MSc Thesis Report

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

Ingmar Wever

October 8, 2018

TU Delft

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

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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

More people start to believe in the possibilities of unmanned and autonomous shipping, as there are many projects which try to develop the necessary technologies [SMASH(2017)] [Eriksen(2017)] [MUNIN(2016)] [Sames(2017)] [Rolls-Royce(2015)] [Waterborne(2016)]. The major reason for the development of autonomous ships are the benefits for operational expenses. But one of the major reasons for acceptance is the mitigation of human errors. Which can be achieved by taking out humans from the chain of command, this will however introduce new challenges [Saarni et al.(2018]. In chapter 1 these challenges and corresponding projects are discussed. One of the less explored challenges is the issue of communication. This becomes harder between manned and unmanned vessels. Communication is used to share information on the intentions or discuss future actions. At the moment there is no protocol which can be used by unmanned vessels. However this is necessary to ensure the safety of all vessels: manned, unmanned, remote, automated and autonomous. To solve this challenge, there are two possibilities: Avoid the need for communication, or develop a new communication protocol.

Context

In many situations is the Convention on the International Regulations for Preventing Collisions at Sea (COLREGs) sufficient to determine the intentions of other vessels [IMO(1972)]. They can be seen as ship separation rules, which guide all vessels to make early and correct alterations to the course. It will take more time to assess the situation when using VHF. Meaning there is less time to act, which limits the possible strategies. These rules do also apply to autonomous ships, and thus can be used when manned and unmanned vessels meet. Examples are to stay on starboard side of the shipping lane and not to cross other ships with small relative angle. Accidents do still occur, even when both vessels follow the COLREGs, such as the accident between Artadi and St-Germain as described in appendix C.2. This occurs more often in complex situations, such as a harbor approach.

The risks when COLREGs are not sufficient can be mitigated by taking decisions well in advance. What well in advance means, depends on the manoeuvrability of a vessel. A cargo vessel will follow common paths, while a small tug boat might move around much more. Which results in more false positives on potential collisions with other vessels when using the same safety domain. The manoeuvrability means that it is necessary to think ahead several minutes with a large ship, while this is much shorter for a small tug boat. This time-domain for decision making depends not only on the ship characteristics, but also the waterway characteristics.

In chapter 2 this will be discussed in more detail, examples are the depth, traffic separation schemes and harbor entrances.

Research questions

This research will be a start, to solve the challenge of communication between manned and unmanned vessel without introducing new systems to the bridge of manned vessels. This can be used as a foundation to build a system for decision making which ensures safe operation of both manned and unmanned vessels. The parts relate to different research domains: Maritime Technology and Computer Science. Which discuss two different research questions:

> *How do ship manoeuvrability characteristics influence the domain for decision making, to ensure that the chosen strategy will result in a passing distance which 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 research will be separated into three parts. In those parts, the challenge of communication between manned and unmanned vessels is considered. The first part gives a more detailed context of autonomous shipping. Using this context and a decision-model, can be shown why communication is a challenge. This is shown in part I

Part II aims to determine how communication can be avoided. This is possible when ships stay away from each other. To accomplish this, decision should be taken in time. Thus studying the time-domain for decision making. This depends on the moment decision are made in critical situation. Using manoeuvring models these situations are simulated, to determine the time-domain and if this can be improved to ensure that communication is needed in fewer situations.

Part III will focus on the critical situations where communication is a must. Currently there is not yet worked on a communication protocol between manned and unmanned vessels. To ensure this will not delay the implementation of unmanned autonomous vessels. A new communication protocol is needed, based on existing systems and protocols. The aim of this part, is to validate if it is possible to define a protocol using the situated Cognitive Engineering (sCE) method, which will be accepted by seafarers.

Part I

The problem of communication for autonomous vessels

It is impossible for a man to learn what he thinks he already knows.

– Epictetus [Adamson(2003)]

Safety at sea has been a relevant topic as long as ships exist. Nowadays communication has become very important to ensure the safety of all ships. Where communication can be all forms of sharing information. Before the invention of radio communication, ships literally lost all connection with the shore and other ships when setting sail. Flags were used when ships were close to others ships or to the shore. This form of communication was not complete as it only gave limited insight in the intentions of other vessels for example. To ensure the safety they made regulations. These regulations were eventually 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, which subsequently led to safer operation. This works very well between manned vessels, as human can work well with limited unstructured information compared to computers. With autonomous ships getting closer, a solution must be found. Also because new technologies have led to more complex situations. As ships get bigger and perform more complex operations. Due to the limited possibility for communication by unmanned ships, it becomes even more important to make the right decisions well in advance to avoid critical situations, or enable those ships to share the right information at the right time.

There are many projects working on unmanned autonomous ships. Chapter 1 describes why these steps are taken towards autonomous and unmanned shipping. Followed by a description of projects. This will give more insight into what others see as challenges for the introduction of unmanned vessels. Also showing that issue of communication between manned and unmanned vessels is less explored. A separation is made between the more exploitative projects aimed to form a vision of the future, and the applied projects aimed develop prototypes on the short term. Resulting in the challenges as defined by others. Chapter 2 relates these challenges to the decision model for ships. This shows how the need for communication depends on the steps taken in the decision process, thus that it might be possible to avoid communication and ensure safe operation.

1 | Steps towards the future

This research will focus on improving safety at sea by mitigating the risk which come with communication between manned and unmanned vessels. This challenge was not yet in the scope of the major projects. This chapter will first show why this transition is happening, followed by the projects who work on autonomous vessels. Thereby is shown how these projects address the problem of communication. To prove that the challenge of communication between manned and unmanned vessels is less explored.

1.1 Why autonomous and unmanned shipping

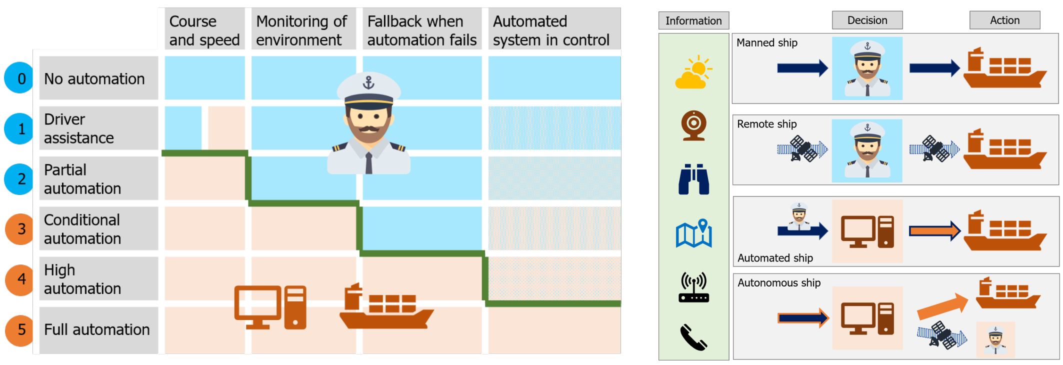
Due to digitalization, ships will become more sophisticated. More data is generated by sensors, improved connectivity and new ways to visualize data. This enables ships to continuously communicate with managers and traffic controllers. At first, this can be used to analyze data and give better advice based on expected weather, fuel consumption and arrivals at bottlenecks like ports and bridges. But further ahead this might result in unmanned vessels, which might be operated remotely. In parallel there is 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 most accidents are caused by human errors. Thereby will there be less crew at the ship, 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. With more automation, less crew is needed, although they need to be schooled better.
- *Higher productivity*, as the utilization rate of ships can improved, by using data more effective. Thereby comes that computers don't have to work in shifts, to go home or take breaks.
- *More comfort and attractiveness industry*, as people can have more regular hours to work and do not have to be away for many weeks when working remote.

Thereby are maritime trade volumes expected to increase in the future and accordingly the numbers of ships needed to transport the freight will grow, as will the number of seamen 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 cited reason for this lies in the unattractiveness of seagoing professions, especially for youngsters. To some extend this is caused 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 with that 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.On the one hand, it could reduce the expected pressure on the labor market for seafarer as it would enable, at least partly, to reduce the labor intensity of ship operation. On the other hand, routine tasks on board would be automated and only the demanding but interesting navigational and technical jobs transferred from ship to a shore side operation center. Making "seafaring" jobs more attractive and family friendly than today. Furthermore, economic and environmental benefits are also expected when implementing unmanned shipping. [MUNIN(2016)]

In the next sections are different projects around the world discussed, which work on the transition towards autonomous or unmanned vessel. Thereby should be considered that the projects are working on different levels of automation. These different levels are shown in figure 1.1a. Where can be seen 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 is responsible for the mentioned activity. Beside these levels of automation, are there also different types of automation, each with their own challenges. The types 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 Projects

The vision of 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 an initial research between 2013 and 2016. Focussing on different elements of an autonomous concept (figure 1.2):

- 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 in relation to a vessel's technical system and develop a concept for autonomous operation of the engine room.
- Define the processes in a shoreside operation center, required to enable a remote control of the vessel.

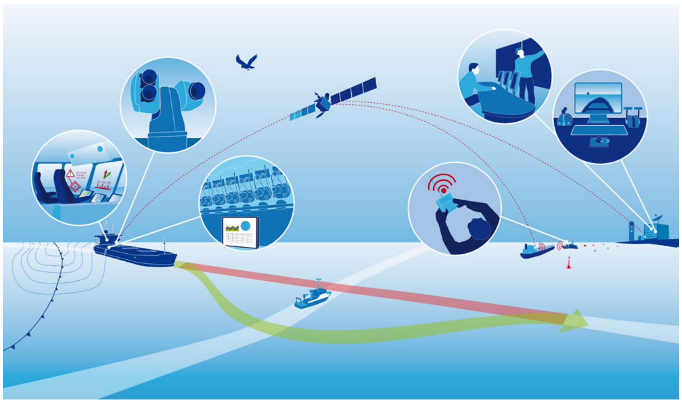


Figure 1.2: Illustration of MUNIN vision

Thereby taking into account the feasibility of the developed solution, including legal and liability barriers for unmanned vessels. They concluded that unmanned vessels can contribute to the aim of a more sustainable maritime transport industry. Especially in Europe, shipping companies have to 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, but comprehensive solution to meet these challenges, as it bears the potential to: Reduce operational expenses and environmental impact. A concept was developed for a bulker vessel, enabling the consortium to do a financial analysis. Showing the viability, but admitting the limited scope of the project [MUNIN(2016)]. They have showed the importance of developing a method to determine intentions of other vessels and systems which are needed. But did not yet make the step towards developing such a method, which is the scope of this report.

1.2.1 Exploratory projects

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
- ReVolt

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.

Keeping in mind that the way towards autonomous, will start with a virtual bridge, which is housed below the containers. Utilizing the opportunities for sensors during safe navigation. By using Radar, camera, IR camera, LIDAR and Automatic Identification System (AIS). The aim of this concept is to have partial autonomy by 2020, remote operation between 2025 and 2030, starting with a reduced passive crew on board. And be fully autonomous in 2035 [Wilson(2017)]. They pinpointed the control room, as the nerve center 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. Their aim is to develop unmanned cargo ships with independent navigational capacity and make market promotion so as to promote the development of intelligent shipping. The alliance would not only promote changes in the ship design and operation, but also facilitate 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 intelligent ship.

