions for situation (7, 8, 9)

Different questions will be asked, to gain insight into the quality of the experiment and the effectiveness of the protocol. Thereby is a link made to the decision process as discussed in section 2:

- What type of situation is this? ♠
- Which criteria are relevant? ♣
- Which strategy did you choose? ♣
- Which actions were taken? ♣
- What was the speed of different vessels? ♠
- How often did the ships change their course? ♠
- Which colour did every ship have? ♠
- Did other ships behave as expected? ♠♣
- Were you in control over the situation? ♣♢♡
- Did you miss any information to come up with the right strategy? ⋆♡
- Was it necessary to communicate? ♠♢
- If there was communication, was this as you expected? ♡
- Would you act differently, if you knew there was a human officer of watch? ♢♡

General questions on protocol (10)

After running the different situations, an interview is held. This part of the experiment is intended to answer the following questions from the participant perspective and explain the purpose of this research:

- Is the protocol around SMCP easy to learn? ⋆
- Is the protocol around SMCP a complete protocol? ⋆
- Do you have any other comments on SMCP? ⋆

11.1.5 Level of measurement

To determine how the resulting "raw data" can be used to draw conclusions, the level of measurement is discussed. Most results of the questionnaire, are on an ordinal level, as these answers explain the "why" or use a scale. For situation awareness is the free cognitive capacity determined by asking participants about the colour of the vessels at an nominal level.

For situational awareness and performance are also higher level measurements used. Such as the metrics CPA and runtime, which are on a ratio level. The estimation of participants for the relative speed of the vessels is measured on an ordinal scale. The participants only answer which ship is the fastest and slowest, not how much faster or the exact speed. Statistics for most of the metrics measured at a higher level will not give more insight in the dependent variables, as there are too many factors influencing the results, such as the chosen strategy and accepted risk which are not measured.

11.2 Evaluation results

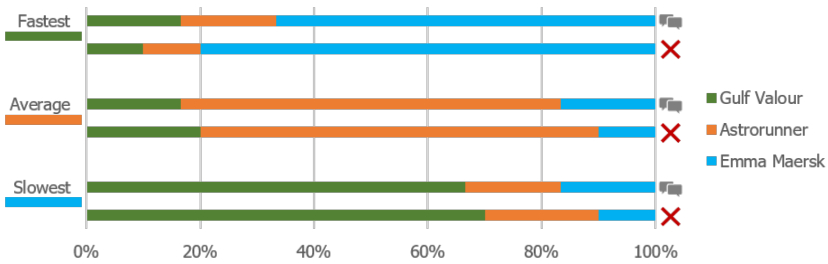
The evaluation results describe the outcomes of the test. Because of the iterative and rapid research cycles, the evaluation does not necessarily include all requirements/claims/use cases available in the system specification. Often the evaluation investigates a subset of the system specification. Therefore, it is often useful to also specify what claims were tested, with the use of what evaluation method, and what artefact was used during the evaluation (i.e. which requirements, technology, and interaction design patterns were included in the artefact).

The results of the experiment are evaluated in a systematic way for the 16 respondents. First, a summary is made of the reactions to the Google form. This summary is made using both a statistical analysis on the ordinal level and classification of answers on the nominal level. Dependent variables are discussed, using this summary. Six of the participants were only able to communicate in the crossing situation at the North Sea. Ten participants had the possibility of communication only in the second situation when leaving the port of Rotterdam via the Maasgeul. The top line represents the results where participants were able to communicate, the second line shows the results when no-communication was possible. The correct answers are shown at the left axis.

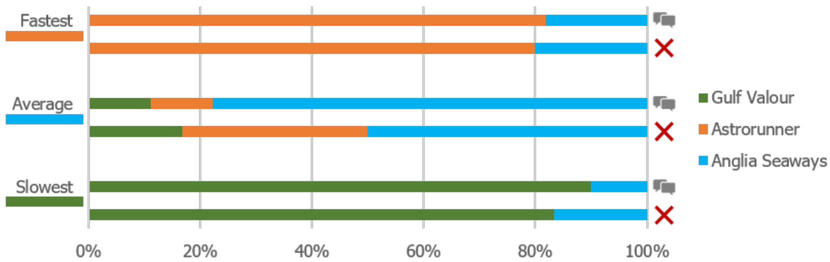
11.2.1 Observations during simulations

Situational awareness is tested by questioning participants about the relative start speed, colour and course changes. The participants focused on possible future risks. Speed estimations did they often base on normal behaviour for different ship types, instead of taking the speed vector into account.

The first case is the crossing situation at the North-Sea. The situation was implemented in such a way, that the container ship was the slowest, and tanker the fastest. As can be seen in figure 11.6a did the participants think the opposite, that can be explained by the usual speed of different vessels. A large container ship (Emma Maersk) usually goes the fastest, the smaller general cargo vessel a bit slower (Astrorunner), and the tanker (Gulf Valour) is often the slowest. Thus opposite to how the scenario was set-up. Between the groups testing the protocol and no-communication, no significant differences are found. Wrong estimations could also be the result of the simulation environment. But the estimates of the participants are opposite to the vertical-horizontal illusion when considering the speed vectors as measurement [Prinzmetal and Gettleman (1993)]. Thereby did participants estimate the speed correctly, when they were able to see the speed vectors and were questioned about the speed during the experiment, instead of making an estimation based on memory.



(a) Situation when crossing at the North Sea



(b) Situation when entering Maasgeul

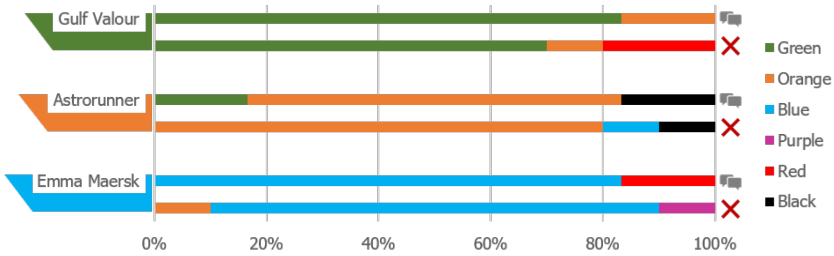
Figure 11.6: Estimation of relative start speed for protocol vs no-communication

The relative start speed in the second situation when leaving the port of Rotterdam via the Maasgeul, had results as could be expected. Figure 11.6b shows this, where most participants did estimate the relative speed correctly. Also, for this case, was there no difference if a participant was able to use the protocol.

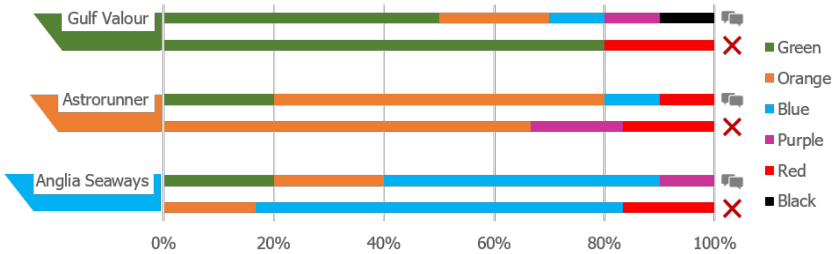
The estimation for the number of course changes went a lot better for the first situation. The Emma Maersk did not alter course, which participants correctly observed, just as the single course change for the Astrorunner to ensure a perpendicular passing of the traffic separation scheme. The course changes of the Gulf Valour depended on the situation. If the participant controlled the Gulf Valour, they said that the Gulf Valour made two course-changes: First alter course to starboard, and second return to original course. While in the case where the participant operated from the Astrorunner, did they often not count the last alteration. Thus did the participants count only one course-change for the Gulf Valour. The attention of the participants can explain this observation. When the Gulf Valour alters course for the second time, the Astrorunner is close to the Emma Maersk, and the participant pays therefor attention to the Emma Maersk and not the Gulf Valour.

In the second situation are the course changes much clearer, as two vessels go straight (Astrorunner and Anglia Seaways), while the Gulf Valour makes one clear turn. It depends on the exact actions the participant took, how many course changes the vessel made. But there were no wrong answers given. Being able to communicate, did affect the strategy and thereby actions, but not the ability to register the right amount of course changes.

The colour is something which does not have any effect on the decision. It is, however, information which shows if the participants remembered irrelevant details about the simulation. These irrelevant details are a measure for the free cognitive capacity, as participants remember more of these when the situation is less complex, also known as inattentional blindness [Most et al. (2000)]. This difference can be seen between the situation when crossing the North Sea, and entering the Maasgeul. Figure 11.7a and figure 11.7b show that more participants have the colour correct in the crossing situation at the North Sea, which is also the less complex situation when it comes to making the right decision.



(a) Situation when crossing at the North Sea



(b) Situation when entering Maasgeul

Figure 11.7: Response to color of vessels for protocol vs no-communication

After each simulation did the participants also answer questions on actions of other vessels, communication and missing information. The results of this are shown in figure 11.8 and figure 11.9. It should be noted that the experiment was not fully counter-balanced and there was a limited number of participants, which means there is a high margin of error. Therefore are conclusions drawn only when there is a significant difference between the results for protocol vs no-communication.

Interesting is that 40% of the participants would have acted differently when no communication was possible. Their explanation for this is that they could not anticipate to other vessels, thus slowed down, hoping that they could deduce from the actions of the other ships what their plans were. If the protocol works well, this is not needed. The other participants said they followed the COLREGs, and expect unmanned vessels to do the same. This reasoning means that the participants would act the same when the other vessel was manned.

A conclusion that was expected is that the participants would miss information when they were not able to communicate using the protocol. In the second situation when entering the Maasgeul, this is the case. However, most participants did indicate they were also missing information on the CPA during the experiment as is usually shown on the ARPA. With the first situation at the North Sea did more than half of the participants think it was not necessary to communicate. Therefore did a similar amount of participants miss the same information in both cases (protocol vs no-communication).

Also did the type of ships participants have operated, influenced their behaviour, as operators who used to sail on small vessels did often take more risk and expected higher accelerations and manoeuvrability. While the operators who used to operate large vessels, such as tankers and cruise ships, preferred to wait for other ships to act first if they were missing information.

In case the participants used the protocol, the communication was in both situations as expected for most of them. This shows that seafarers expect to be able to use natural language variation on SMCP.

The participants are questioned about their trust in autonomous systems, in all cases, they want to know if a ship is unmanned, so that they can anticipate to it. They gave as an example that it is likely that an autonomous vessel will follow COLREGs more strict, than ships operated by a non-western crew (e.g. Filipino or Pakistani). But in emergencies, such as failure in the engine room, the participants trust autonomous ships less. A definitive conclusion cannot be drawn whether autonomous vessels will be trusted more or less, compared to manned vessels.

11.2.2 Evaluation of the protocol

The questionnaire tries to validate design choices for the protocol. A design choice which is based on COLREGs, but unknown if it works in practice is the usage of the ship's horn to communicate the intended manoeuvrer. All participants said that ships only use the ship's horn in two situations. When a ship wants to get attention from another ship, in case other means of communication do not work. Or in case of fog, then is the fog horn sounded every few minutes to make other ships alert of presences [IMO (1972)].

The most important form of communication is the VHF radio, although new systems are used more often, such as AIS text messaging and INMARSAT-C. INMARSAT C provides two-way data and messaging communication services to and from virtually anywhere in the world. This type of messaging improves the ship-to-ship communication, the disadvantage of these systems is that surrounding vessels are not able to follow the conversation and thus will not receive the shared information.