1.2.2 Industry projects

Where the exploratory projects work on the vision and far future of autonomous. Are some companies 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 fully electric manned vessel, but plans are that it will sail autonomously in 2020. Operating between different Yara facilities in Norway, transporting fertilizers and raw materials. Meaning the path and quay are always the same, which reduces the amount 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. Which is a collaboration between AMS Institute and MIT.

Where most of the previous projects were focussed around developing a vessel which has to operate in the current environment. Does the smart shipping challenge (SMASH) focus 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 intelligent exchange of information and the optimization 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 the fuel consumption. This will not only be acquired by improving the hull shape and machinery, but also by sailing smarter. For example by optimizing the speed, based on opening times for bridges and availability of the quay [SMASH(2017)].

A future project from the Netherlands is a joint industry project, under the name Sovereign. The research conducted on communication and decision making will support the final result

Figure 1.3: Render of Electric Blue

Figure 1.4: Render of Yara Birkeland

of this project via Damen Shipyards and the Technical University of Delft. In this project did European companies, research institutes and the Technical University of Delft partner to develop a technology to deal with difficult environments and complex transport missions, within short sea and port traffic situations. Which is also applicable to other autonomous waterborne operations, such as inland waterways transport and coastal/inter-island short range ferry services. This should result in a ship for the shipping company Amasus.

Based on the above mentioned projects, 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 extra actuator in dynamic positioning systems.

1.3 Stakeholders

When these ships will sail, does not only dependent on the rate in which the technology can be developed. But there are also regulatory bodies, such as International Maritime Organization (IMO) and classification societies which need to incorporate autonomous vessels in their frameworks. The exploratory projects are very important, as this will help them to prioritize 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 the 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, which could be used for unmanned vessel. For example using computer vision, protocols for classifying systems and connecting ships.

The last, but probably most important are the customers, as a technology will only be used if you can make money with it. More and more companies are convinced this is possible. This 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 above mentioned projects it is clear that many project work on different challenges. All challenges are related to the safe operation of unmanned vessels, while optimizing profit. One of the most critical cases is when manned and unmanned vessels meet, in those cases is often ship-to-ship communication needed. Many of the projects so far, try to avoid these situations. As technologies for communication are costly to develop, is the aim to avoid communication when possible. To accomplish this, the first step is to adjust the operational strategies for unmanned ships to avoid complex situations. This means a strategy should be developed on how these ships can avoid communication. The most easy way is to operate only in area's where all risks are known. But to enable a ship to operate everywhere, the best solution is to avoid the need for communication, by taking decisions well in advance and to make intentions clear. Still some challenges are open, as not all complex situations can be avoided. 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. This is based on challenges from above mentioned projects and current research, where a decision model is used as stepping stone.

2 | Decision model

In the previous chapter, several projects are discussed, which gave insight in the challenges towards unmanned and autonomous shipping. Using a model for decision making, this challenge can be tackled in a structured way. This model shows which factors influence the decision-making process and how this is supported by relevant research.

The decision process within the model is based on Boyd's OODA loop, Endsley model for situational awareness, 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. In figure 2.1 a visual of the decision model is shown. The first step describes what can be observed, to form a mental model. The next step is to orient, in which the situation and hazards are identified. This will result in a set of strategies, which will be evaluated using different criteria, resulting in a decision. After this decision, an action is executed. This chapter will discuss these phases in more detail and how they relate to external factors and relevant theory.

2.1 Decision process

The decision process is the core of this model. The decision process will be used in part II on a less abstract level than described in this chapter. The steps taken in this decision process are similar for manned and unmanned vessels. Although their way of thinking differs 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 own acts and their consequences. To make this representation sensor data about the environment is used. This raw data must be interpreted, to become information which can be combined into knowledge. These steps require still 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 manned vessel, to form a correct mental model. For this research, only the result of this step is relevant: Is the acquired knowledge sufficient

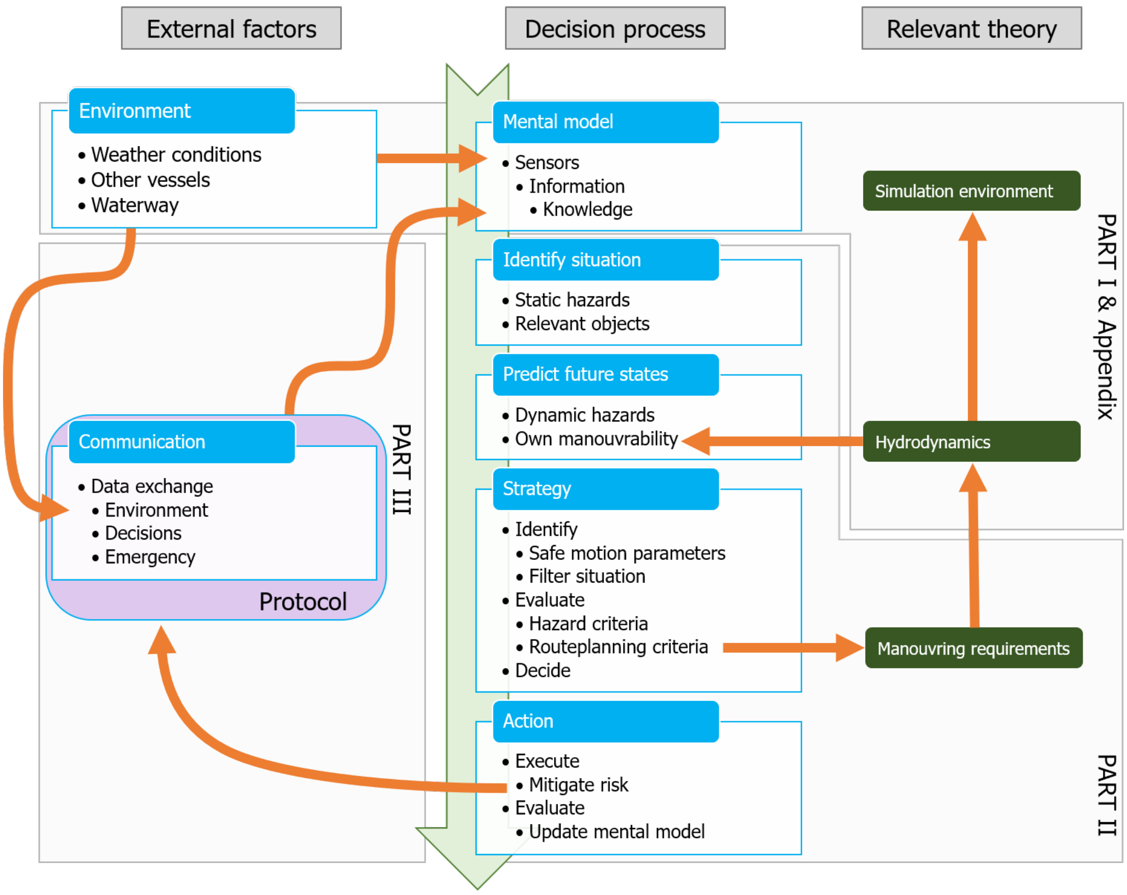


Figure 2.1: Decision model

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 can be combined into 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 is taken to identify critical situations which should be evaluated during the design phase of an autonomous ship. This research will define a method to evaluate these critical situations. The situation and scenario are defined by the layout of the waterway, other nearby vessels, relevant regulations, etc.

Predict future states and decide on strategy

Based on the situation different strategies might be possible. These strategies have to be evaluated. This is done by predicting how the different strategies will influence the path of the different 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 linearized algorithms in common ARPA systems. Using non-linearized methods with 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 linearized and non-linearized methods are described. The simulation is done with the tool as described in appendix B, but this tool is not optimized for such calculations. Therefore will it not be able to do these calculations in real-time. The hydrodynamic model used in the simulation also described in appendix B.2.3. After this phase different manoeuvers are evaluated which corresponds to the different strategies. How this will be done for common critical strategies is discussed in chapter 6, 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. The situation is mostly influenced by environmental factors. In some cases are the static sensors not sufficient to analyze 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

As discussed before, is the mental model mostly a representation of the environment in which the vessel acts. The sensors will measure this environment. Many critical situations occurred due to weather conditions. The reason is that the sight is limited during heavy rain or snow. Also might the wind and waves limit the manoeuvring capabilities of a vessel. This is also the reason some vessels are not allowed to enter a port when winds are too high. This is mostly due to the layout of the waterway. Due to currents, operations (e.g. maintenance and fishery) or limited depth, might some area's be restricted. This information is often acquired via communication channels, but communication channels which only allow receiving and not sending, such as Navigational text Messages (Navtex). The same goes for basic 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 could have worse performance, as heavy rain creates noise at the radar. In the situations where sensors do not function as expected. Communication is needed, even if whole decision process itself is optimized to avoid communication. The same goes for communication with shore-based stations such as traffic controllers or in the future remote pilots. These often have information which could not be retrieved via sensors or current systems. Such as a place and time to berth or pick-up a pilot.

2.2.2 Communication

As described are there still cases in which communication is necessary. In part III the case where communication between manned and unmanned vessel is needed is discussed. 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 Standard Maritime Communication Phrases (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

Effect of manoeuvrability on decision making

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 the model, as shown in 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 passing distance which does not require communication?*

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

More detailed descriptions of the different phases within the decision-making process are discussed in the next chapters. First the identification of the situation and scenario is discussed in chapter 4. Which branch to take in the decision trees, is determined by evaluating criteria. These criteria determine if there are hazards and which manoeuvers are feasible. This works in two ways: While sailing these criteria can be used to determine the right strategy. While a ship designer can use these criteria to ensure a ship can sail safely in specific situations. The criteria to evaluate what kind of problem there is, are described in chapter 5. The criteria used to evaluate if strategies are feasible for critical situations are described in chapter 6. In chapter 6 is also described how designers can use these manoeuvers to determine the manoeuvring requirements for safe operation. To evaluate if these criteria are useful, manoeuvers are simulated with the tool as described in appendix B. These are also used to test several scenarios and see how these criteria affect the decision-making process.

The result of this part is a design matrix which can be used by designers to determine the effect of manoeuvring capabilities on the moment decisions have to be made. This is done for some specific manoeuvers, showing the minimal time and distance needed to make decisions in order to have a safe distance between vessels. This matrix depends on the manoeuvring characteristics, speed and type of manoeuvrer.

3 | Decision making process

A rule-based time-domain decision model is used, to acquire more insight into the decision-making process. Using this can be answered what the situation is, and what problems might occur. This is done in a structured way by using a decision tree. Where the nodes are described with tags. This generalized model can be optimized in later stages to create a fully functional decision algorithm for autonomous and unmanned ships. Using advanced modeling techniques and machine learning algorithms. 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. The aim of this decision model is to gain insight into the decision process. To show 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.

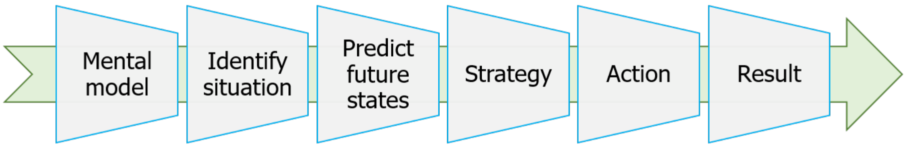


Figure 3.1: Decision process

Class	Description
Mental model	Acquire knowledge about the situation, not within the scope of this research
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

To describe the nodes within the decision trees, short keywords are used. These describe in short what kind of situation, problem, strategy, action or result there is. By using the same terms, confusion is avoided. Definitions for those terms are given in this section.

Encountered situations

This 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 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

To identify if a problem will occur, different criteria are being evaluated. 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 prediction of future states. A limited number of strategies might be possible. The strategies will result in actions, but can be categorized in the groups as described in table 3.4. The possible actions per strategy are shown. To determine if an action is necessary and possible, the distance and time which is left to avoid a problem are evaluated. 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 chosen strategy, actions will follow. These action are a combination of an action type, and a moment to execute 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, can the chosen action 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 safety domain as described by Coldwell is used [Coldwell(1983)]. This domain is based on an ellipse, which is not centered at the location of the vessel, as shown in figure 3.2. This 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.

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 combing the nodes as described in the previous section, very large decision trees are obtained. The decision tree for specific situations and scenarios is much smaller, than a tree covering all possibilities. Although a generalized model of the tree can be drawn, based on the previously described nodes. This model is shown in figure 3.3. Where the orange blocks show evaluation criteria and the white blocks are choices. Thereby should be considered that the actions are evaluated in a similar manner compared to predicting future states.

When all possible paths are considered, this will result in a very big decision tree. Which does not result in more insight in the critical paths. Using identification and evaluation criteria several common critical paths can be identified . These paths will be identified and evaluated in the next chapters.

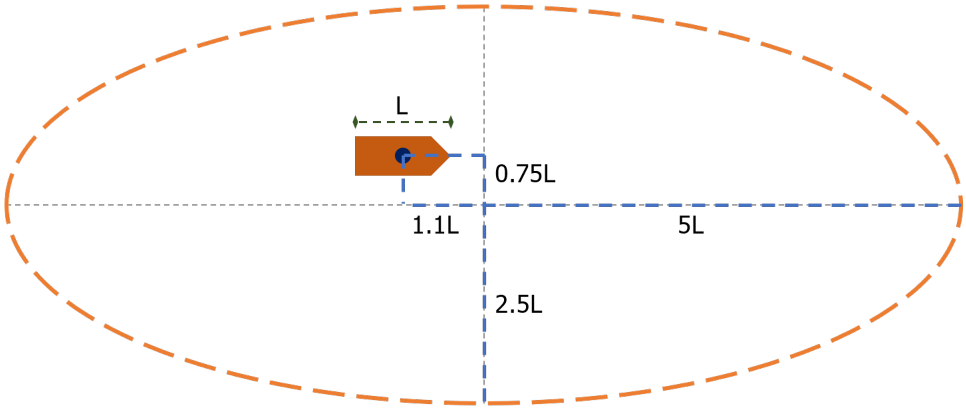


Figure 3.2: Model for safety domain by Coldwell

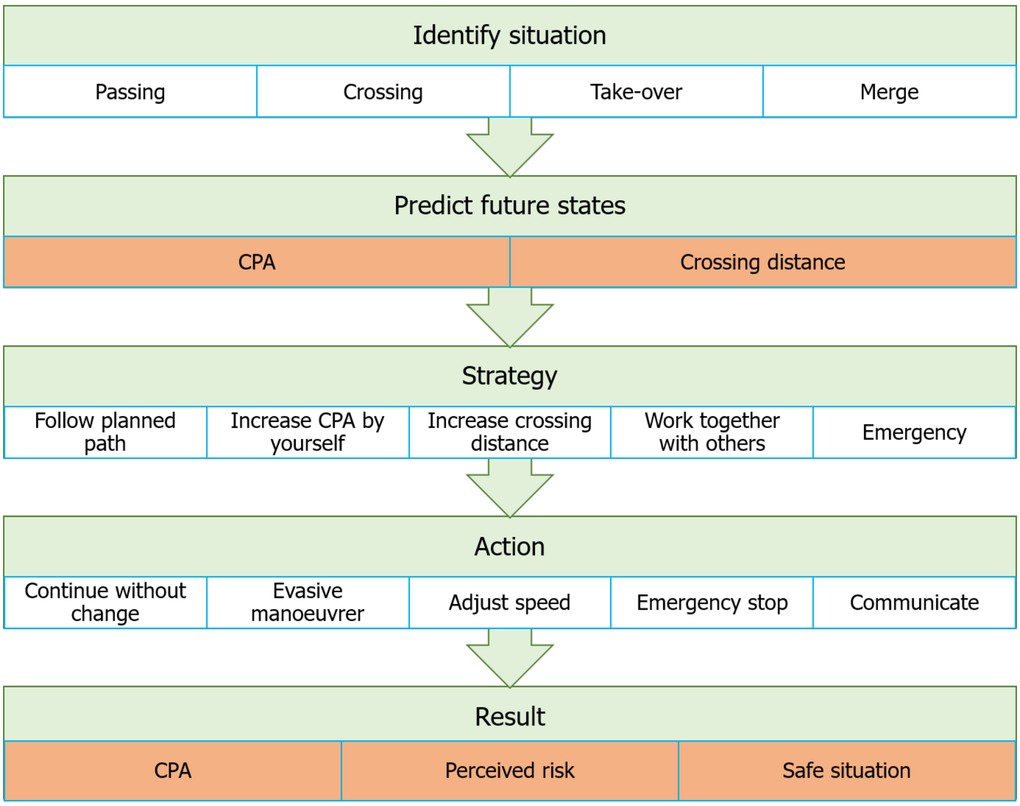


Figure 3.3: Generalized model for decision tree

4 | Identification of situation and scenarios

The start of the decision tree as described in chapter 3, is the identification of the situation and scenario. This identification 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. Which 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 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. This can be influenced by traffic separation schemes, forbidden zones or land masses. To determine the situation, a classification of paths is used. To do this systematically, paths will be based on figure 4.1 and can be written as: [current position, direction].

To classify a situation where two vessels encounter each other, the paths are considered. Key is to determine the angle between those paths. This way it is possible to classify them 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. Which 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 color of the light will be white. When in doubt if 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

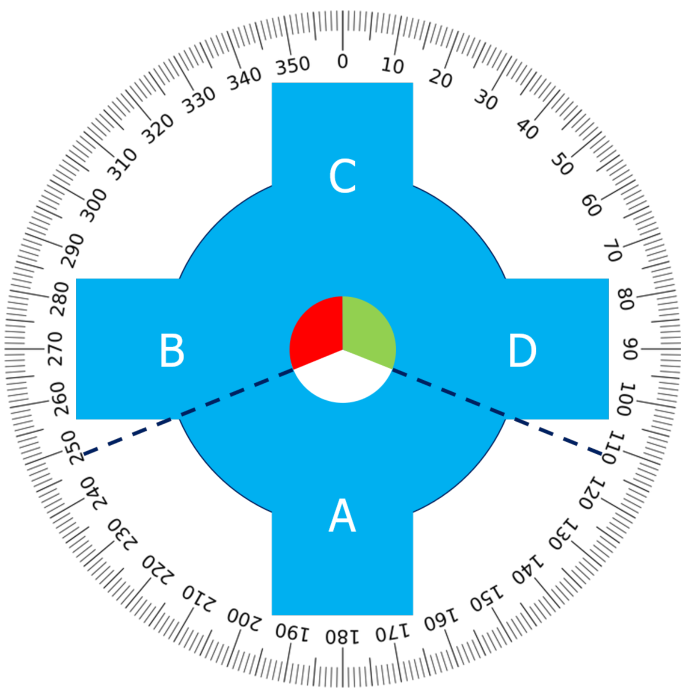


Figure 4.1: Path description for situation identification

4.2 Situations which limit possible strategies

Beside this first identification of the situation. More details must be taken into account to eventually form the right strategies, 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 which have to be evaluated, are strategies filtered based on the physical properties of the waterway. As this might restrict the area where can be sailed, or does behavior differ. For example is it common to over-take ships in open-water on starboard side. While on restricted waterways ships will sail as far as possible to starboard already. Which means that the ship which is over-taking will have to pass on the port side of the other vessel, at the center of the waterway.

In the next step other static hazards are considered to check if 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. Examples of static hazards which could be evaluated in future iterations are buoys, forbidden zones, bridges, quays, port mouths or shallow waters. As possibilities for over-taking or evasive manoeuvers are limited in those cases for example. This means the strategies are limited.

Another limiting factor related to waterways are the difference in regulations between waterways. Most obvious 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 manoeuvrer. Or more directive signs on obligated directions or speed limits. This is 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, which come close. But in future developments of the decision model, objects which 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 are of course that the 'forbidden zone' around these objects change over time. This means more complex evaluation methods are needed to determine if there is no perceived risk, and thus a safe situation.

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. Thereby might it be possible in future developments to take into account the human factor to improve the path prediction. This could be based on the experience of the crew, availability of a pilot or if the vessel is completely unmanned.

Examples of such dynamic objects which limit the possible strategies, are for example: 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

Using the information about the properties of the waterway and actors, the scenario can be identified. Where the situation is based on observations and describes the current state. Do 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 their implications are on the possible strategies. The same goes for the estimated path of dynamic objects. This might also narrow down the possible strategies.

Using the above mentioned information in the decision model, the strategies can be narrowed down. This 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 does a probability exist. Using a probability index for the decision of other vessels will in this case improve the eventual decision making. This can be taken into account by for example 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 if a problem might occur. These criteria are eventually used to determine the most critical common situations.

5 | Definition of criteria

The second step of the decision process was to identify the situation and scenario. In order to determine if a problem might occur in those situations or scenarios, different criteria are evaluated. Most of these criteria are already calculated by the current systems, such as ECDIS and ARPA. However, do they use linearized algorithms. These do not predict the CPA and crossing distance correctly while turning, often resulting in many dismissed alarms. The description of different criteria is given, followed by the calculation needed to evaluate them. This is done for both the linearized algorithms and proposed algorithms. Later in the process, these criteria can be used again. To ensure that the chosen strategies ensures 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 linearized algorithms, which results are not correct when turning. The false alarms given due to these wrong results can be easily dismissed by humans, but computers do not always handle 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 (CPA)

The CPA refers to the positions at which two dynamically moving objects reach their closest possible distance. This is an important calculation for collision avoidance. The linearized form uses two points moving at fixed speed and fixed direction. An example is shown in figure 5.1. Where P and Q are the moving points, with corresponding direction vectors u and v, which include the speed and direction.