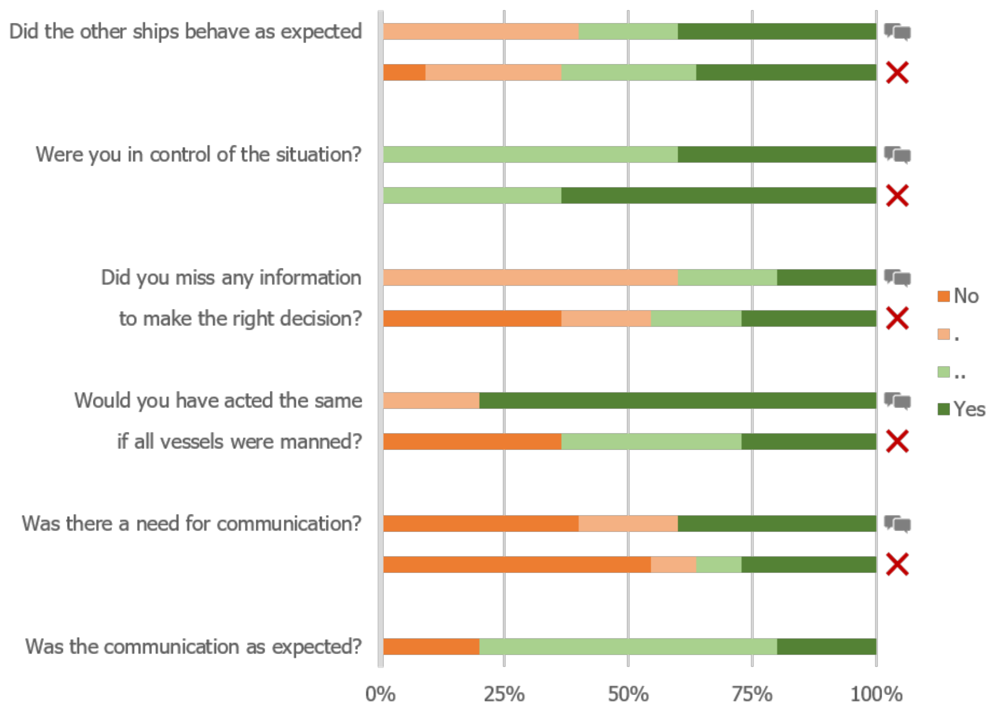


Figure 11.8: Protocol vs no-communication when crossing at the North Sea

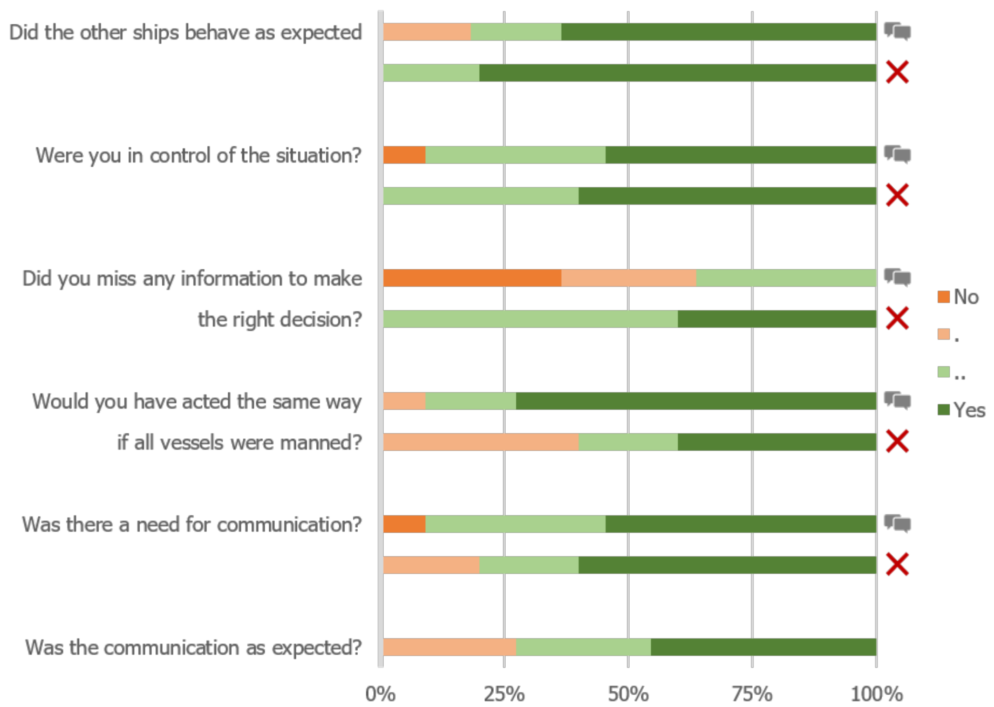


Figure 11.9: Protocol vs no-communication when entering Maasgeul

According to the participants are conversations via VHF based on SMCP, but do not follow the protocol strictly. The participants describe a few key characteristics:

- Start of every message has the purpose to get attention, by calling specific vessel: "($<$ *name other vessel* $>$, $<$ *name other vessel* $>$. This is $<$ *name own vessel* $>$)"
- Common practice is to use the words as defined by SMCP (alter course, instead of change course). The sentences are often not used as described by SMCP.
- Marker words are not used.
- When responding, the previous message is repeated.
- Message is ended with over, conversation with over and out.

In general, they do state that the protocol is easy to use, easy to learn and complete. as figure 11.10 shows. The drawback is that the protocol covers too much. Therefore people can't always remember how they should follow the protocol and make variations to it.

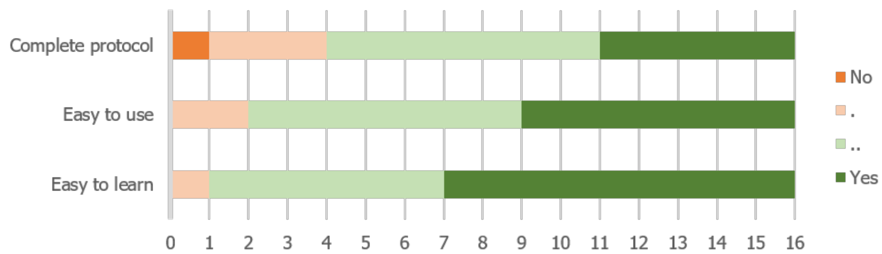


Figure 11.10: Opinion of participants on SMCP

Less relevant for SMCP, but more for the final design of the protocol is the knowledge of English. As the level of and pronunciation of English is not at the right level for all officers, certainly for non-western crews, such as Filipino, Indian or Pakistani crew. This problem means that voice recognition should be tested for a variety of accents. It is also essential to know the names of different systems (e.g. LORAN, DSC, etc.) and places (e.g. camping, seal beach, etc.), which vary per ship and area and cannot always be found on maps.

Thereby was the identification of vessels hard before the introduction of AIS, which should be considered during the development of such a protocol. As it should also be possible to identify ships when the AIS fails, this means it should be possible to identify vessels without knowing the call-signs and name via AIS.

Due to the speed and starting point of the simulation, the operators did have to decide if they wanted to communicate quickly. Therefore was commented by some of them, that they would have liked to communicate earlier, than the moment the simulation started. So they would have had enough time in case the other vessel did not respond immediately, although the designed protocol and the current usage of VHF differ in the way how operators should use SMCP strictly. Does it take the same amount of steps, and a similar amount of words. Therefore it is not expected that the conversations will take longer if the voice recognition works correctly.

11.3 Conclusion based on experiment

The experiment aims to determine if the designed protocol will ensure safe navigation and more situational awareness when manned and unmanned vessels encounter each other. This can be answered by looking into different measures on how the participants and protocol performed during the experiment, which shows what should be taken into account in the next iterative steps while developing the protocol. The following research questions are answered:

1. Does the protocol influence the performance of seafarers?
2. Are seafarers confident that the protocol will act as they expect?
3. Has the protocol a negative impact on the situation awareness?
4. Do seafarers like to use the designed protocol?

The *performance (1)* is a measurement to verify whether the participant followed regulations and made the right decisions. None of the cases did result in an accident, even though there were some close encounters. There was no clear correlation between the ability to communicate and the closest point of approach (CPA), as some participants took more risk when the intention of another vessel was known. The protocol did help to acquire the right information to chose a strategy earlier in the process. This time gave participants more control over the situation and ensured them that the other vessels would also follow COLREGs. Thereby was the communication as expected when using the protocol, after reminding participants how the communication should be according to SMCP. This corresponds with the opinion of participants that it is a complete protocol, which is easy to use and learn.

Trust (2) is the second measurement that is evaluated. This means that the participants are confident that the system works as expected. The participants were most worried about voice recognition, definitely for non-western crews, as these have an accent that is hard to understand for humans. The words and sentences within the protocol itself shouldn't be the problem, as it is optimised to be well understandable via radio. The recognition of speech acts could be difficult, but it has the advantage that the protocol uses explicit keywords. Thereby is every response started with a confirmation of the previous message, which helps to increase trust in the protocol and unmanned vessels in general.

The third measurement is *situation awareness (3)*. This is measured by checking if the participants were aware of relevant and irrelevant details such as estimating relative speed, number of course changes and the colour of a vessel. The relevant details went better in the complex situation which demanded high attention. Irrelevant details such as course changes of vessels which already passed, or the colour of a vessel were remembered less in these situations. These results were however not influenced by the protocol, which means that the protocol has a small effect on the free cognitive capacity.

The last measurement is *satisfaction (4)*, i.e. whether the participants like to use the protocol. Here is the voice recognition most important, if this will understand natural language variations to SMCP, are most participants very positive. As SMCP itself is an 'idiot proof' system. If it is possible to communicate this way with vessels, will strategies not differ from interactions with manned vessels.

Critically looking at the way the results are acquired shows the relevance of these results. The main strength of the experiment is that a participants are used with different backgrounds, as the participants are both experienced and inexperienced on small and large vessels. The group of 16 participants is sufficient to draw conclusions for this first iteration and answers the main question for this chapter:

> *Will the described protocol ensure safe navigation and more situational awareness, when manned and unmanned vessels encounter each other?*

The conclusion is that it is feasible to develop a protocol using SMCP and a conversational agent. When implementing the full protocol more evaluations are necessary. These evaluations should consider more different situations. These will not only say if there is an impact on the performance, trust, situation awareness and satisfaction of seafarers. But the results of these evaluations should also show what this impact is. This means it is possible to mitigate a negative impact, or exploit the advantages.

12 | Conclusion

This part has shown that it is possible to solve the challenge of communication and ensure safety by enabling unmanned vessels to communicate with manned vessels. The communication challenge is solved by designing a protocol for communication, based on existing maritime systems and protocols, using the situated Cognitive Engineering (sCE) method. The first phase includes a description of operational demands, relevant human factors and envisioned technologies. The second phase consists of design-scenarios and use-cases, which result in a list of requirements. These requirements are used to define an ontology for the system and a description of the capabilities of the system. With experts is evaluated whether this is indeed enough to ensure that unmanned vessels can cooperate safely with manned vessel. All this combined answers the question:

> *Will a protocol based on existing maritime systems and communication protocols be sufficient to ensure safe navigation, while manned and unmanned vessels encounter each other?*

Using Standard Maritime Communication Phrases (SMCP) as the core for a new protocol, will ensure safe navigation. As the advantage of SMCP is that it is already optimized for radio communication. The clear speech acts will make it easier to automate the communication. This means than unmanned vessels are able to use the same protocol as is currently used by manned vessels. Thereby did experts confirm that it is an idiot proof system, which is easy to use and learn, certainly when the speech recognition tool will be able to handle natural language variations on SMCP. This will be easier when officers use the protocol as it is designed. After recent accidents between manned vessels was already decided that pilots and masters should use English speech and SMCP in all cases, to avoid misunderstanding. Avoiding misunderstanding will result in better situational awareness, which results in safer navigation. Thus it is possible to ensure safe navigation when manned and unmanned vessels meet, by developing a protocol. The designed protocol uses existing maritime systems and communication protocols. For this design is the situated Cognitive Engineering (sCE) method used.

This research was a first iteration for developing a functional protocol for communication between manned and unmanned ships. It has showed that it is possible and what should be taken into account. The next step is to map different speech acts, to specific situations. One of the key challenges is thereby the recognition of situations. The mapping can eventually be used to define the full ontology which should be implemented in the conversational agent.

Part IV

Wrap-up

All truths are easy to understand once they are discovered. The point is to discover them.

– Galileo [Galilei (1632)]

13 | Final conclusion and recommendations

Digitalisation and automation will change the maritime industry. Vessels are connected to the shore and data is used in smarter ways. These technologies boost the development of autonomous and unmanned vessels, resulting in a significant amount of research and development projects. The challenge of communication between manned and unmanned vessels has not been within the scope of these projects.

This study focused on a design philosophy to solve the challenge of communication between manned and unmanned vessels. Two solutions for this challenge are discussed: Operate without communication or develop a protocol for communication.

13.1 Impact of manoeuvrability on sailing without communication

Part II targets a method to test if vessels can operate without communication. This method is developed to evaluate specific situations and manoeuvres, resulting in an extensive analysis of the common critical evasive manoeuvre. This analysis shows that ships like the Emma Maersk (400 meter) will have to communicate when crossing traffic lanes with traffic from both sides, whereas small cargo ships like the Astrorunner (140 meter) can manoeuvre with ease and turn 90 degrees, which changes the crossing situation into a passing or overtaking situation. For the ships like the Gulf Valour (250 meter) it is possible to sail without communication, but these ships can't avoid a crossing situation. Improvement to the manoeuvring characteristics will help to prevent these critical situations and give them too enough space to turn 90 degrees.