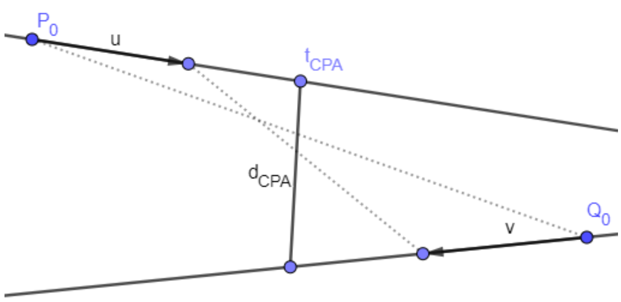


Figure 5.1: Example for closest point of approach (CPA)

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 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. This 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:

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

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

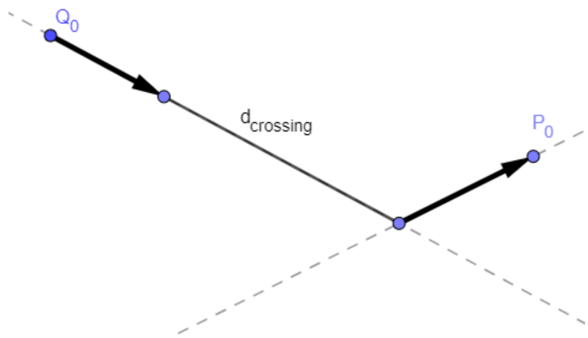


Figure 5.2: Example for crossing point and distance

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

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

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

To improve the evaluation of criteria, better non-linearized methods are necessary for the calculation of the CPA and crossing point. By predicting the likely path of a vessel, better estimations can be made. Which first uses a first order change, based on rate of turn and course. This 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 needed, while also introducing uncertainty with the numerical solver. The first step will be to make a combination of both the linearized and non-linearized methods. The calculations have to be done for every combination of ships.

The Bézier curve is used to describe the paths in a non-linearized manner. The definition of a Bézier curve is first given. 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-linearized manner.

5.2.1 Bézier curve

The first iteration of the algorithm is semi-linearized. Where the path of own ship is represented by a Bézier curve, based on its waypoints and strategy. To describe the Bézier curve, points have to be fitted along the planned path. This is similar to the method as described by Taams [Taams(2018)]. While the path prediction for the other ship is still linearized, as not enough information on the strategy and waypoints is known without introducing new systems and protocols.

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:

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

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

5.2.2 closest point of approach (CPA)

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 the linearized 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 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
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 path 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.

In the next chapter criteria will be described which depend on the manoeuvrability characteristics of a ship. Using the calculations for CPA and crossing distance, it can be determined if the chosen strategy without communication will result in safe operation.

6 | Dependence of decision domain on manoeuvrability

Add to all graphs units!

The criteria as described in the previous chapter are aimed to determine if there is a problem. In case there is a problem. Different actions can be undertaken to mitigate the risk. To determine which manoeuvers are feasible, different criteria are used. As the simulation of all possible manoeuvers can't be done in real-time due to its complexity. Can a look-up table be used. This look-up table has matrices for different manoeuvers 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). To make these matrices, simulations are performed for different ships and scenarios. In this chapter is described which manoeuvers are critical and will be tested in the simulation environment. The information gathered about the manoeuvers can be used to fill the matrices and determine if an action is possible. Thus in this chapter is information gathered about the time and distance needed for a manoeuvrer. Followed by an evaluation of the impact that the manoeuvrer has on the CPA.

6.1 Manoeuvrer descriptions

Strategies often result in actions which can be categorized in different types of manoeuvers. Most common to avoid critical situations, are evasive manoeuvers. The time needed to do an evasive manoeuvers, depends on the way it is executed and the manoeuvring characteristics of the ship. To ensure that the results from simulations are correct. Are manoeuvers used which are also used in sea-trials. These manoeuvers are used to validate if the manoeuvrability of a vessel is similar to the real-life situation. Examples of these manoeuvers are the zig-zag test and turning circle test. In this section the manoeuvers from sea-trials and the evasive manoeuvrer are described.

6.1.1 Sea-trial

Manoeuvring capabilities of a ship are determined during the sea-trials. Using the same manoeuvring tests and metrics as currently used by ship designers, will ensure that the results of other tests are reliable. Different tests are performed to ensure the vessel complies with regulations and its contract on manoeuvring capability. The manoeuvers used to determine this, are the turning circle and zig-zag test. In this section these will be described. The resulting metrics are discussed section 6.2. These metrics can be 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 manoeuvrer

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, till the ship has turned 90 degrees. The tactical diameter, which is the distance between the starting point and maximum distance the ship traveled 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.

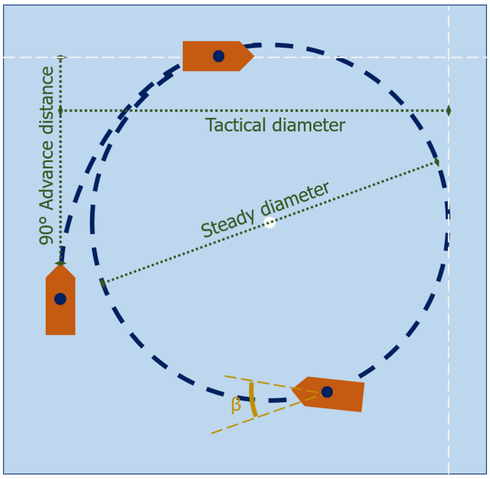
Zig-zag test

The second test is the zig-zag test. Herein is the initial turning time, yaw checking time and overshoot tested. This is done by putting the rudder at an angle of 10 or 20 degrees to port side, till the course change is also 10 or 20 degrees, than the rudder is changed to starboard side. This is repeated several times to get a good measurement of the overshoot. The overshoot is determined by measuring the course changes. In figure 6.2 the zig-zag test is shown. In figure 6.2b the rudder, course and heading changes are shown during a zig-zag test, together with the effect on the speed, acceleration and drift angle (β). 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 desired course change (10 or 20 degrees). The larger the overshoot, the better the yaw checking ability, but this will result in a lower path changing-ability.

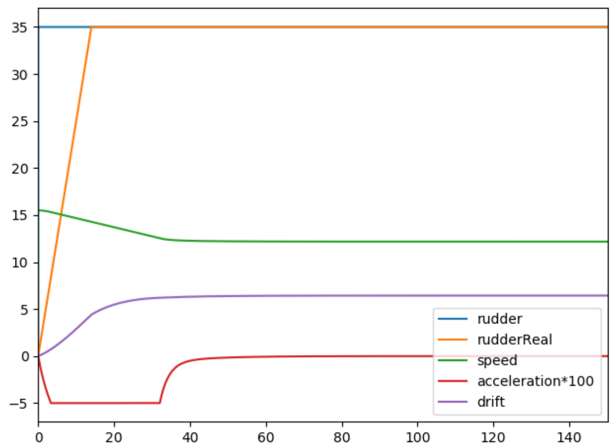
Show overshoot and remove irrelevant lines in figure

6.1.2 Critical evasive manoeuvrer

The critical evasive manoeuvrer 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

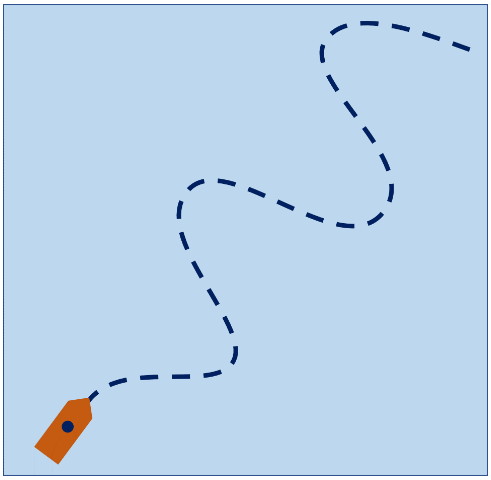


(a) Illustrative path

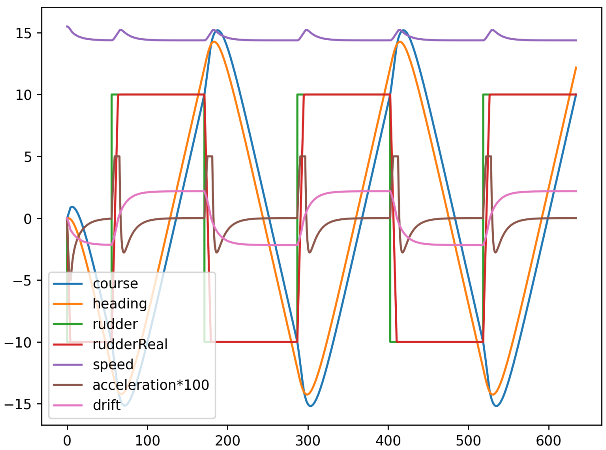


(b) 15kn with 140m cargoship

Figure 6.1: Turning circle test



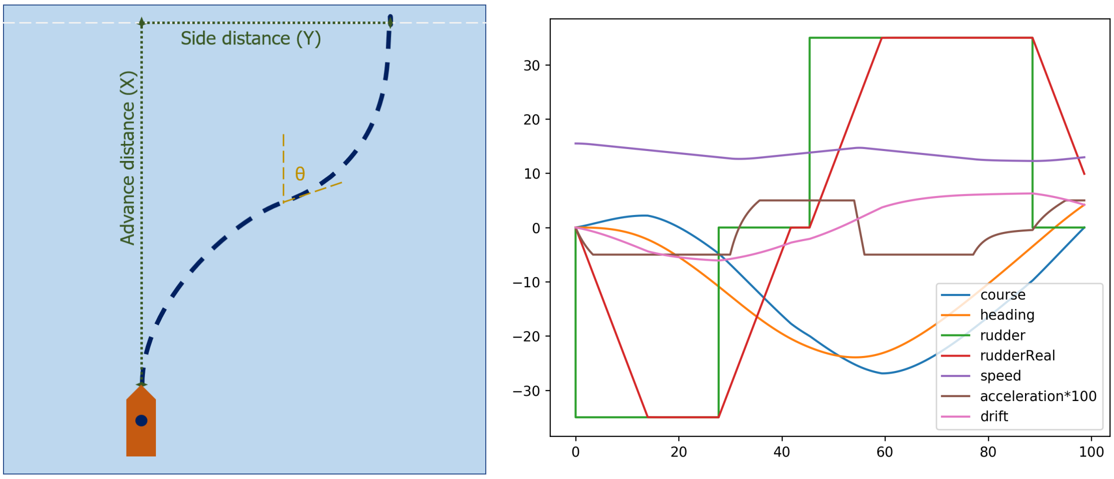
(a) Illustrative path



(b) Zig-zag 10:10 test at 15kn with 140m cargoship

Figure 6.2: Zig-zag test

vessel is supposed to keep course and speed the same, while the give-way vessel is supposed to manoeuvrer. There are many ways an evasive manoeuvrer can be done. However, the most critical situation is when maximum rudder is given to avoid another ship which has a perpendicular course. Thereby is te aim of the give-away vessel to end the manoeuvrer with the same course as it started with. In figure 6.3 an example of such manoeuvrer is shown for the give-way vessel. Figure 6.3b shows how the rudder is used during the evasive manoeuvrer. Also can be seen that the speed reduces, mostly due to the drift angle. The manoeuvrer is simulated for different speeds and with different maximum course changes.



(a) Illustrative path

(b) 20 degrees at 15kn with 140m cargoship

Figure 6.3: Evasive manoeuvrer

6.2 Tool validation

To validate if the results will be as expected, the same manoeuvers as in sea-trails are used. Thereby are different input settings tested to for the evasive manoeuvrer, to improve the final result. These manoeuvers are described in the previous section. This section will discuss the validation of the tool as discussed in appendix B. This is first done for the used hydrodynamic model. And than for the evasive manoeuvrer which will be used to determine the dependence of decision domain on manoeuvrability.