The method starts with the identification of critical situations, which are evaluated using commonly used criteria such as the passing distance and CPA, to determine if a ship stays well clear. This report has proven the value of the method for evaluating if the manoeuvrability of a ship is sufficient for specific situations. The results of these test can be used during ship design, traffic scheme design, and the definition of situation-dependent speed limits.

13.2 Development of a protocol based on existing systems

In part III are the first steps taken to develop a protocol for the communication between manned and unmanned vessels. The first iterative step is made with the situated Cognitive Engineering (sCE) method. This method takes the human factor into account, which results in a protocol that performs well, the method ensures that other seafarers trust unmanned vessels, the situation awareness of seafarers may not degrade, and the method ensures that seafarers like to use such a protocol, as the way of working is familiar to them. These conclusions have been evaluated using an experiment, the results of this experiment showed that this method works well to develop a protocol for communication between manned and unmanned vessels, this protocol is based on existing protocols and systems. The experiment did thereby also give insight into factors which should be taken into account in the next step, such as the importance of good speech recognition. Seafarers expect for example that foreign accents are hard to understand, thereby is there the possibility to use text messaging via AIS or INMARSAT-C. In future iterations, the protocol should thus be tested with more complex situations.

13.3 Combining previous results

In chapter 2 is a decision model shown which shows what should be taken into account when solving the problem of communication between manned and unmanned vessels. The results of part II and III combined to support each other to solve the problem of communication in all situations and scenarios. The most important challenge which comes after this research is the mapping of situations to the possible strategies and communication. More information is desired to ensure that ships can operate safely in any situation.

13.4 Recommendations for future research

This study has been a first step in solving the challenge of communication between manned and unmanned vessels. Since this study was a first step in solving the challenge, there are still bumps on the road which require other methods to solve them. Beside the manoeuvring criteria and seafarers, do more factors influence the decision-making process.

The first recommendation is directly related to the developed method for finding the relation between manoeuvrability and operation without communication. This method has proven itself to be successful. The used hydrodynamic model gives thereby realistic results. The results could, however, be improved for more different vessels with extreme characteristics, by varying the input for the hydrodynamic model.

When it comes to the protocol itself, are the two stakeholder groups who should also be taken into account. The first group are the vessels nearby. We did not look into the impact of this protocol on the performance, situational awareness, trust and satisfaction of operators on nearby ships. Information overload is here a key factor.

These problems are even more relevant in emergency situations. At the moment has not been looked at the expected behaviour of unmanned vessels in emergency situations of other vessels. Should they assist or stay away as far as possible. This strategy becomes even more relevant in cases where assistance from other vessels will take more time to arrive, such as the middle of the ocean. In those situations, interventions from the shore might be a good solution.

But there is also a lot of communication with the shore in everyday situations. At the moment do traffic controllers guide all ships trough busy area's. The traffic controllers inform all ships via radio whom may go first. Thereby do they divert from COLREGs in many cases, as that would often result in fewer manoeuvres for the ships. In future studies should be looked if the automation of current systems and protocols for traffic controllers is sufficient, or if the information shared by traffic controllers is too elaborate and require new systems.

Another critical issue within the whole maritime industry is redundancy. The focus of the first iteration was on common critical situations, where it is possible to use all available systems. The consequence of failing components such as AIS for identification or VHF radio have not been studied. To ensure trust by seafarers in the system, should the redundancy of autonomous systems be much higher than that of the current system.

The next step is the mapping of speech acts to situations. Here is the identification of situations important. This identification has currently been done at a level where data from sensors has already been converted to information. Current projects work already on this conversion of data to information, but considerable steps have to be taken, to correctly interpret the whole environment. These steps will include the identification of small vessels in the Malacca Strait or floating containers at open sea. Radar and sight are the most important sensors to perceive these.

These recommendations are all aimed at academia and future research projects, while the results of this thesis could already be used in practice. The protocol itself is not yet ready to be used in practice. Regulatory bodies can however emphasize already that it is important to use SMCP as it is designed.

The first conclusions and plotted graphs for the critical evasive manoeuvre can be directly used for ship design, as this is one of the most critical situations where the manoeuvring criteria should be considered. Thus the results give for example insight in the relation between the desired CPA and the required advance distance.

Part V

Appendices

Studying history will not tell us what to choose, but at least gives us more options to choose from.

– Yuval Noah Harari [Harari (2016)]

A | Systems for safe navigation

Before developing new systems and procedures to improve safety, the first step is to know what is currently available. Thereby should be considered how different types of information can be supplied. Nowadays decisions on navigation are taken from the bridge. Thus all information must be available there. In this chapter these elements will first be discussed, how they are in theory. This is followed by a discussion on the differences between this theory and practice which results in a conclusion on relevant systems for the communication between manned and unmanned ships.

A.1 Bridge system elements

The bridge is divided into four elements as described by DNV-GL. The human operator, procedures, technical system and the human-machine interface [DNV GL (2011)], as shown in figure A.1. This section describes every element in more detail.

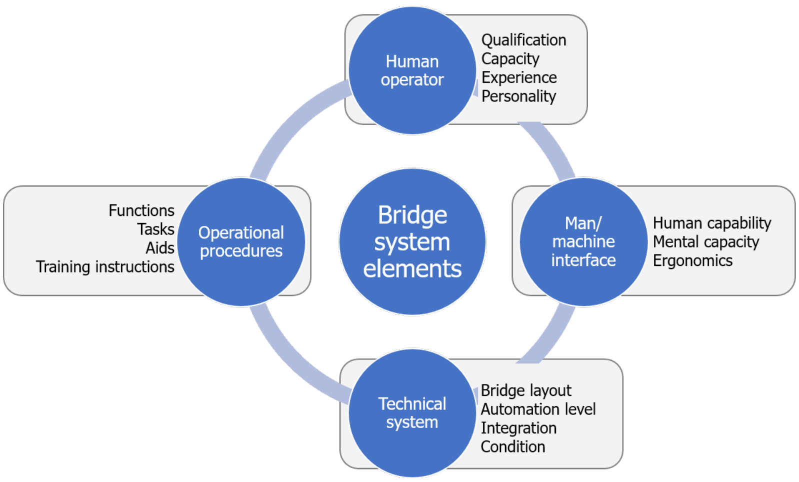


Figure A.1: Bridge system elements

A.1.1 Technical system

The first elements which will be discussed are the instruments and equipment at the bridge, the technical system. The different classification societies prescribe the equipment which is obligated to have at the bridge. These are based on the regulations for navigational equipment on board of ships from the International Convention for the Safety of Life at Sea (SOLAS). A modern ship should at least have:

- Magnetic compass
- Gyro compass
- ECDIS
- Transmitting heading device
- Automatic Identification System (AIS)
- Receiver for Global Navigation Satellite System (GNSS)
- Internal communication system
- Bridge Navigational Watch Alarm System (BNWAS)
- Telephone for external communication
- Radar
- Radar beacon
- Daylight signaling lamp
- Speed and distance measuring device
- Echo sounding device
- Rudder, propeller, thrust, pitch and operational mode indicators
- Rate of turn indicator

Based on this list, DNV-GL demands at least the following equipment shall be installed at the bridge [DNV GL (2011)]. The equipment may have different roles. To control the ship, to present information, or to communicate:

- Propulsion control
- Emergency stop machinery
- Manual steering device
- Steering mode selector switch
- Heading control
- Window wiper and wash controls
- Control of dimmers for indicators and displays
- Steering gear pumps
- Gyrocompass selector switch
- Navtex receiver
- Automatic Radar Plotting Aid (ARPA)
- Electronic Chart Display Information System (ECDIS)
- Automatic Identification System (AIS) transceiver
- General alarm control
- Very High Frequency radio (VHF) unit
- Whistle and manoeuvring light push buttons
- Internal communication equipment
- Central alert management system

Some of these systems will be highlighted to show the relevance for the development of unmanned vessels, as these systems are currently the most important systems while navigating. Thereby should be considered that more details on underlying procedures are given later in this chapter.

Navigational text Messages (Navtex)

Navtex (Navigational Telex) is an international automated medium frequency direct-printing service for delivery of navigational and meteorological warnings and forecasts, as well as urgent maritime safety information to ships. Navtex was developed to provide a low-cost, simple, and automated means of receiving this information aboard ships at sea within approximately 370 km (200 nautical miles) offshore. The National Weather Authority, Coast Guard or other navigational authority typically transmits information. The system is a vital element in the Global Maritime Distress Safety System (GMDSS). Therefore does SOLAS mandate certain classes of vessels must carry Navtex. Examples of messages which can be received are:

- Navigational warnings
- Meteorological warnings
- Meteorological forecasts
- Search & rescue information
- Piracy information
- AIS messages

The receiver automatically prints the messages. The officer of watch keeps track of the received messages and anticipates on them when necessary.

Very High Frequency radio (VHF)

Marine VHF radio refers to the radio frequency range between 156 and 174 MHz. In the official language of the International Telecommunication Union, the band is called the VHF maritime mobile band. A marine VHF set is a combined transmitter and receiver and only operates on standard, international frequencies known as channels. For example is channel 16 (156.8 MHz) the international calling and distress channel. Transmission power ranges between 1 and 25 watts, giving a maximum range of up to about 60 nautical miles (111 km) between aerials mounted on tall ships and hills, and 5 nautical miles (9 km) between aerials mounted on small boats at sea level (figure A.2). Frequency modulation (FM) is used, with vertical polarisation, meaning that antennas have to be upright to have good reception.

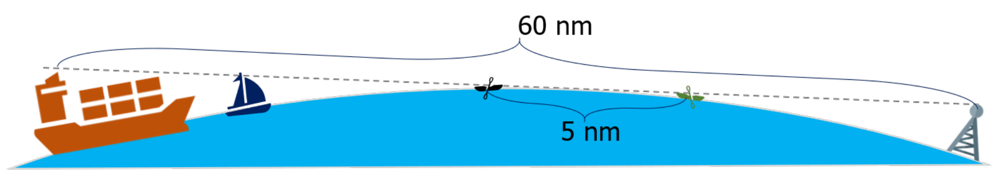


Figure A.2: Very High Frequency radio (VHF)

Modern-day marine VHF radios offer not only basic transmit and receive capabilities. Permanently mounted marine VHF radios on seagoing vessels are required to have certification of some level of "Digital Selective Calling" (DSC) capability, to allow a distress signal to be sent with a single button press.

Marine VHF mostly uses "simplex" transmission, where communication can only take place in one direction at a time. A transmit button on the set or microphone determines whether it is operating as a transmitter or a receiver. Some channels, however, are "duplex" transmission channels where communication can take place in both directions simultaneously when the equipment on both ends allow it (full duplex), otherwise "semi-duplex" is used. Each duplex channel has two frequency assignments. Duplex channels can be used to place calls on the public telephone system for a fee via a marine operator. When full duplex is used, the call is similar to one using a mobile phone or landlines. When semi-duplex is used, voice is only carried one way at a time, and the party on the boat must press the transmit button only when speaking. This facility is still available in some areas, though its use has mostly died out with the advent of mobile and satellite phones. Marine VHF radios can also receive weather radio broadcasts, where they are available.

Automatic Radar Plotting Aid (ARPA)

Radars have been playing a vital role in ship navigation for several decades now, assisting in collision avoidance and early detection of obstacles. The history of marine radars goes a long way back to the time of World War II when radars were introduced and effectively used by warships for tracking and detection. Radar technology has improved immensely since the post-WWII period to the present, and the application of computer technology to commercial marine radar sets resulted in the introduction of Automatic Radar Plotting Aids (ARPA). Figure A.3 shows a print-screen of an ARPA system.

Automatic radar plotting aids are utilised to improve the standard of collision avoidance at sea. Primarily designed as anti-collision radar, the ARPA technology removed the chore of plotting targets manually on a reflection plotter or separate plotting aid. The system is able to acquire information automatically and can continuously monitor a number of targets, plot their speeds and courses, present these as vectors on the display screen, updated with each sweep of the antenna, and calculate their closest points of approach to own ship and the time before that will occur.