6.2.1 Validation of hydrodynamic model

The hydrodynamic model which is used is described in section B.2.3 and the paper by Artyszuk [Artyszuk(2016)]. 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 will give ranges in which the metrics from the sea-trials can be expected. By using the same vessels and manoeuvers as are stored in the database, the quality of the hydrodynamic model can be validated. This validation is done by comparing the resulting metrics from the simulation model to expected metrics, which 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, if the input characteristics result in behavior which can be expected. For example should a tug 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 on the quality of the model. The model is accepted when the results of these tests are close to the expected results. As not all input coefficients have been optimized for each ship to behave as realistic as possible. The optimization 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 change of course at 10 degrees and for 10 degrees of rudder. The turning circle test starts by giving the maximum amount of rudder. Both test start when sailing at design speed. For the small tug boat the results are not within the expected range. The overshoot and advance distance lare for the other vessels within the expected range.

The tactical diameter is however relatively too large. This larger difference between expected results and simulation results is seen more often [Tjøswold(2012)]. This has been identified as an error with non-linear damping. The critical evasive manoeuvrer 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 manoeuvrer, it should be considered that the model works better for larger cargo vessels and manoeuvers 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 manoeuvrer

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

1. Start of manoeuvrer. 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.

This will result in a manoeuvrer which 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. Everything is known except the "few seconds". This will be further referred to as "change time". Thereby does the initial direction depend on the location of the crossing vessel. How the initial rudder direction should be, depends on the location and direction of the other vessel. This is shown in figure 6.4. In order improve the CPA, you should steer away from the others path. This 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. Where the orange cross shows the initial collision location. The change time is determined using different tests, these are described in appendix B.2.4. Based on these tests is chosen to set the change-time to 18 seconds.

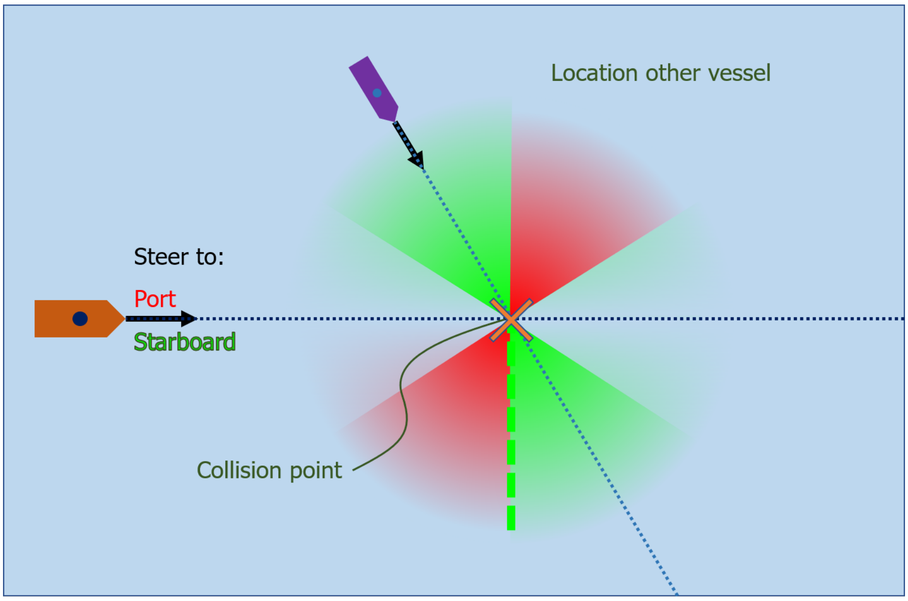


Figure 6.4: Direction for evasive manoeuvrer in crossing situation

6.3 Trial results

During the tests as described in section 6.1, different results can be acquired. Using the simulation tool as described in appendix B different criteria can be evaluated, such as CPA and crossing distance. The primary input for these results depend on the ship manoeuvrability and starting speed of the vessel. To eventually calculate the closest point of approach and passing distance, the speed of the other vessel and crossing angle should be taken into account. To evaluate the above mentioned criteria, are the metrics acquired as described in table 6.2 and shown in figure 6.3a.

Metric	Description
Time needed for manoeuvrer	Time from first rudder, till ship returned to original course
Advance distance (X)	Distance traveled forward in direction of original course
Side distance (Y)	Distance traveled perpendicular to original course
Extra time	Time needed for manoeuvrer, minus the time it would have taken to travel the same distance forward
Extra passing distance	Adding the distance to the side to the extra time times the speed of the other vessel

Table 6.2: Metrics for evasive manoeuvrer

When two ships are parallel, the situation becomes a head-on or take-over situation. Which is less critical and more easy to solve than a crossing situation. To get into one of these situations from a crossing situation, the ship has alter its course. In the case of a crossing angle of 90 degrees, the ship has to turn the most. As can also be deducted from figure 6.4. Therefore is the used crossing angle during the tests for the critical evasive manoeuvrer: 90 degrees. As this is the most critical crossing angle.

Due to the perpendicular approach the passing distance becomes most relevant. As this can also be used to calculate the increase in CPA, in the case where the CPA is not sufficient, but there is not risk for collision. This can be easily calculated by adding the distance to the side, to the speed of the other vessel times the extra time needed for the manoeuvrer. For the speed of the other vessel is in this case 12 knots. As this is a minimal speed, that most large cargo vessels sail at open sea.

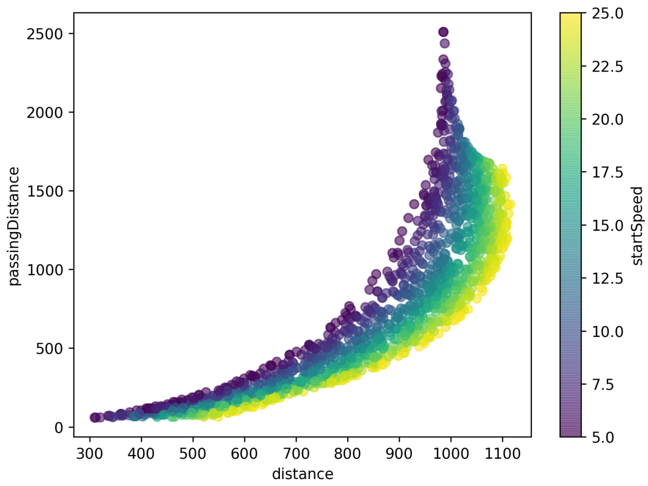
Results of trials showing the dependency of passing distance on distance till crossing point and starting speed are shown in figure 6.5. As can be seen does there exist an asymptote at a distance for every ship and speed. This distance is equal to the distance needed to turn 90 degrees. As in this case the ship can sail parallel to the course of the other vessel. Therefor no simulations are done for these distances. Only the minimal distance till a possible problem is needed, which results in a passing distance.

Update images with new run

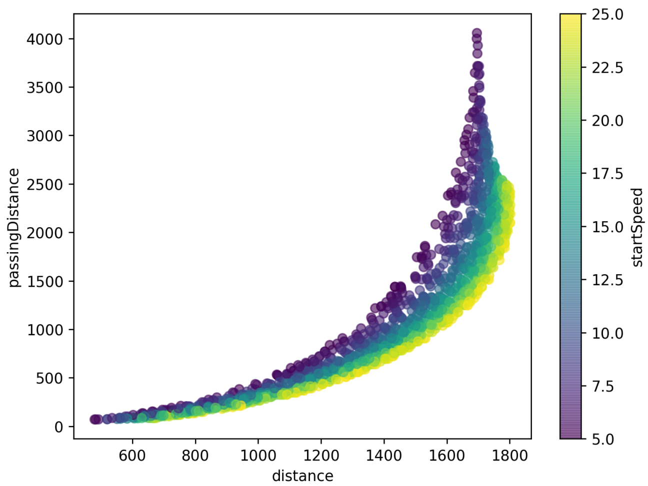
Explain some of the points in results

Update names on axis (distance till crossing point)

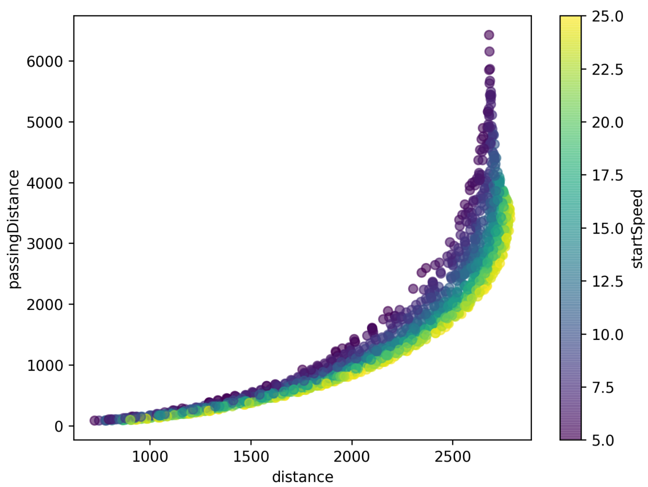
e.g: if I want to pass the other ship at at least 2500 meters while sailing very slowly, I need to start my manoeuvrer at least 970 m before I would have reached the CPA?' and At 25 knots, I need to respond at least 550m before CPA if I want to avoid a collision. Next step is to check if due to small bandwith some lines can be drawn trough



(a) Astrorunner (140m cargoship)



(b) Gulf Valour (250m tanker)



(c) Emma Maersk (400m containership)

Figure 6.5: Dependency of passing distance on distance till CPA and current speed

7 | Result

Summarize results of verification and validation and if it can be used in the next step. Thereby also explaining which strategies could be communicated to pilots, seafarers and traffic controllers. To make shipping safer. But on the other hand also show where it lacks support.

7.1 Improvement CPA using manoeuvrability characteristics

Describe how CPA can be improved

7.2 Examples of resulting design matrix

Proefvaarten met schepen om draaicirkel en zigzag te bepalen.
Van schepen is bekend hoeveel tijd en afstand kan worden gewonnen met welke manouvre.
Dit combineren kan worden gebruikt tijdens scheepsontwerp.

Give example of resulting design matrix

7.3 Lessons learned

The model developed in this part will start with a sensory information on a situation, it will classify this situation and make a decision based on the evaluation of criteria. The result is an advise to execute a specific strategy, or if the model can't evaluate criteria sufficiently a subset of possible strategies and the remark it needs more information to narrow it down further.

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

Answer research question

Part III

Necessity of a protocol to enable teamwork 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]

In the previous part a decision model is described which tries to avoid communication between vessels by taking the right decision at the right moment to ensure safe operation. However this is not always possible. 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 is used to acquire the missing information or discuss strategies with other ships. This is likely also necessary when unmanned vessel operate between manned vessel. In this part the development process of such a protocol is discussed and the relevance will be proved using an experiment, answering 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 and/or receipt of a message. Where it is most straight forward to use verbal communication, will it 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 currently happens between vessels is most common when COLREGs do not result in clear strategies, or when intentions are not clear. Other communication which will not be within the scope of this research, such as the communication with traffic controllers and how conversations are interpreted by other vessels. Thus this research is a starting point to develop a full protocol needed for the acceptance of unmanned vessels.

Using the situated Cognitive Engineering (sCE) method, this protocol can be developed using an iterative process, where a requirement baseline is continuously refined by reviews and prototype evaluations. How to apply sCE is described by Neerincx and Linderberg [Neerincx and Linderberg(2012].