Electronic Chart Display Information System (ECDIS)

The Electronic Chart Display Information System (ECDIS) is a development in the navigational chart system used in naval vessels and ships. With the use of the Electronic Navigational

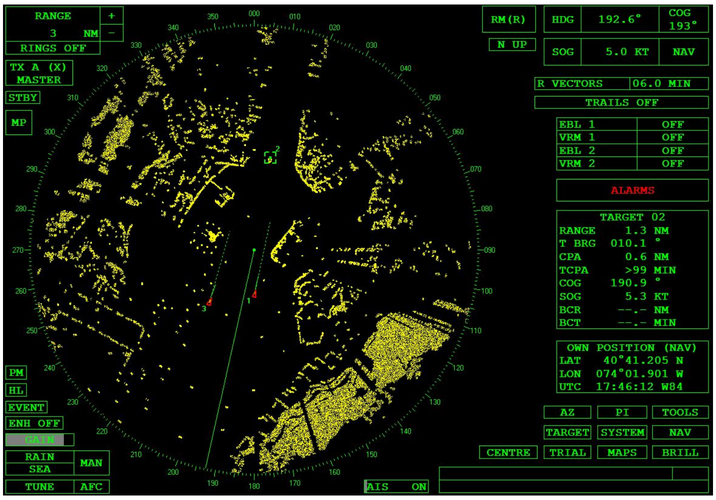


Figure A.3: Automatic Radar Plotting Aid (ARPA)

Chart (ENC) system, it has become easier for a ship's navigating crew to pinpoint locations and attain directions. ECDIS equipment complying with SOLAS requirements can be used as an alternative to paper charts. Besides enhancing navigational safety, ECDIS greatly eases the navigator's workload with its automatic capabilities such as route planning, route monitoring, automatic ETA computation and ENC updating. In addition, ECDIS provides many other sophisticated navigation and safety features, including continuous data recording for later analysis. How the ECDIS is integrated in the bridge can be seen in figure A.4.

Figure A.4: Electronic Chart Display Information System (ECDIS)

The ECDIS utilises the feature of the Global Positioning System (GPS) to successfully pinpoint the navigational points. It also has to be noted that the ECDIS adheres to the stipulations set by the International Maritime Organisation, and thus it adds to the trustworthiness of the electronic chart system. ECDIS is basically a navigational information system, interfaced with other navigational equipments such as the GPS, Gyro, RADAR, ARPA, Echo Sounder etc.

Automatic Identification System (AIS)

AIS is designed to be capable of providing information about the ship to other ships and to coastal authorities automatically. The SOLAS regulations require AIS to be fitted aboard all ships of 300 gross tonnage and upwards engaged on international voyages, cargo ships of 500 gross tonnage and upwards not engaged on international voyages and all passenger ships irrespective of size. The requirement became effective for all ships by 31 December 2004, this means there are still ships which do not have AIS. Ships fitted with AIS shall maintain AIS in operation at all times except where international agreements, rules or standards provide for the protection of navigational information.

The regulations require the AIS to provide information on ship's identity, type, position, course, speed, navigational status and other safety-related information. Which will be automatically send to appropriately equipped shore stations, others ships and aircraft. While also being able to receive such information automatically from similarly fitted ships, to monitor and track them. Lastly they should be able to exchange data with shore-based facilities.

The messages were sent originally on a regular basis via a VHF transmitter. The information originates partly from ship's navigational sensors. Other information, such as the vessel name and VHF call sign, is programmed when installing the equipment. Some information must be filled in by hand, such as the status or destination, which is often forgotten. The received information can be displayed on a screen or chart plotter, showing the other vessels' positions in much the same manner as a radar display. A tracking system which uses a Self-Organized Time Division Multiple Access (SOTDMA) transmits data.

There are different types of transmitters. The object on which the transmitter is installed determines what kind of messages can be sent and which protocol is used to access AIS slots. Below relevant types are described:

- Class A, the most common type of AIS transceiver for large merchant vessels.
- Class B, AIS for smaller vessels.
- Base station, shore-based AIS transceiver, able to manage AIS slots.
- Aids to navigation, shore- or buoy-based transceiver operating in fixed time-slots. Designed to collect and transmit data related to sea and weather conditions, or forward AIS messages to extend reach.
- Search and rescue transceiver, designed to function as an emergency distress beacon, with a high probability of success for transmission.

As mentioned before, there are different types of AIS messages. Identification numbers are used to identify the type of message within the NMEA string. The following types of messages are relevant for this research and the development of unmanned ships [US Coast Guard (2018)]:

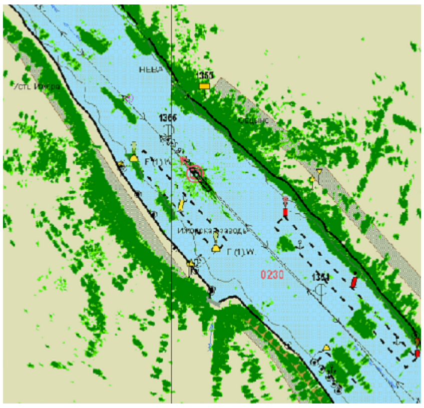
- Position report, reports navigational information.
- Standard class B equipment position report, with less details
- Base station report, used by base stations to indicate presence.
- Static and voyage related data gives information on a ship and its trip
- Binary addressed message and acknowledgement, an addressed point-to-point message with an unspecified binary payload.
- Binary broadcast message, a broadcast message with an unspecified binary payload.
- Standard Search and Rescue Aircraft Position Report, used by an aircraft (helicopter or aeroplane) which is involved with search and rescue operation on the sea (i.e. search for and recovery of survivors of an accident at sea).
- Addressed Safety-Related message and response, used to send text messages to a specified vessel.
- Interrogation, used by a base station to get the status of up to 2 other AIS devices.
- Aids-to-navigation report (buoys, lighthouse, etc.).
- Multiple slot binary message with communications state used to transmit binary data from one device to another.

A.1.2 Man/machine interface

Previously all information was plotted by hand on navigational charts. With the developments of integrated bridge systems and for example the ECDIS, this is not necessary. A digital representation of the environment is already made, including calculations, relevant to navigational safety. These also give warnings to avoid collisions or represent information received via VHF. This is done in a way which is more easy to interpret by the officer of watch, as AIS, ENC and the radar are combined. Examples of the different systems can be found in figure A.5.

These screens are all integrated in some way into the bridge console. Depending on the size of the vessel, the layout may differ. Although, there are also regulations for the placement of systems in SOLAS. Examples of these bridge layouts can be found in figure A.6.

(a) Separate screens for ECDIS and Radar



(b) Radar overlay on ECDIS

Figure A.5: Radar and ECDIS

(a) Alphatron AlphaBridge

(b) DAMEN ASD Tug 2310 (Patriot)

(c) BIBBY WAVEMASTER 1

(d) DAMEN Stan Patrol 5009

Figure A.6: Various examples of bridge designs

These layouts also show that bridges are operated in different ways. Where the officer of watch walks around on bigger ships, which also enables the crew to look together and discuss further actions. While on smaller ships the operator can see every screen from its seat. Especially in those situations, it is essential to have the right balance between supplying the operator with enough information to decide on the right strategy. But avoid information overload.

A.1.3 Human operator

The human operator has two sides, the formal role as an operator which can be described with a list of tasks depending on their function. And the more difficult and unpredictable side of being a human which relates to the situational awareness and decision making ability.

Role as operator

To give more insight into the different roles on board of a merchant's vessel is the structure shown for officers in figure A.7. At smaller vessels, roles are combined where possible. The Navy has in some cases even more operational crew members. Apart from the licensed officers who manage the vessel, the crew does also consist of ratings who have hands-on skills within their domain. [Nedcon Maritime (2013)]

For this research the Deck crew is most relevant, as they are in charge of the vessel navigation, watch keeping, maintaining the ship's hull, cargo, gear and accommodation, taking care of the ship's lifesaving and firefighting appliances. The deck department is also the one in charge of receiving, discharging and caring for cargo. According to the vessel's hierarchy, the deck officers are as follows: Master, Chief Officer, Second Officer, Third Officer and Deck Cadet (deck officer to be).

The supreme authority on board a merchant's vessel is the Master or Captain. The entire crew is under his command. He is responsible for the safety, use and maintenance of the vessel and makes sure that every crew member carries out his work accordingly. He is also in charge of the following: payroll, ship's accounting, inventories, custom and immigration regulations, and the ship's documentation. In order to become Master, a seafarer must first have several years of experience as a deck officer and as Chief Officer. According to the vessel's hierarchy, the first deck officer and the head of the deck department after the Master is the Chief Officer. He is in charge of the vessel navigation, watch duties, charging and discharging operations. The Chief Officer also directs all the other officers on deck, creates and posts watch assignments and implements the Master's orders to maintain safe operations and maintenance of the vessel.

Second Officer or Second Mate is the next in rank after the Chief Mate. He is the ship's navigator, his main duties are the ship's passage plans, and keep charts and publications up to date. Apart from watchkeeping, the Second Officer may also be designated to train the cadets on board or to fulfil the rank of security, safety, environmental or medical officer. The Third Officer or Third Mate is the fourth deck officer in command and is usually the Ship's Safety Officer, responsible for ensuring the proper functioning of the fire-fighting equipment and lifesaving appliances. He undertakes bridge watches and learns how to become a Second Officer. A Cadet on board a merchant's vessel receives structured training and experience on board and learns how to become a deck officer.

Apart from the officers, the deck department crew also consists of ratings, such as AB (Able Body Seaman), OS (Ordinary Seaman) and Boatswain. The AB is part of the deck crew and has duties such as: taking watches, steering the vessel, assisting the Officer on watch, mooring and un-mooring the vessel, deck maintenance and cleaning. The AB also secures and un-secures the cargo and carries our deck and accommodation patrols. OS is the crew member whose primary duty is to maintain the cleanliness of the whole ship and serves as an assistant for the AB. Being an OS is considered to be an apprenticeship, a period called "sea time" to be allowed to take courses and training for AB. Both AB and OS are usually supervised by a Boatswain. The structure for the deck department on board merchant vessels is mainly the same on all vessel types. [Nedcon Maritime (2013)]

Human factor

At unmanned autonomous vessels, the human operator will be replaced by a computer. This change means that a computer will execute the duties as described above. This automation step has unknown consequences for the ability to observe and decision making while it has clear advantages when it comes to memory and reduced concentration due to fatigue.

Situational awareness is a model to determine the ability to observe and make decisions. How well humans perform is determined by their (learning) experience [Underwood et al. (2013)]. As a result of this, it is important to notice that situational awareness is not limited to perceiving, but has multiple levels. This is described using the Endsley model (figure A.8). The first step is to acquire situational awareness. This is based on three different levels of information processing [Kalloniatis et al. (2017)]:

Perception Data is merely perceived.

Comprehension Interpretation of data, enabling understanding of relevance concerning tasks performed and goals to be attained, forming a holistic picture of the operational environment. Identifying the significance of objects and events in that environment.

Projection Making a forecast for likely future states of the situation. This is based on the interpreted data, experience and knowledge.

Based on the situational awareness, a decision is made that results in an action. Changing the system and repeating the whole process. There are however factors which influence the effectiveness of this process. These can be internally or from the environment. Where automation is less prone to environmental factors, it will have a disadvantage when it comes to setting goals, preconceptions, acquiring knowledge or learning from experience, as many of the machine learning techniques are too much of a black box approach or are not yet useful for the assignments where ships have to navigate for example. There's also that indefinable matter of common sense that humans have but robots lack. Hundreds of thousands of years of evolution have provided us with a pretty good ability to recognise and make sense of things.

Whereas the human operator is more prone to environmental factors where the workload is a major factor in the ability to concentrate and thus the ability to forecast future states and therefore make the right decisions. The workload might be too high due to an overload of information [Speier et al. (1999)], when tasks are too easy [Washburn and Putney (2001)], or when limited attention is desired for a long time, and something unexpected happens [McMorris et al. (2018)].

These factors do only consider the single individual within the human operator team. But with larger ships, there are multiple persons at the bridge, all with their responsibilities. Research has shown that many of these crews have various cultures and nationalities work next to each other. Which often have an agreed working language which is not their first. This leads not only to minor irritations. But in some cases to hazardous situations [Hetherington et al. (2006)] when conversations happen via a noisy radio.

A.1.4 Procedures

Different skills and knowledge must be acquired to become a certified seafarer. The IMO has developed several conventions to standardise this knowledge globally. The International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW) is leading here. They ensure that ships sailing in international waters have skilled crew which know what to expect from other vessels. They have navigational abilities such as plotting with ARPA and know the conventions and systems used for safe navigation. Below some of these are explained in more detail. Followed by a description of known flaws of these systems and differences when compared to procedures used in practice.

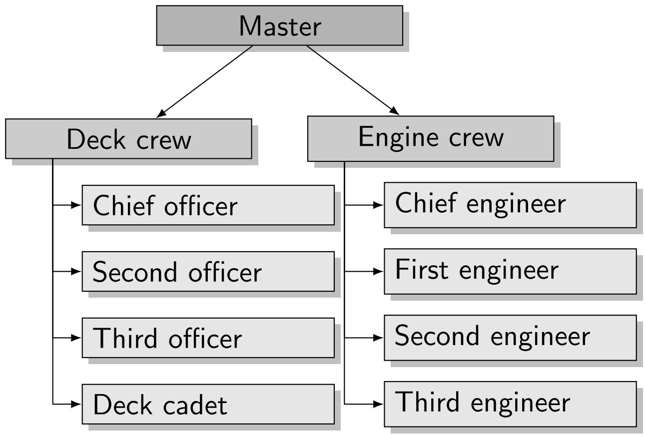


Figure A.7: Basic crew structure organogram

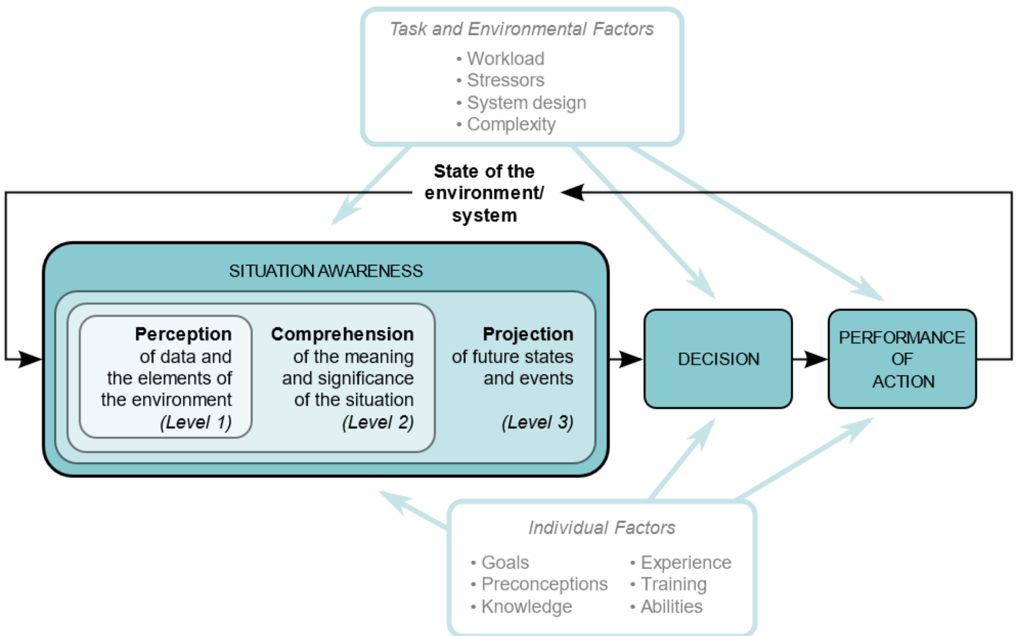


Figure A.8: Endsley model for situational awareness

Convention on the International Regulations for Preventing Collisions at Sea (COLREGs)

The COLREGs set out the navigational to be followed by ships and other vessels at sea, to prevent collisions between two or more vessels. Although rules for navigating vessels inland may differ, the international rules specify that they should be as closely in line with the international rules as possible. In most of continental Europe, the Code Européen des Voies de la Navigation Intérieure (CEVNI, or the European Code for Navigation on Inland Waters) apply. In the United States, the rules for vessels navigating inland are published alongside the international rules.

Before the development of a single set of international rules and practices, there existed separate practices and various conventions and informal procedures in different parts of the world, as advanced by multiple maritime nations. As a result, there were inconsistencies and even contradictions that gave rise to unintended collisions. Vessel navigation lights for operating in darkness, as well as navigation marks, also were not standardised, giving rise to dangerous confusion and ambiguity between vessels at risk of colliding. Different nations already came up with their own set of rules. But the first version was amended together with SOLAS in 1960. Additions were made including traffic separation schemes in 1972.

The COLREGs includes 41 rules divided into six sections: Part A - General; Part B - Steering and Sailing; Part C - Lights and Shapes; Part D - Sound and Light signals; Part E - Exemptions; and Part F - Verification of compliance with the provisions of the Convention. There are also annexes containing technical requirements concerning lights and their positioning; sound signalling appliances; additional signals for fishing vessels when operating in close proximity to other ships; and international distress signals. Where part B is most relevant for this research, with subjects like safe speed, obligation to determine the risk of collision and take action with all means available, how to act in different situations with other ships, or within restricted waterways.

Standard Maritime Communication Phrases (SMCP)

As navigational and safety communications from ship to shore and vice versa, ship to ship, and on board ships must be precise, simple and unambiguous, to avoid confusion and error, there is a need to standardise the language used. This is of particular importance in the light of the increasing number of internationally trading vessels with crews speaking many different languages since problems of communication may cause misunderstandings leading to dangers to the vessel, the people on board and the environment.

In 1973 IMO started to develop the Standard Marine Navigational Vocabulary (SMNV), which was replaced by the SMCP in 2001. The ability to understand and use the SMCP is required for the certification of officers in charge of a navigational watch on ships of 500 gross tonnage or more. To assist in greater safety of navigation and of the conduct of the ship. To standardise the language used in communication for navigation at sea, in port-approaches, in waterways, harbours and on board vessels with multilingual crews which is all instructed at maritime training institutions. These are not intended to supplant or contradict COLREGs or special local rules or recommendations made by IMO concerning ship routeing. Just as radiotelephone procedures should be followed strictly as set out in the ITU Radio Regulations.

It is a collection of phrases used to standardise and simplify the communication, where synonyms and contracted forms are avoided. Some examples of the usage of SMCP are shown below, including message markers to indicate the type of message:

Advice Standby on channel 6 - 8.

Information The fairway entrance is at position: bearing 1-3-7 degrees true from North Point Lighthouse, distance: 2 decimal 3 miles.

Warning Buoy number: one - five unlit.

Intention I intend to reduce speed, new speed: eight knots.

Question What are your intentions?

Instruction You must alter course to starboard.

Request Immediate tug assistance.

A.2 Difference between theory and practice

In the previous section is described how different systems and components should function to form the bridge system. This is however not always the case. These exceptions should be taken into account when developing an unmanned vessel. It is not within the scope of this research to find all exceptions. But based on conversations with seafarers can some already be identified which are relevant for solving the problem with communication.

Natural language

The first challenge is the usage of a protocol. Every seafarer learns today the Standard Maritime Communication Phrases (SMCP). But during operation, many natural language influences are used. This includes the usage of a local language, such as Dutch near the North Sea ports. This was one of the main issues during the collision between AL ORAIQ and FLINTERSTAR, as described in appendix C.1. Another example which occurred when I sailed at inland waters was the usage of location descriptions. It is very common to tell at which point a decision is taken. Many of these locations exist on maps, but in some cases, it also happens that area's get names which are not written down on charts. For example, there was a camping between Rotterdam and Dordrecht, which does not exist anymore. Operators still refer to the bend close to this former camping, as the camping. Autonomous systems should be able to interpret natural language and recognise when manned vessel make natural language variations to known protocols. Or using completely different ontologies.

Incorrect AIS information

Another important issue is the usage of AIS, as mentioned on the VHF Data Exchange System (VDES) conference is AIS victim of its success. Due to the popularity, more and more information is sent over these radio frequencies, limiting the number of AIS transmissions per ship per minute. This limit automatically reduces the accuracy and relevance, as information is older. This makes it harder to predict paths on the AIS information, it is therefore obligated to use ARPA. ARPA is, however, harder to interpret. These would together result in sufficient information which can be used by the autonomous system. There is another problem in this case. As shown by Loodswezen do some ships tweak their AIS information, to ensure that the officer of watch uses its ARPA. This can be seen in figure A.9. The vessel has an error of approximately 150-200 meter compared to the ARPA. How to cope with this is not within the scope of this research, but is something which should be discussed within organisations, such as International Maritime Organization (IMO), as it will determine which solutions are possible.

A.3 Summary of relevant communication systems

In the previous sections, a lot of different systems are discussed. But not all these systems are relevant for the development of communication between manned and unmanned ships. In table A.1 the most relevant systems and technologies are discussed, this will be the basis for the envisioned technology. This only includes systems for the communication. Not the systems to make decisions and create situational awareness, such as the ECDIS and ARPA.

Radio communication	Usage of message markers Availability on VHF Natural language variations on SMCP NATO phonetic alphabet and numbing AIS messages
Visible signals	Light signals Mast head signals Flags Heading, position and movements
Audible signals	Horn Speakers

Table A.1: Current relevant systems and technologies

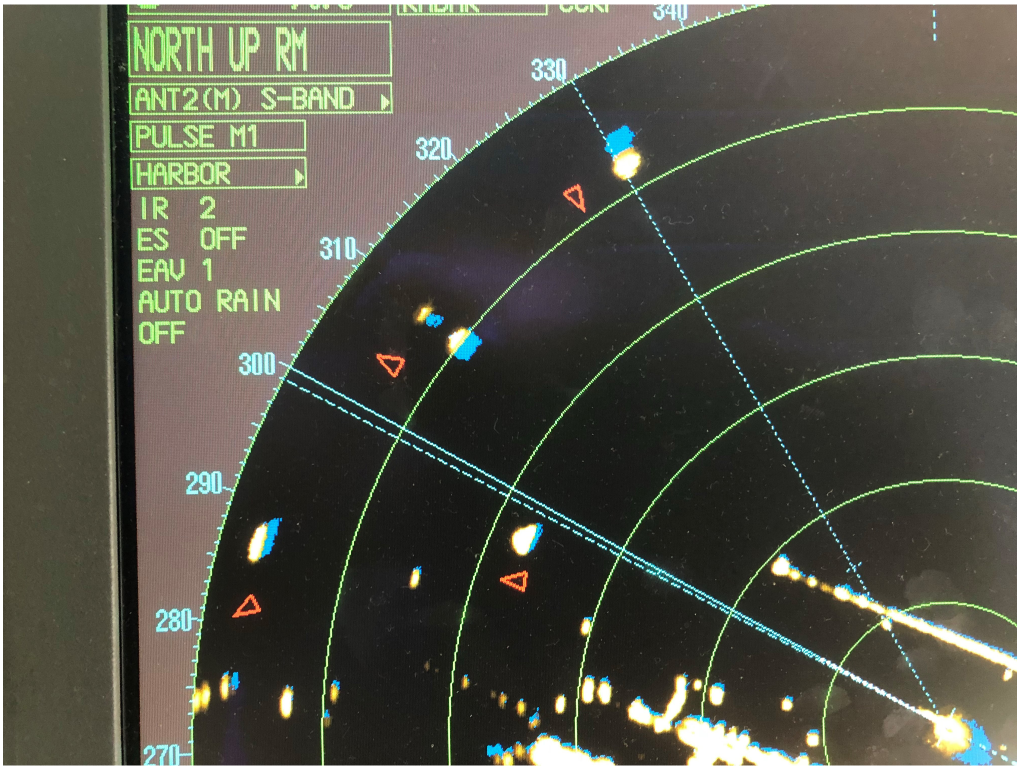


Figure A.9: Wrong AIS input when plotted on ARPA

B | Simulation environment

This appendix will describe the development process of the simulation tool. This tool will be used to simulate situations and manoeuvres. For part II this is done to evaluate criteria for the decision model and problem identification. While part III aims to get expert feedback on the protocol.

The reason to use such a tool is that full-scale testing will cost much more money, time and effort, while it is harder to control. Only using algebraic solutions will give less insight, while introducing much more complexity. Therefore is chosen to build an application in which models can be simulated and tested numerically. A start is made with a tool with basic functionality, which will continuously be improved. Changes in requirements have appeared during the whole research. The code is written in such a way, that it is easy to maintain and can be improved by adding or improving modules.

B.1 Foundation

The first step is to set the goals and requirements for the tool. This does not mean a full description of the tool but a description of features it should at least have to be able to support the research. The most important requirement is that ships within the simulation behave similarly to ships in reality, even when not all hydromechanics characteristics are known. But ships should have similar behaviours when turning or changing speed. This behaviour can be based on sea-trials and done using a mapping of current speed, current rotation, rudder angle and throttle to the future speed and turning speed. This mapping is combined with a model for hydrodynamic calculations by Artyszuk [Artyszuk (2016)], which is based on the often used 2^{nd} order Nomoto model [Nomoto and Taguchi (1957)]. The second requirement should be that it is flexible. This means different scenarios can be added, tested and visualised easily. Thereby changing ship characteristics, shared information and other inputs. The third requirement is that it should be possible to simulate with pre-determined actions, paths and manoeuvres.

The next step is to define users stories from the requirements. User stories are in a form: *"As a [user] I want [action] so that [result]"*. Extending them with acceptance criteria will result in the features which should be implemented.

Within the tool, there will be different roles. For which these user stories can be used. These can be split between users and objects. Below these are described:

- *Operator*. The person who set-up the simulation and fills in the different properties for the ships and specific scenario.
- *Viewer*. Someone who uses the application to view a specific scenario. Thereby trying to answer the research questions.
- *Ship*. The simulated object which is affected by the state of the simulation.