The first step is to create a foundation. The current situation of the problem is discussed, which have to be solved. Thereby considering existing knowledge which might be relevant to solve the problem and finally in short the envisioned technology. The next step is to define the system design specification. In which scenarios are described which 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 which is being evaluated to make improvements in next iterative steps.

8 | 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.

8.1 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 and their characteristics, and the problem description and analysis thereof.

8.1.1 Problem scenario

Convention on the International Regulations for Preventing Collisions at Sea (COLREGs) have been developed long before bridge-to-bridge voice communications became available. They are supposed to be unambigious. It is the responsibility of all bridge watch keepers to know how to apply them instinctively, on the basis of observation primarily by sight and radar. They work effectively when ships in an interaction obey them; they also specifically address circumstances where one ship does not.

However, as shown in the previous parts, are COLREGs not always sufficient to decide on the right strategy. For example due to missing information. This happens already more often due to larger ship, more complex manoeuvers and more traffic. In those cases the VHF radio can be used for verbal bridge-to-bridge communication. Leading here are the Standard Maritime Communication Phrases (SMCP). The primary task of this 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.

Reasons for safety related verbal communication are: when you will deviate from the rules, deviant behavior is registered, or more information is needed to decide on the right strategy. This is often necessary due to lack of visual information. For example due to bad weather, obstacles like bridges and terminals, or the information received via Automatic Identification System (AIS) is not reliable. This does not only impact the information you get by looking out of the window, but also the quality of the Electronic Chart Display Information System (ECDIS) and Automatic Radar Plotting Aid (ARPA) is worse.

When using SMCP, marker words are used to introduce the content and purpose of the communication. In appendix A.1.4 the SMCP are described in more detail. Examples for all marker words are given 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.

After this message there is a confirmation that the message is received, followed by a repetition of the send message, or an answer to the question. Indicated with the corresponding marker word.

The different ways for communication are not developed to be used by unmanned vessels. On the other hand, is it not feasible to require all manned vessel 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.

When using the current systems in a way they are not designed for. This might result in misunderstanding and problems with communication. Due to for example information overload of the crew and communication channels. This can be caused by the way the VHF is designed. 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 send at the same time, both senders will not receive the others message.

8.1.2 Problem analysis

To avoid misunderstanding which could result in hazardous situations. It is important that manned and unmanned vessels are able to communicate. To solve this problem, a more extensive analysis is made. 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. This means the most important actors for unmanned and manned vessel are:

- Manned vessel
  - *Officer of watch*. He is the responsible person. He might work together with a helmsman and a lookout. He has to ensure a proper functioning of all available systems. Thereby does he discuss with other crew members if there are any unusual activities. He is responsible to follow a proper navigation plan, while having his own safe passage plan, to avoid collisions. He will use sight, Automatic Radar Plotting Aid (ARPA) and Electronic Chart Display Information System (ECDIS). Thereby is he 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. This is only possible when he stays concentrated, to acquire this, the tasks must be challenging and he needs to have a form of autonomy.
  - *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(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 it can acquire via all different means. Including newly developed communication protocols, computer vision and algorithms to transform sensory data to 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. However do not want to receive all discussions.

As this will result in an information overload.

Secondary actors

Beside the first group of actors, others could also be influenced by the new protocol. 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 traveling.
  - Shipowners of unmanned vessels, monitoring vessel from remote location.
- Not within 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. Such 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.

This means that manned vessels should be updated only when requested or in case of an unusual activity which could affect their strategy. And manned vessel should be aware when unmanned vessels desire more information to decide on the right strategy.

Using the same philosophy, it might be possible to develop a protocol for communication with traffic controllers in later iterations. This becomes more important when the time needed to develop a new systems for traffic controllers also takes too much time to develop and/or implement.

Infeasible solutions

The easiest solution for unmanned ships would be to just install a new system. This is however not feasible as mentioned before. To implement this, it would mean that all ships which could encounter an unmanned ship will have to install this too. It might be possible to make it obligatory via regulations, this will however cost a lot of time and money. Making the introduction of unmanned ships less likely. This is 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 are only possible when regulations are changed.

8.2 Human factors

When designing technology, there are two driving questions that need 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 is able to 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 emphasize 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 important 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 how to solve the problems that have been identified in the problem analysis. The key problems relevant for human factors are the information overload, situational awareness, autonomy, and learning a new protocol. Thus 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. Therefor the developed system should be context aware so it can limit this risk by adapting the message to the situation [Arimura et al.(2001].
  - Overload might appear due to a competition for the operator's attention that is going on between different information items. If many tasks are handled by automated systems, 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(2008)].
  - The information acquired at one particular 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 of information overloading. Admittedly it is plausible to deliver needed information for the coming task by task detection, the user might still fail to keep pace to the rapid changing system and fulfill multi-threaded tasks[Porathe et al.(2014].

- Which information is needed for situational awareness?
  - Understanding the current picture is not enough for full situational awareness. Expert decision makers must be able to project their understanding into the future. This enables them to make the decision they must take now to create the best options in the future. Projection requires to have good mental models of the dynamic relationships between the relevant parts of the environment over time. Expers focus a lot on creating their own futures via present decisions. In turn, these decisions are formed 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 of actively?
  - Attention profoundly modulate the activity of sensory systems and this can take place at many levels of processing. Imaging studies, in particular, 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 it is requested. 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 operationalize the quality of the intended behavior 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?
- Does the protocol act as expected?
- Will it solve the problem of missing information?
- 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 8.1.

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

Table 8.1: Interaction design patterns

8.3 Envisioned technology

The envisioned technology describes the available options of using existing technology and/or the need to develop novel technology in order to come to a system solution. The sCE method asks designers to specify what devices (hardware) and software could be used 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 particular type of technology.

The envisioned technology will use only existing systems to develop a no-UI. Different systems which are currently used, are described in appendix A. Below different systems and protocols are mentioned which can be used in the new protocol. Using these already existing systems will shorten the development, learning and implementation time. The used systems, equipment and protocols are given in table 8.2.

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 8.2: Envisioned technology

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

The type and amount of information presented to users must be tailored to the unique situation in which the information is to be used. 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]. Therefor it is beneficial for the cooperation between manned and unmanned vessels to clearly show if it is an unmanned vessel. This will firstly be done using visible signals, and also at the start of radio communication. This also happens in industry projects such as Google Duplex [Nieva(2018)].

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

9 | System design specification

Make sure that this chapter describes how a good protocol looks like

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.

9.1 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 contextualized view on:

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

Manned ships are able to understand intentions of unmanned ships, resulting in good situational awareness. In cases they desire more information, they are able to acquire this using current systems. Without the risk for an 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 similar to the interaction with other manned ships. This resulted in acceptance of unmanned ships on the general waterways. Where the risk for collisions and perceived risk reduces, or at least does not increase.

Information extraction from problem scenario

In the previous chapter the problem is described which has to be solved with the envisioned technology. To solve the problem, the following issues have to be tackled:

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 above mentioned problems are tackled are shortly 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. 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 can be used.
2. The protocols which are currently used by the officer of watch are the same. The purpose is to make it more easy to get information. This means that the situational awareness will minimally be affected by the system on board of the manned vessel. Also here the current level of situational awareness can be used as a threshold.
3. By introducing an negotiating agent, decisions can be made in a similar manner to current ships. Using the decision tree it will have a favorite strategy, but it might be possible to use others if this is better for the encountered manned ship. This will ensure that the officer of watch at the manned ship, still has a feeling of autonomy, similar to that of the current situation.
4. Although the current systems are not designed to be used by unmanned vessels. Are there major developments on conversational agents in the last few years. This means that voice communication is starting to become more easy to develop. Certainly when considering that a lot of radio conversations are recorded. Thus it will be more easy to train the agent. Thereby must still be considered the importance of transparent communication. Thus also being open about being a robot.
5. 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 addressed messages are not often used at the moment. They will use the SMCP in a similar way to how it is currently used. So not much will change compared to the current situation for manned ships.

9.2 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 with each other in a given action sequence. Use cases make the design scenario more concrete by describing exactly how the 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 are: To give insight in all interactions during a common critical situation at sea. Tags are used to relate them to the situations and scenarios as described in chapter 3. By making it very specific, better insight is acquired in factors which should be taken into account when defining functional requirements.

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

Tags: Crossing, Move away from other, Evasive manoeuvrer 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. In which she will pass a 150 meter container ship (Reefer), sailing at 14 knots. The FCS2610 noticed the Reefer late and has to make an evasive manoeuvrer to pass in front of the Reefer with a distance of 900 meter or 0.5 Nautical mile. Which is just accepted according to the safety domains [Szlapczynski and Szlapczynska(2017b], using criteria from chapter 5. To ensure the Reefer understands the intentions of the FCS2610, communication is necessary. This will take place in the following manner:

- The AIS, masthead and flags are showing the vessel is sailing autonomously. This means there is no crew, but the autonomous systems listens 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.

9.3 Functional requirements and claims

In the sCE method, use cases are used to derive functional requirements and claims, i.e. specific functionalities the technology should provide to its user followed by the system's objectives, and the hypotheses to be tested during system evaluations. This is accomplished by annotating all functional requirements 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 a functionality that does not achieve its underlying claims. User stories are used to do this, these are usually in a from: "As an $\langle actor \rangle$, I want to $\langle what? \rangle$, so that $\langle why? \rangle$". Followed by an acceptance criteria, to determine when this part is correctly implemented.

Actors

The primary actors who will be taken into account in this first iteration are:

- Officer of watch
- Unmanned vessel
- Nearby vessel

User stories

- As an officer of watch, I want to know if there are unmanned ships in the area, so that I know if I have to adapt my way of communication. AIS shows if ship is manned, and what its status is.
- As an officer of watch, I want to validate if information received via AIS is correct, so that I can base my decision on correct information. When officer of watch asks unmanned ship via VHF, the answer should be reliable and based on current information.
- As an officer of watch, I want to make my intentions clear towards all other ships, so that they can anticipate to this. Shared intentions should be incorporated into the decision making process of unmanned ships.

- 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 the message, even if its not exactly 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 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 ship sails where and what the interactions could be in order to make the right decision.
- As an unmanned vessel, I want to validate if acquired information is correct, so that I can base my decision on correct information. Check via communication if digital model is correct.
- 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.

9.4 Ontology

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 they are categorized in status, messages and situations.

9.4.1 Status

By defining different states for the system, does the system know which functions and protocols should be executed. The different states are described below:

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 send 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.

9.4.2 Types of messages

Both in the messaging and negotiation states, will there be messages send. These messages form the conversation. In the different phases of the conversation, different messages will be send. These are described below:

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

Acknowledge Accept 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 conversation.

Close End conversation with greeting.

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

9.4.3 Situation

To make the link with the decision model and problem identification as described in part II. Will the protocol use the same identifiers for situations.

Passing The paths of both ships are in opposite direction, and do not cross.

Crossing The final direction of both ships differs, 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 differs, but the final direction is the same.

These situations are described in more detail in section 4.1, using path descriptions.

9.4.4 Design overview

Give overview of speech acts using SMCP cheatsheet. Add some pictures to make it more lively

10 | Design evaluation

Make sure that this chapter shows if this leads to the desired result

The last part of the sCE method is the design evaluation. The design evaluation aims to test and validate the system's design, or to discriminate between multiple design options, such that the current design can be improved upon in incremental development cycles. The sCE method describes three parts that are relevant with respect to the system evaluation: (1) the artefact, (2) the evaluation method, and (3) the evaluation results.