Below are examples of user stories given:

- As an operator, I want to add vessels to the map, by selecting them in a list, so that they become part of the simulation.
  Acceptance criteria: Ship visualised and can be selected to operate.
- As an operator, I want to define a path, so that I can test manoeuvres.
  Acceptance criteria: Waypoints can be set and added.
- As a viewer, I want to see what intentions are of other ships when they sail automated.
  Acceptance criteria: Waypoints are shown on the map.
- As a ship, I want to be manoeuvre in a realistic way, so that the simulation is relevant for a real-life situation.
  Acceptance criteria: The hydrodynamic model is validated.

B.1.1 Software architecture

Based on the above-described requirements and user stories, different modules are defined. The "model-view-controller" design pattern has resulted in the following general modules:

World The world is the class in which everything happens. Thus a kind of façade.

Simulation The simulation adds processes which are relevant for simulating situations in real-time. This module ensures that the right steps are taken at the right moment, such as updating the GUI and moving ships around. Thereby does it coordinate which objects are active within the simulation

Viewer This module only listens to the world to check if things change. This is shown in the GUI. Also without this visualisation, the simulation will still be able to run.

DynamicObject In this modules are the used ships defined which can be used in the simulation.

The above modules are for the general functionality of the tool. The implementation of more specific functions are in the following modules:

Ship Ships are used in the simulation. Within this module are the characteristics of the ships stored, including the visual representation and its safety domain.

ManoeuvringModel The manoeuvring model only contains a single method, in which each numerical step is calculated. Thus it receives a ship, the ships current state and the time-step. It finally returns the new speed, course, heading and location. Thereby it does check if the input values are correct. It does not matter in which world it is, or how it is visualised.

Gonio Some calculations have to be done many times, such as rotating points and polygons around another point. Functions for these calculations can be found in the Gonio module.

For the specific implementation of both parts of this research, two packages are used: Testing manoeuvres (MTexperiment) and scenario descriptions for the expert reviews (Scenarios).

The MTexperiment uses a bit different design pattern, as the goal is to have as many simulations as possible in the shortest time where only the final result is visualised. This is acquired by using a module with general functions such as ship creation, manoeuvre ship and store the results. While other modules are used to define the tests, select the executed tests and plot the results.

For the expert reviews, the GUI is crucial. The Scenarios package contains all different scenarios which can be used for the expert review. In those scenario descriptions, the objects used are defined, both static and dynamic object (e.g. ships). Also is given which waypoints ships should use and which part of the map is shown.

This is done to make the code readable and make sure that is known what is happening where. Using these modules enabled me to work efficiently and improve parts, without having the risk that other parts will break. For even better maintainable code, the tool could be split up in more packages and classes. This would result, however, in much more time, without improving the result of this research.

B.2 Design specifications

The theory behind the specific modules is described in this section. This will include the necessary information for a ship which has to be added, information on the environment and the hydrodynamic model.

B.2.1 Ship description

The key characteristics for a ship are given in table B.1. Beside these input values, there is also information stored by the simulation about the vessel. Table B.2 describes these and how these are included in the Ship object.

Input	Unit	Description
Name	-	The name of the vessel
Color	-	Color of the vessel as shown in visualization
MMSI	-	Unique identification number
LBP	meter	Length of the vessel between perpendiculars
Width	meter	Width of the vessel
Draft	meter	Current draft of the vessel
Displacement	metric ton	Its weight based on the amount of water its hull displaces
Nominal speed	knots	The speed the ships sails on average
Max speed	knots	The maximum possible speed on flat water

Table B.1: Input for ship characteristics

Input	Unit	Description
Last Update	seconds	Time in simulation at last update of location
Location	[meter, meter]	X and Y position
Course	degrees	Course, thus direction of movement
Heading	degrees	Heading, thus direction of bow
Drift	degrees	Difference between course and heading
Speed	knots	Current speed
Inertia turning	radians/second^2	Inertia due to rotational movements
Acceleration	meter/second^2	Inertia due to mass moving
Telegraph speed	%	Speed-setting at bridge
Rudder angle	degrees	Angle of rudder from straight
Waypoints	[meter, meter]	X and Y postion of waypoints
GUI objects	-	Objects describing what should be plotted, such as direction arrow, ship shape, safety domain, etc.

Table B.2: Ship details from simulation

B.2.2 Controller

Based on the waypoints there is a simple controller to adjust the rudder angle automatically. This controller steers based on the relative angle between the next waypoint and the current position. This is done in the *adjustRudder* function. The distance and relative angle are calculated, this is used in a simple decision tree to decide on the rudder angle, which is similar to a so-called "proportional controller". To enable ships to sail around automated, this is sufficient and gives enough accuracy. For a better result, a "PID-controller" could be implemented. In table B.3 the criteria for the decision tree are shown where the relative angle is the angle between the current course and the angle to from the current position to the waypoint.

Relative angle (°)	Rudder angle (°)
25-180	35
10-25	25
0-10	0.8 x Relative angle

Table B.3: Rudder angle based on relative angle

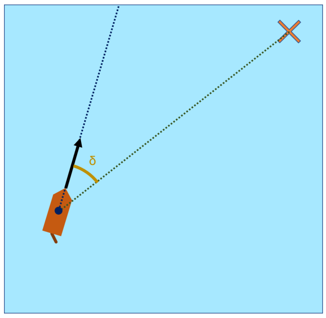


Figure B.1: Calculation of relative angle

This controller is limited due to the maximum turning rate of the rudder. This is discussed in multiple publications. Based on regulations from IMO the rudder should at least turn with 2,3 deg/second. But in reality, this is often closer to 3 degrees/second [Molland and Turnock (2007)]. The value used by Artyszuk is 2,5 degrees/second [Artyszuk (2016)]. When validating the model with the sea-trials, it seems that 3 degrees/second gave the most realistic results. Thus this has been used during the evasive manoeuvres and other experiments.

B.2.3 Manoeuvring

Ship manoeuvring is the ability to keep course, change course, keep track and change speed. Minimal requirements are given by IMO standard. However, shipowners may introduce additional requirements. The following characteristics describe ship manoeuvrability:

- Initial turning ability (start turning)
- Sustained turning ability (keep turning)
- Yaw checking ability (stop turning motion)
- Stopping ability (in rather short distance and time)
- Yaw stability (ability to move straight ahead)

During sea-trials, these capabilities can be determined. This project will, however, aim at predicting manoeuvrability while using limited input. Thereby is there a difference between the maximum limits and what a ship is likely to do. This will eventually lead to the possible movements of the vessel.

IMO standard

The manoeuvrability of a ship is considered satisfactory if the following criteria are met:

1. *Turning ability*. The advance should not exceed 4.5 ship lengths (L), and the tactical diameter should not exceed five ship lengths in the turning circle manoeuvre.
2. *Initial turning ability*. With the application of 10°rudder angle to port or starboard, the ship should not have travelled more than 2.5 ship lengths by the time the heading has changed by 10°from the original heading.
3. *Yaw-checking and course-keeping abilities*.
   (a) The value of the first overshoot angle in the 10°/10°zig-zag test should not exceed:
      i. 10°if L/V is less than 10 seconds
      ii. 20°if L/V is 30 seconds or more
      iii. (5 + 1/2(L/V)) degrees if L/V is between 10 and 30 seconds

      where L and V are expressed in m and m/s, respectively.

   (b) The value of the second overshoot angle in the 10°/10°zig-zag test should not exceed:
      i. 25°if L/V is less than 10 seconds
      ii. 40°if L/V is 30 seconds or more
      iii. (117.5 + 0.75(L/V)) degrees if L/V is between 10 and 30 seconds

   (c) The value of the first overshoot angle in the 20°/20°zig-zag test should not exceed 25°.
4. *Stopping ability*. The track reach in the full astern stopping test should not exceed 15 ship lengths. However, this value may be modified by the Administration where ships of large displacement make this criterion impracticable, but should in no case exceed 20 ship lengths.

Empirical model

To describe manoeuvring correctly a hydrodynamic model is needed. Using an empirical model, instead of a fully physical correct model shortens the implementation time. By validating the model with known data from sea-trials, can be determined if the accuracy of the model is sufficient for the tests. The model used is described by Artyszuk [Artyszuk (2016)]. This linear dynamic higher-order model is based on the 2^{nd} order Nomoto model [Nomoto and Taguchi (1957)].

The input for this model is based on different papers and real-life comparisons, to be able to simulate the ships as accurately as possible. It is a numerical model. Which means the input for the manoeuvring function is a ship and a time-step.

The first step is to gather relevant ship characteristics and the current state of the vessel, as shown in table B.4

This information is used to estimate the accelerations. An estimate of the forces is used in this case where two forces are calculated, the propelling force and the resistance. The propelling force is based on the setting of the telegraph and drift angle which determine the steady state speed. This is multiplied with a force factor to get the right results. The resistance depends on the current ship speed and a force factor. The difference between these two determines if the ship can accelerate and how much. Thereby is there a filter which limits the maximum acceleration due to inertia. This eventually results in a new ship speed.

Parallel to this calculation, a new course and heading are calculated. Based on the course, heading, manoeuvring characteristics and rudder angle. Different dimensionless factors are used, these are given in table B.5. When more information on the hydrodynamics of a vessel is known, these inputs can be adjusted. These inputs are validated for the used vessels. The resulting values did not differ significantly. This was most notable when running the different sea-trials with variable inputs. Artyszuk [Artyszuk (2016)] discusses the full calculation.

B.2.4 Numerical settings

The simulation environment uses a numerical model. This means that the input values highly influence the results. Two of these inputs are the time-step during the simulations, and the moment the rudder is changed to limit the overshoot in the critical evasive manoeuvre.

Time-step for simulation

The time-step has a big influence on the quality of the simulation and runtime. When the time-step is too large, the results of the calculations are wrong. But when the timestep is too small, the runtime becomes too large. This trade-off must be made, to do this in a substantiated way, different tests are done for different time-steps. The key performance indicator is the error of the final position and maximum course for an evasive manoeuvre. This is determined by calculating the difference between a time-step and a very small time-step (0.00001 seconds per step). This is done for different ship types. The error in passing distance varied from 0.002 when using 0.001 seconds, to 20 meters when using 1 second as time-step.

Input	Unit	Description
Length	meter	Length of the vessel (L)
Width	meter	Width of the vessel (B)
Depth	meter	Depth of the vessel (T)
Displacement	meter^3	Displacement of the vessel (∇)
Cb	-	Block coefficient $(displacement/L \cdot B \cdot T)$
Drift	degrees	Angle between course and heading
Inertia turning	radians/second^2	Inertia due to rotational movements
Speed	knots	Current speed
Telegraph speed	%	Speed-setting at bridge
Rudder angle	degrees	Angle of rudder from straight

Table B.4: Input for manoeuvring model

Name	Value	Description
k_{11}	1.004	Sway added mass coefficient
r_z	0.247	Ship's gyration dimensionless radius
r_{66}	0.225	Added gyration dimensionless radius
Y_b	0.0043	Hull hydrodynamic derivatives
Y_w	0.0260	Hull hydrodynamic derivatives
N_b	0.0024	Hull hydrodynamic derivative including Munk moment contribution
N_w	-0.0630	Hull hydrodynamic derivatives for moment
A'_R	0.0177	Dimensionless rudder ratio $(Ar/(L * T))$
w	0.326	Propeller wake fraction
c_{Th}	2.127	Thrust coefficient propeller
$\partial C_L/\partial a$	0.0385	Rudder lift coefficient derivative, which depends on α and c_{Th}
a_H	2.5	Empirical factor for rudder force due to hull-rudder interaction
c_{Ry}	1.0	Empirical multiplier to the rudder geometric local drift angle
x_{Reff}	-0.5	Effective rudder longitudinal position

Table B.5: Dimensionless coefficients based on Artyszuk

When the results are within 0.5 meters other factors will have a much more significant impact, such as the quality of the hydrodynamic model. This is the case for a time-step below 0,01 seconds. Therefore this is used during the simulations. The error in the resulting overshoot for a time-step of 0.01 seconds, for all ships below 0.02%.

Change time for critical evasive manoeuvre

The change time determines when commands should be given. The optimal change time is when the least time is needed to increase the closest point of approach as much as possible, as this is most relevant for critical situations. The change time has been tested for multiple vessels to evaluate this criteria. The used criteria is calculated by dividing the distance to the side (Y) by the advanced distance (X) (as shown in figure 6.3a). This is plotted against the time it took to make the manoeuvre. Figure B.2 shows from left to right the results for a 140-meter container vessel, a 250-meter Tanker and a 400-meter cargo vessel.