The artefact gives a short summary of the developed protocol and its workings, together with the tool in which it can be simulated. The evaluation method will be an experiment within a simulation environment where participants have to decide on the actions, followed by a questionaire related to this experiment. The participants are experienced seafarers. The aim of the interviews is 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. Key variables are: Trust, situation awareness, effectiveness, efficiency and satisfaction. In this chapter, these will be described in more detailed. Thereby is the aim of this chapter, to test if the protocol as described in chapter 9, will indeed result in more situational awareness, which results in safer navigation.

10.1 Artifact

Klopt het dat Artefact hier staat en klopt inhoud met artefact

The artifact is an implementation or prototype that incorporates a given set of requirements, interaction design patterns, and technological means. This first iteration will aim at finding flaws based on expert knowledge. To acquire this a simulation environment will be used. This means that there is no implementation using hardware which might be used in latter stages. The simulation environment is created to test situations with experts. Where is verified if experts believe that the protocol is sufficient to get to the right decision, as described in chapter 9.

To get the right feedback, several situations will be simulated. These situations are based on the accident reports as described in appendix C, common situations around the port of Rotterdam and cases used in literature. The situations are simulated and visualized using the tool as described in appendix B. This 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).

10.2 Evaluation method

The evaluation method can take many forms, such as a human-in-the-loop study, a use-case-based simulation, or an expert review. In this case a so-called Wizard of Oz evaluation is used. This technique enables unimplemented technology to be evaluated by using a human to simulate the response of a system. As the technology itself has not yet been implemented. The "wizard" simulates the system's responses in real-time. Using seafarers and the Wizard of Oz method, an expert evaluation can be acquired on the proposed system without implementing it.

10.2.1 Experiment set-up

To do the experiment, a participant is needed to have the role of Officer of Watch (OoW) and tools to execute. During the experiment there will be different variables, which have to be taken into account to be able to draw the right conclusions. These are described in this section.

Experiment design

Describe experiment design

meet niveau ratio, nominal –¿ this determines which statistics methods can be used `https://en.wikipedia.org/wiki/Level_of_measurement` Also information on the balance with participants, everybody the same

Participants

The participant is in this case the Officer of Watch (OoW). The experiment will be done with at least 10 different participants. The formal requirements are as follows:

- Nationality: Dutch, due to location of experiment.

- License: Completed training as a maritime officer.
- Experience: At least 3 years of experience as seafarer.
- Attitude towards autonomous shipping: Both positive and negative.
- Age: 25-60

The different participants will receive different scenarios of the same situation in different orders. Such that they are counter-balanced.

Tools

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

- Laptop with second screen to show simulation environment.
- Questionnaire to be used before, during an 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. The simulation environment is shown in figure 10.1. Where the map is shown on the left, which is updated regularly. The side-bar can be used to control the selected vessel. In the status-bar at the bottom of the screen, information is given on possible actions, errors and status of simulation.

Dependent variables

During the experiment different variables will be evaluated. These are based on the human factor measures as described in section 8.2. This will be a combination of both quantitative and qualitative measurements. Thus combining numerical values with non-numerical arguments. Using the variables can be concluded if the system acted as expected and will result in safe navigation when using existing protocols. The first variables relate to experiment:

Performance Simple evaluation if the participant acted correctly. Thus did he safely navigate the vessel by making the right decisions. For more detailed results, the closest point of approach (CPA) can be used. This shows that the protocol is prompt and thorough (effective), while also easy to understand and use (efficient). This is measured by evaluating criteria such as CPA and is checked if participants consciously chose the right strategy.

Trust The system acts not only out of self-interest, but in order to acquire a pareto-optimal solution. This means that the system is honest, approved by well-known institutions and ensure fairness. This is only possible when the system is able to communicate correctly, and others are confident that the system did indeed take the right decisions [Ozawa and Sripad(2013]. This is partly subjective, therefore a survey is used. Also is the amount of cooperation measured, which is based on interactions with the system .

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. This is measured by asking if the participants have noticed some changes in the simulation together with an observer rating system [Naderpour et al.(2016].

Satisfaction Pleased feeling, as the participant likes the way he acted and how the system works. As this is subjective, a survey is used.

10.2.2 Experiment task

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

More specific will he sail a vessel in different scenario's. It depends on the scenario how and if the participant can communicate with other vessels. He will do this by directing a vessel on a 2D-map as shown in the simulation environment. He will have access to the same information as any other bridge, also presented in a similar way, except for the visual 3D-view. But this lack of information is compensated by more reliability for the ECDIS and Radar. Within the experiment, tests will be done for different situations and scenarios. The resulting strategies are listed below.

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). This situation is shown in figure 10.2. The relevant information on these ships is given in table 10.1.

	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	m
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 10.1: Relevant information crossing at North-Sea

add names of quays and waterways to situation sketch

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 cargo vessel (ANGLIA SEAWAYS). This situation is shown in figure 10.3. The relevant information on these ships is given in table 10.2.