The optimal change time should be at the upper left corner. As this means the increase of the passing distance and thereby the CPA is as long as possible, in the shortest time and travelled distance. When looking at the figure can be seen that this is the case around 18 seconds. It should be noted that larger vessels have a longer optimal change time, the larger inertia of these vessels can explain that. A higher speed has a similar result. The effect of these larger change times is however insignificant compared to other factors. Examples of these factors are the maximum turning rate of the rudder or rudder-hull interaction coefficient. Therefore is chosen to use a single change time for the evasive manoeuvre tests. The change time selected is 18 seconds.

B.3 Build

The final design of the tool is discussed in this section. This shows what outputs can be generated and how the simulation environment can be viewed. Thereby also discussing shortly how the simulation can be controlled by the user and what the simulation does by itself.

B.3.1 User interface

The simulation environment uses a tkinter GUI. This GUI has three parts. A big block which shows the map with a vessel, speed vector, safety domains, land masses and forbidden zones. Using the buttons in the bottom left the map can be changed, this means moving around and zooming. At the bottom is an information bar which gives information on the current status of the simulation and possible actions. At the right of the screen is the control panel.

The user selects if he wants to modify the simulation or sail around. When in modify mode, the ships can be added, removed or edited. When sailing, only the rudder angle and RPM of the engine for each ship can be changed. It is also possible to add waypoints which the ship will follow. Figure B.3 shows that some basic information for the selected ship is presented, such as the speed [knots], course [degrees] and rudder angle [degrees].

B.3.2 Output

Besides simulations within this GUI, it is also possible to execute them without showing the map. This will limit the computational time. Different outputs are stored to visualise these results. These are logged during the simulation. The outputs are stored in a dictionary so that they can be labelled easily. Table B.6 shows the different outputs for the simulation. These outputs can be plotted as scatter, path or line plots. These are shown in chapter 6. This makes it possible to test manoeuvres many times with small variances. The configured tests are described in table B.7.

B.3.3 Level of implementation

Currently is a hydro model implemented based on [Artyszuk (2016)]. This makes it possible to have realistic behaviour of the vessels in flat water. Thereby it is possible to steer the ship similarly to current bridge operation. Thus by setting the RPM of the engine(s) and changing the rudder angle.

Thereby is there also an automated way, which helps to steer the ship automatically via predefined waypoints. Thus does it not take into account where other vessel sail, or how the map looks like. The distance between vessels is calculated continuously, which gives warnings when ships are too close. The simulation keeps on running when ships touch or collide with land masses, the effects of these collisions are not modelled.

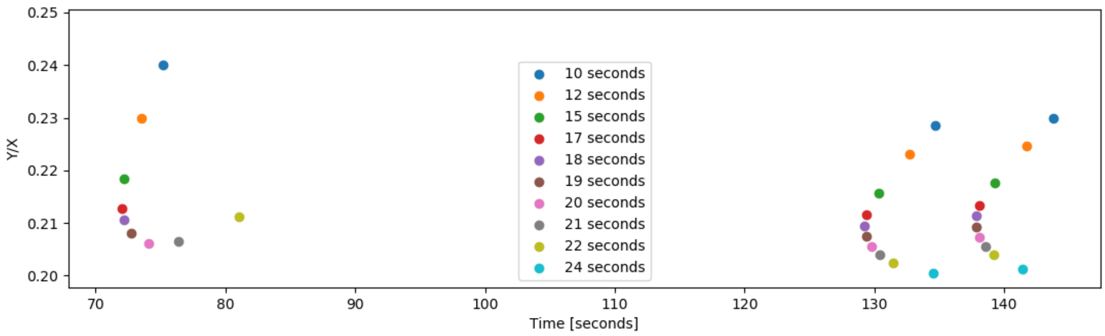


Figure B.2: Change time during evasive manoeuvre for different ship types

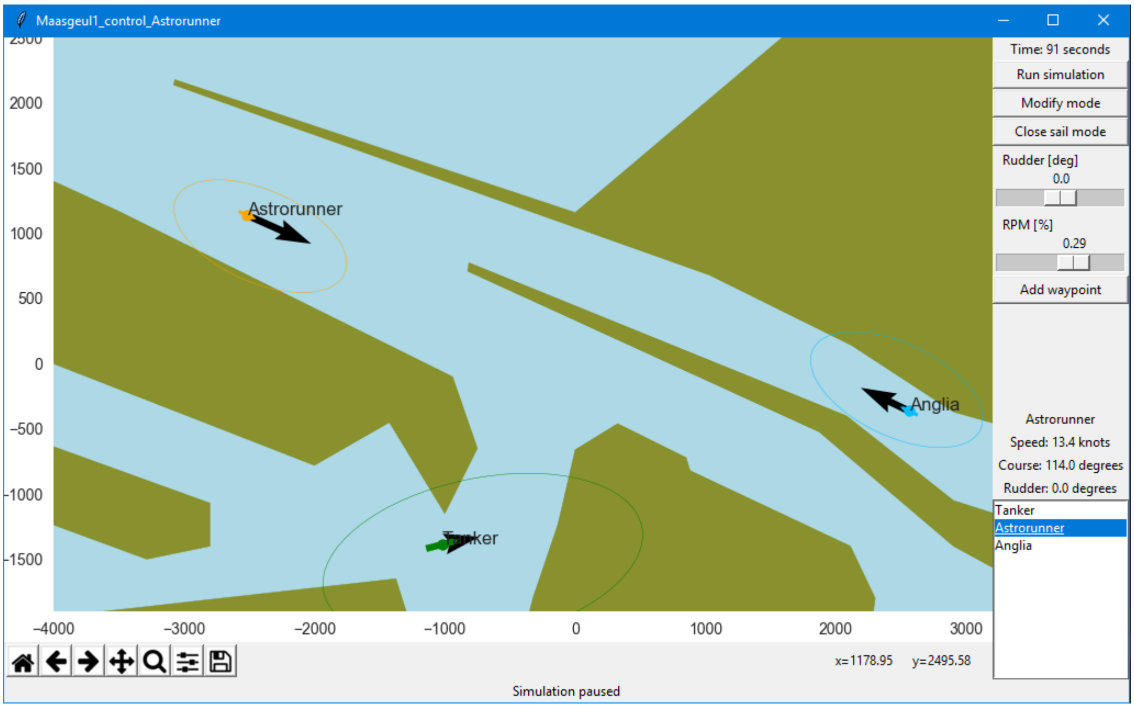


Figure B.3: Simulation environment

Label	Type	Description
Shipname	string	Name of ship which is subject of test
Testname	string	Exectued test with details about input
Start speed	float	Initial speed of vessel before manoeuvre
Time	integer	Variable which stores the simulated time
Timestep	float	Time per numerical step
Location	list	X and Y location of vessel in environment
Speed	list	Speed of vessel at every time-step
Acceleration	list	Acceleration of vessel at every time-step
Course	list	Course of vessel at every time-step
Heading	list	Heading of vessel at every time-step
Drift	list	Course - heading of vessel at every time-step
Set rudder angle	list	Set rudder-angle of vessel at every time-step
Real rudder angle	list	Real angle of rudder at every time-step
Manoeuvrer specific	-	Resulting passing distance, max angle, overshoot, calculated passing distance, speed other vessel, turning circle, advance distance, etc.

Table B.6: Standard output for manoeuvres

Name	Goal
Sea-trial	Execute zig-zag and turning circle test
Rudder test	Test performance of rudder and how it responds
Evasive manoeuvre	Compare behaviour for different angles
Change time	Test correct moment to start rotating rudder
Timestep	Compare the quality of simulation using different time-steps
Random	Determine the effectiveness of evasive manoeuvre to increase the crossing distance and CPA by varying ship characteristics, rudder amplification factor, start speed, maximum course change and maximum rudder change

Table B.7: Different manoeuvring tests

C | Accidents

In the last centuries, much has changed to improve the safety vessels and decrease the risk of collision. Some were reactions to major accidents which occurred. Such as the disaster with the TITANIC in April 1912, which triggered the development of SOLAS. But also new innovations, such as the introduction of Global Positioning System (GPS), ARPA and AIS. But accidents still occur. To get insight into factors that result in hazardous situations. Four accidents are discussed, showing the importance of proper communication on different levels. The accidents which will be discussed are:

- Collision between MV AL ORAIQ and MV FLINTERSTAR
- Collision between MV ARTADI and MV ST-GERMAIN
- Collision between USS FITZGERALD and MV ACX CRYSTAL
- Collision between USS JOHN S MCCAIN and MV ALNIC MC
- Collision between MV CONTI PERIDOT and MV CARLA MAERSK

C.1 MV AL ORAIQ and MV FLINTERSTAR

During the night between 5th and 6th of October 2015 at the Northsea near Zeebrugge, a collision occurred between the LNG tanker AL ORAIQ and Dutch cargo ship FLINTERSTAR. The FLINTERSTAR sank almost immediately as a result of the collision, an illustration of the accident is shown in figure C.1. The captain of the FLINTERSTAR was badly injured during the incident, the other ten people on board and the pilot were rescued out of the water unharmed.

Figure C.1: Illustration of collision MV AL ORAIQ and MV FLINTERSTAR

The collision occurred because the bridge team on board of the AL ORAIQ wrongly assessed the traffic situation, vessel's speed and distance from the S3 buoy, before contacting the nearby vessel Thorco Challenger. After informing the Thorco Challenger, they did pass on the starboard side. On board of AL ORAIQ were coastal pilots who did not receive feedback from the watchkeepers, nor was there feedback from other vessels via VHF radio. The communication via VHF radio was mostly in dutch, the officer on duty at AL ORAIQ did not request the Coastal pilots to translate. On board the FLINTERSTAR, there was insufficient attention for watchkeeping duties as several VHF radio communications between Traffic Centre Zeebrugge and other participants within the area monitored by Traffic Centre Zeebrugge, concerning or involving the presence of an inbound LNG carrier were missed by the Pilot and other crew at the bridge on board the FLINTERSTAR.

The pilot on board of AL ORAIQ did not attempt to work together with the crew. Thereby making decisions without consulting the crew, such as overtaking other vessels. The sea pilot on board of the FLINTERSTAR got engaged in a casual conversation with the officer of the watch, drawing his attention away from monitoring the traffic situation. The Sea Pilot was advising the officer of the watch from what appeared to be routine. [Backer (2015)]

C.2 MV ARTADI and MV ST-GERMAIN

An example where the COLREGs were followed but still resulted in two persons killed in the collision between MV ARTADI and MV ST-GERMAIN on February 21st, 1979. The Liberian bulk carrier ARTADI collided with the passenger ferry ST-GERMAIN in the Dover Strait, killing two people and injuring four more. An illustration of the accident is shown in figure C.2. Both ships followed COLREGs according to the accident report. Due to a lack of communication and wrong presumptions on the intentions, the accident did occur.

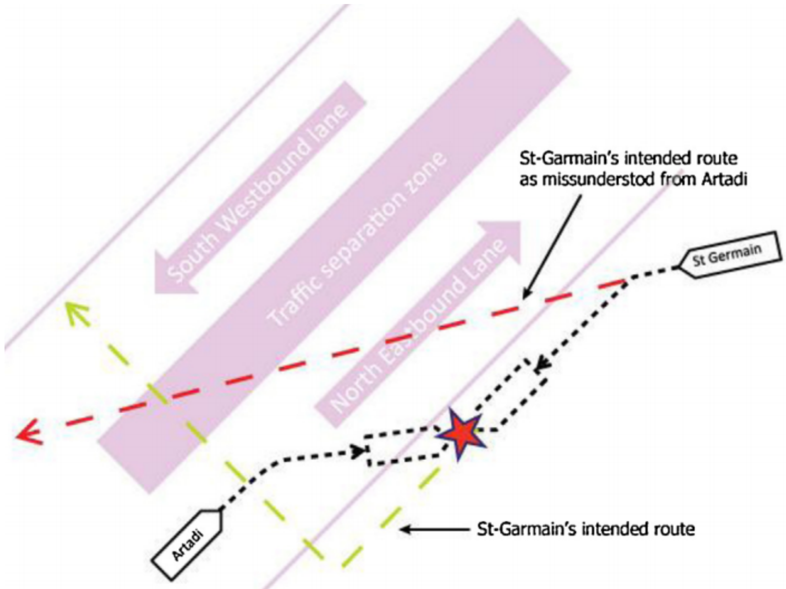


Figure C.2: Illustration of collision between MV ARTADI and MV ST-GERMAIN

The ferry was spotted in good time on the radar of the ARTADI. Coming from starboard, ST-GERMAIN was the stand-on ship according to rule 15 of the COLREGs. The pilot and master of the ARTADI expected her to keep speed and course and started to make a starboard turn to give way. However, on-board the ST-GERMAIN the intention was not at all to cross the traffic separation scheme diagonally in front of ARTADI, but instead to turn port and follow outside the border of the NE going traffic lane until the traffic cleared and she could make the crossing at a right angle (according to rule 10c) [Porathe et al. (2013)].

C.3 USS FITZGERALD and MV ACX CRYSTAL

A more recent collision was between the USS FITZGERALD and ACX CRYSTAL on June 17, 2017. The US destroyer hit the Philippines container vessel, resulting in the death of 7 US Sailors. An illustration of the accident is shown in figure C.3. According to the accident report did failures occur on the part of leadership and watch-standers. There were failures in planning for safety, adhere basic navigational practice, execute basic watchstanding practice, proper use of available navigation tools and wrong responses.

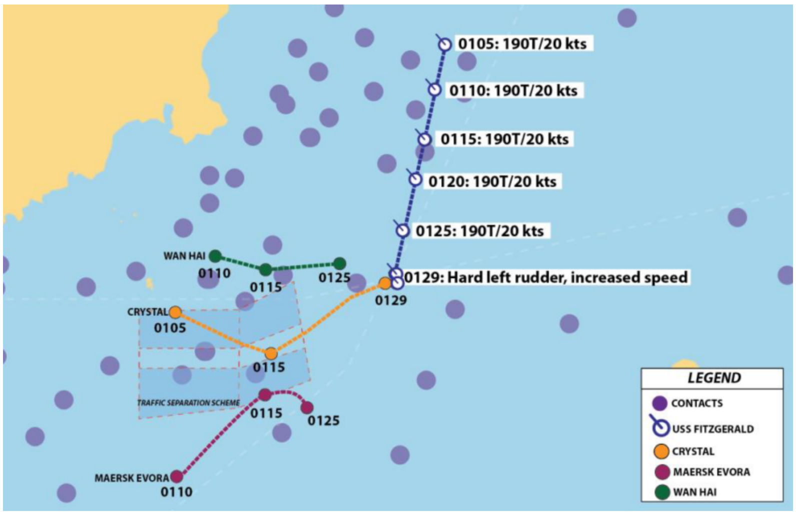


Figure C.3: Approximate collision location USS FITZGERALD and MV ACX CRYSTAL

In accordance with international rules, the USS FITZGERALD was obligated to manoeuvrer to remain clear from the other crossing ships. The officer of the deck responsible for navigation and other crew discussed whether to take action but choose not to, until it was too late. While other crew members also failed to provide more situational awareness and input to the officer of the deck. Did the officer of the deck, exhibit poor seamanship by failing to manoeuvrer as required, failing to sound the danger signal and failing to attempt to contact CRYSTAL on Bridge to Bridge radio. In addition, the Officer of the Deck did not call the Commanding Officer as appropriate and prescribed by Navy procedures to allow him to exercise more senior oversight and judgment of the situation. This was mandated to an unsatisfactory level of knowledge of the international rules of the nautical road by USS FITZGERALD officers. Thereby were watch team members not familiar with basic radar fundamentals, impeding effective use. Key supervisors were not aware of existing traffic separation schemes and the expected flow of traffic, as the approved navigation track did not account, nor follow the Vessel Traffic Separation Scheme. Secondary was the automated identification system not appropriately used. [US Navy (2017)]

C.4 USS JOHN S MCCAIN and MV ALNIC MC

Even more recent is the collision between the USS JOHN S MCCAIN and ALNIC MC on August 21st, 2017. The US Destroyer hit the Liberia flagged oil and chemical tanker. Resulting in the death of 10 US Sailors. An illustration of the accident is shown in figure C.4. According to the accident report did the US Navy identify the following causes for the collision: Loss of situational awareness in response to mistakes in the operation of the USS JOHN S MCCAIN's steering and propulsion system, while in the presence of a high density of maritime traffic. Failure to follow the international nautical rules of the road, which govern the manoeuvring of vessels when a risk of collision is present.

Leading up to the accident did the commanding officer notice that the helmsman had difficulties maintaining course, while also maintaining control over speed. In response, he ordered the watch team to divide the duties of steering and speed control. This unplanned shift confused the watch team, which led to improper transfers of control, of which the crew was not aware. Watchstanders failed to recognise the configuration. The steering control transfer caused the rudder to go amidships (centerline). Since the Helmsman had been steering less than 4 degrees of right rudder to maintain course before the transfer, the amidships rudder deviated the ship's course to the left. Additionally, when the Helmsman reported a loss of steering, the Commanding Officer slowed the ship to 10 knots and eventually to 5 knots. Due to the improper transfer did only one shaft slow down, causing an un-commanded turn to the left (port). The commanding officer and others on the ship's bridge lost situational awareness. They did not understand the forces acting on the ship, nor did the understand the ALNIC's course and speed relative to USS JOHN S MCCAIN. Three minutes after the reported loss of steering, was it regained, but already too late to avoid a collision. No signals of warning were sent by neither ship, which is required by international rules of the nautical road. Nor was there an attempt to make contact via VHF bridge-to-bridge communication. Many of the decisions made that led to the accident were the result of poor judgment and decision making of the commanding officer. That said, no single person bears full responsibility for this incident. The crew was unprepared for the situation in which they found themselves through a lack of preparation and ineffective command and control. Deficiencies in training and preparations for navigation were at the base of this. [US Navy (2017)]

C.5 MV CONTI PERIDOT and MV CARLA MAERSK

The last accident which will be discussed is the collision between MV CONTI PERIDOT and MV CARLA MAERSK on 9th March 2015. At 12:30 central daylight time, the inbound bulk carrier CONTI PERIDOT collided with the outbound tanker CARLA MAERSK in the Houston Ship Channel near Morgan's Point, Texas. The collision occurred in restricted visibility after the pilot on the CONTI PERIDOT was unable to control the heading fluctuations that the bulk carrier was experiencing during the transit. As a result, the CONTI PERIDOT crossed the channel into the path of the CARLA MAERSK. No one on board either ship was injured in the collision, but an estimated 2,100 barrels (88,200 gallons) of methyl tert-butyl ether spilt from the CARLA MAERSK, and the two vessels sustained about $8.2 million in total damage. In figure C.5 the fluctuations in heading can be seen of the CONTI PERIDOT.

The National Transportation Safety Board identified several safety issues. Inadequate bridge resource management: Despite the pilot's difficulty controlling the CONTI PERIDOT's heading leading up to the collision, he and the master did not work together to solve the problem. The pilot did not involve the master because he was unsure whether the master could do anything to help; the master said nothing because he was likely unaware of the vessel's heading fluctuations and may have generally been reluctant to question the pilot. Insufficient pilot communications: Although the pilot on the CONTI PERIDOT was having difficulty controlling the vessel and had an earlier near-miss meeting with an oncoming ship, he did not alert the pilots on subsequent oncoming vessels, including the CARLA MAERSK. Lack of predetermined ship movement strategies during restricted visibility in the Houston Ship Channel: On the day of the accident, local pilot associations determined that the increasing fog was significant enough to suspend pilot boardings of inbound ships. However, piloted vessels already under way continued the transit in the fog. Investigators found no existing predetermined ship movement strategy for piloted vessels already underway at the onset of hazardous weather conditions.

The National Transportation Safety Board determines that the probable cause of the collision between bulk carrier Conti Peridot and tanker Carla Maersk in the Houston Ship Channel, was the inability of the pilot on the Conti Peridot to respond appropriately to hydrodynamic forces. This happened after meeting another vessel during restricted visibility, and his lack of communication with other vessels about this handling difficulty. Contributing to the circumstances that resulted in the collision was the inadequate bridge resource management between the master and the pilot on the Conti Peridot. [NTSB (2016a)][NTSB (2016b)]

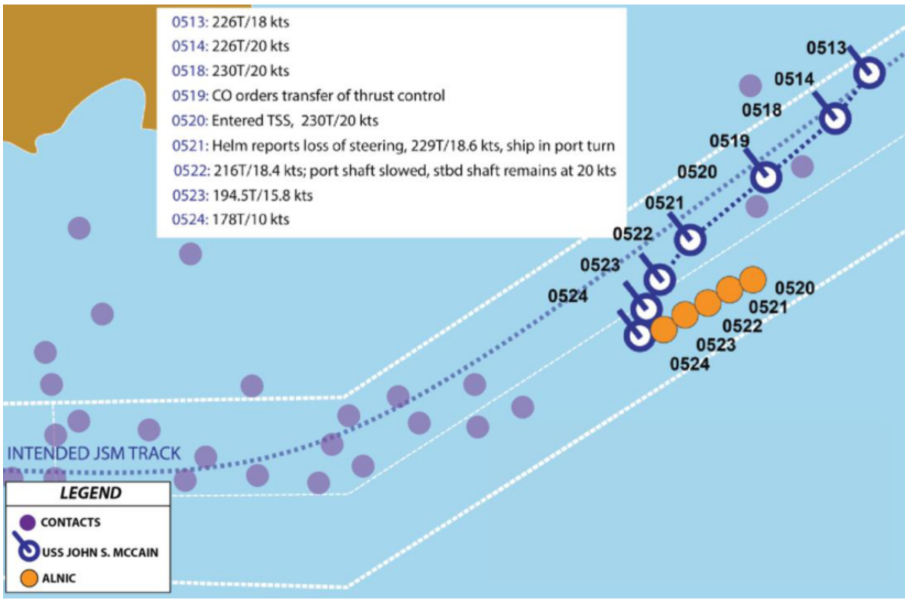


Figure C.4: Approximate collision location USS JOHN S MCCAIN and MV ALNIC MC

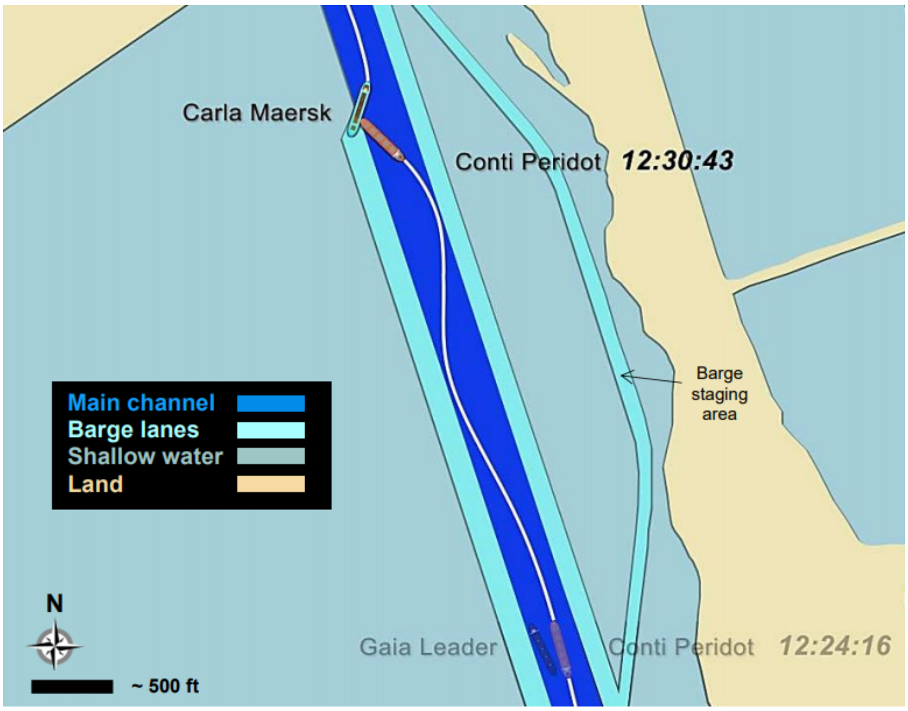


Figure C.5: Illustration of collision MV CONTI PERIDOT and MV CARLA MAERSK

C.6 Lessons learned

Mistakes were made in all of the above-described accidents. But in all cases was there not sufficient communication, to warn the other vessel. If this had happened, they could have taken actions to avoid the collision. There should be a universal protocol, to achieve effective communication. This protocol should be used under all circumstances. Thereby it is important that all seafarers understand this protocol and can work with it. Communication with this protocol should be engaged in all cases when there is any doubt if intentions are understood, or if full control over the situation is lost. This is also part of proper bridge resource management where a good balance of crew should be at the bridge, to avoid overload. But more importantly also avoid the bystander effect in cases there are too many [Fischer et al. (2011)]. The crew that is available at the bridge should be aware of forces acting on the vessel, the effect of these forces and notice when the ship does not act as expected. In these situations, an emergency protocol or strategy should be executed, which is known by all active crew members.

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