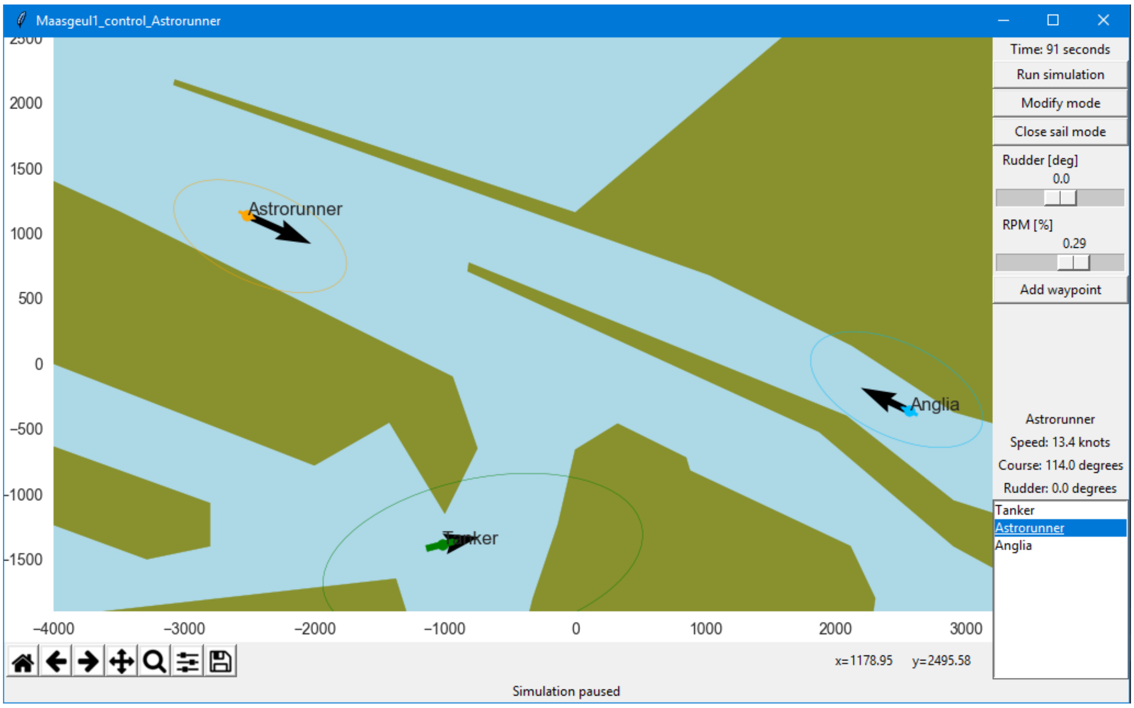


Figure 10.1: Simulation environment

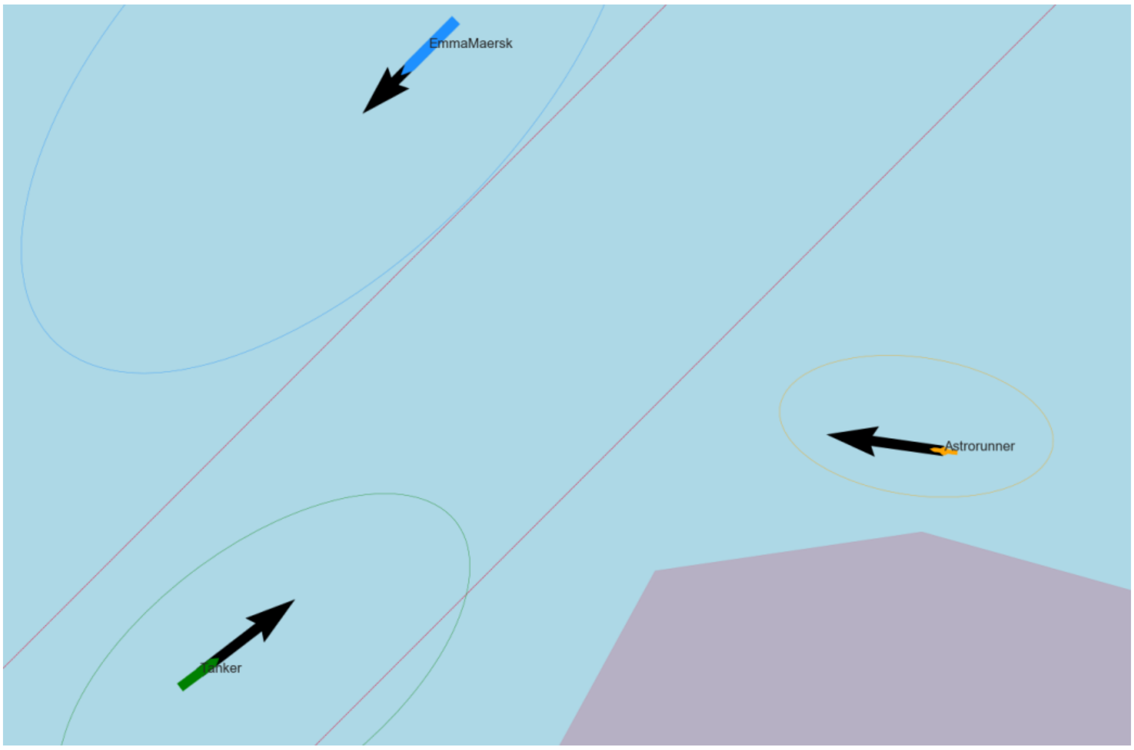


Figure 10.2: Situation sketch crossing situation North-Sea

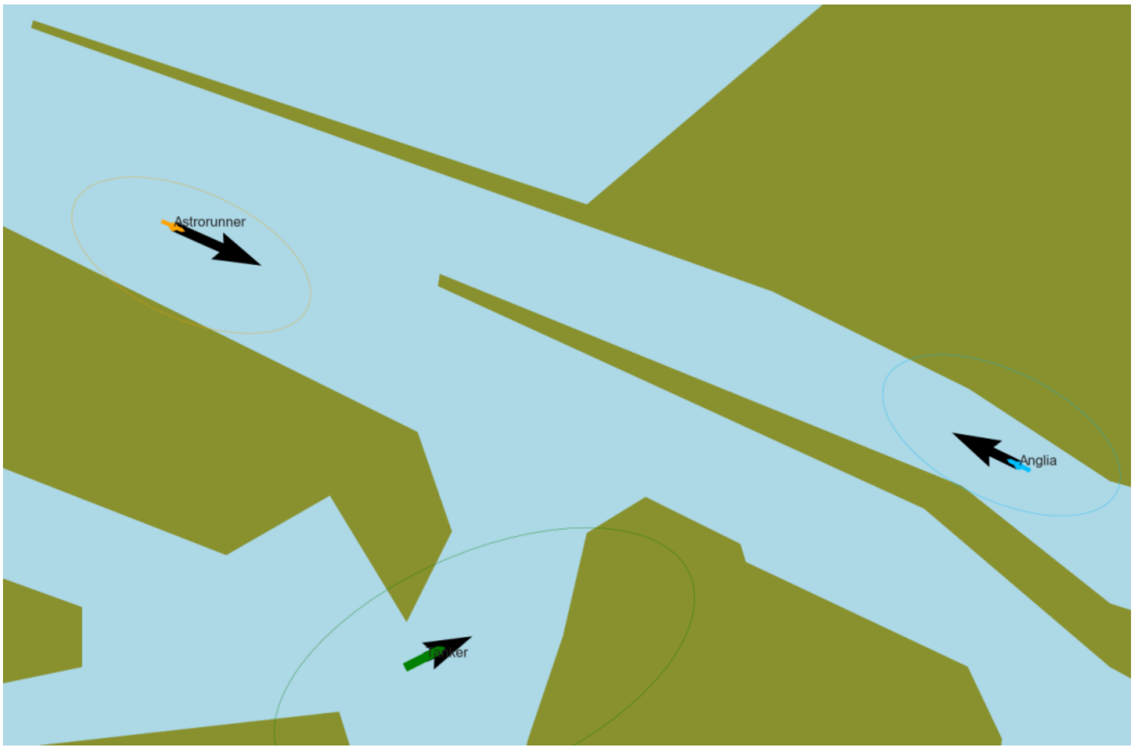


Figure 10.3: Situation sketch port of Rotterdam

	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	m
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 10.2: Relevant information entering Maasgeul

10.2.3 Experiment procedure

To execute the experiment. Several steps are taken together with the Officer of Watch (OoW):

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 situation to OoW in a similar way to common hand-over. Only describe relevant issues for navigational duties.
4. Start playing simulation.
5. Depending on the simulation, let autonomous ship take actions or wait for the OoW to engage in communication.
6. End simulation.
7. Question OoW why which decision was made.
8. Question OoW on several "what if"-scenarios and how that would have changed its actions.
9. Repeat step 3-7 for more situations.
10. Question OoW about advantages and challenges of protocol.
11. Question OoW about human factors.

The answers to the questions are collected using a Google form. This form includes the same questions as described below. The URL to the questionnaire is:

`https://goo.gl/forms/9U42QcKdW8VcBAAb2`

Explanation (1, 2)

The participant is not explicitly informed about the exact purpose of the research. It will however get a short introduction on how to use the simulation environment. This includes the commands it can give as an officer of watch. It should be easy to use, as similar action should be executed when operating a vessel. Thereby is some information about the participant acquired:

- Which licenses do you have?
- What is you experience?

- What do you expect from the developments towards autonomous shipping?
- What do you see as the biggest challenge for introducing autonomous and unmanned vessels?

Situations and scenarios (3, 4, 5, 6, 9)

The next steps are repeated several times for the different situations. The situations are described in section 10.2.2, thereby does it depend on the experiment order in which situation it is possible to communicate:

1. Crossing situation at Nort-Sea
2. Entering Maasgeul from Maasvlakte

Relevant questions for situation (7, 8, 9)

To gain insight into the quality of the experiment and effectiveness of the protocol, different questions will be asked. Here there is also a link with the decision model as described in section 2:

- What type of situation is this?
- Which criteria are relevant?
- Which strategy did you choose?
- Which actions were taken?
- 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 expected?
- Can you explain why?
- Would you have acted differently is you knew there was a human officer of watch?

General questions on protocol, autonomous shipping and human factors (10, 11, 12)

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:

- Do you expect to trust autonomous ships more, when they would pass the Turing test?
- Do you want to know if a ship is unmanned?
- Are ship's horns still used to communicate intended manoeuvers?
- Do you still use Standard Maritime Communication Phrases (SMCP) consciously?
- Is the protocol around SMCP easy to use?
- Is the protocol around SMCP easy to learn?
- Is the protocol around SMCP a good protocol?

10.3 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. Oftentimes 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, interaction design patterns were included in the artefact).

10.3.1 Outcomes

Describe outcome of experiment

10.3.2 Conclusions

Answer research question for CS

> *Are existing systems and protocols for communication, sufficient to ensure that manned and unmanned ships can operate side by side safely?*

Part IV

Wrap-up

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

– Galileo [Galilei(1632)]

11 Results

Describe results when both researches are combined. Do they support each other. Relate this to the model

Is the acquired knowledge sufficient to identify the situation correctly, or is more information desired via communication? from chapter 2

write final conclusion of report

12 | Recommendations for future research

what was not within the scope

what are the next steps

Recommendations for future research

Part V

Appendices

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

– Yuval Noah Harrari [Harari(2016)]

A | Current 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

To gain insight in a structured way, the bridge is split 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.

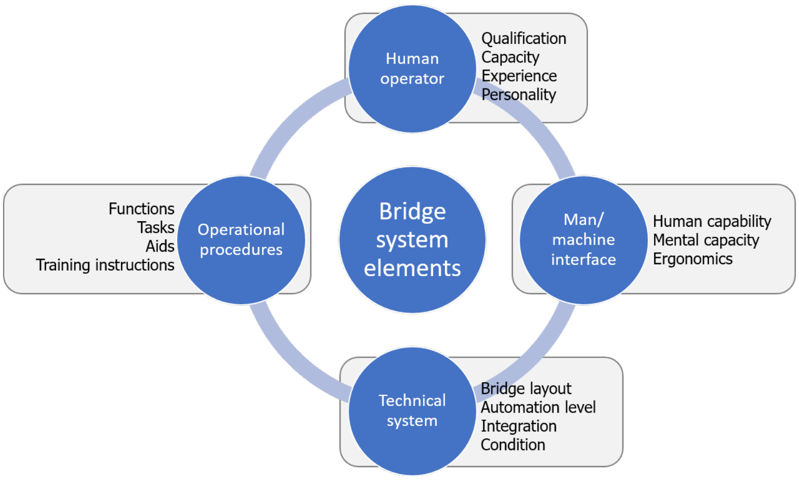


Figure A.1: Bridge system elements

A.1.1 Technical system

The first element 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) off shore. Transmissions are typically transmitted from the National Weather Authority, Coast Guard or other navigational authority. The system is an important 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 polarization, meaning that antennas have to be vertical in order to have good reception.

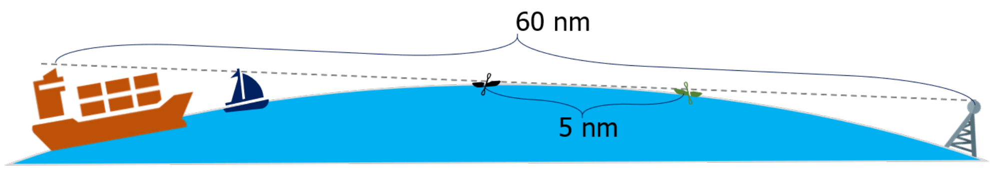


Figure A.2: Very High Frequency radio (VHF)

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 largely 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 war ships for tracking and detection. Radar technology has improved immensely from 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). A print-screen of an ARPA systems can be seen in figure A.3.

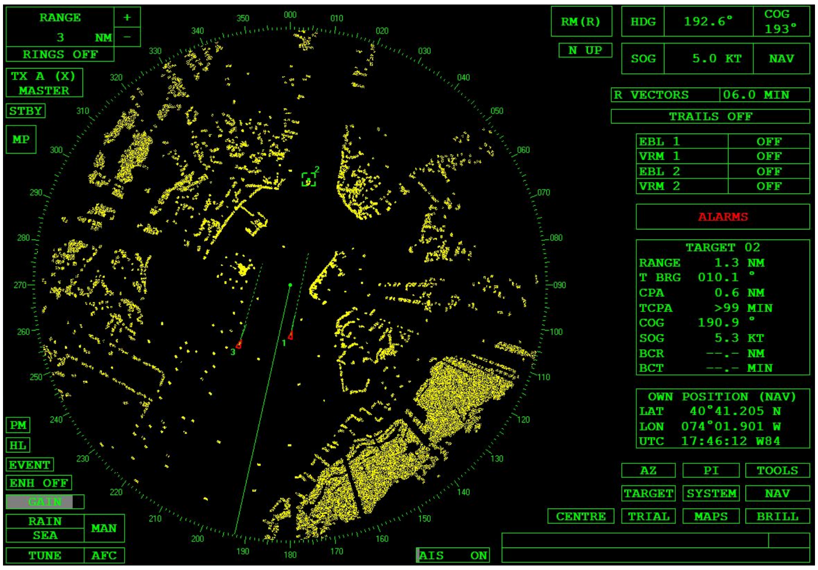


Figure A.3: Automatic Radar Plotting Aid (ARPA)

Automatic radar plotting aids are essentially utilized 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 automatically and constantly monitor 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 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 aircrafts. 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.

Originally the messages were send regularly 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. Data is transmitted via a tracking system which makes use of a Self-Organized Time Division Multiple Access (SOTDMA).

There are different types of transmitters. Depending on the object it is installed on. This determines what kind of messages can be send 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, shored-based AIS transceiver, able to maanage 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 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, less detailed report for vessels using class B transmitters.
- 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 acknowledgment, an addressed point-to-point message with unspecified binary payload.
- Binary broadcast message, broadcast message with unspecified binary payload.
- Standard Search and Rescue Aircraft Position Report, used by an aircraft (helicopter or airplane) 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, used by an (AtN) aid to navigation device (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. This also means that a digital representation of the environment is already being made. Including calculations, relevant for 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 for example AIS, ENC and the radar are combined. Examples of the different systems can be found in figure A.5.

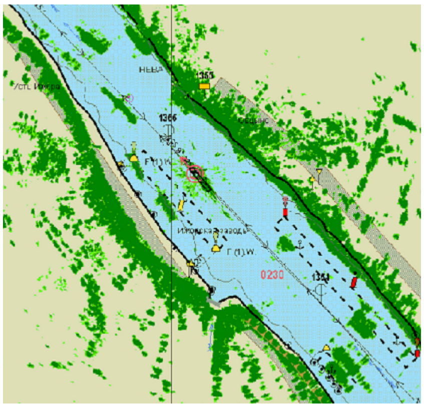
These screens are all integrated in some way into the bridge console. Depending on the size of the vessel, the lay-out may differ. Although, there are also regulations for the placement of systems in SOLAS. Examples of these bridge layouts can be found in figure A.1.

These lay-outs 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. Certainly in those cases is it important to have the right balance between supplying the operator with enough information to decide on the right strategy. But avoid an information overload.

A.1.3 Human operator

The human operator has two sides, to formal straight forward 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.

(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

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, does the crew also consist of ratings who have hands-on skills within their own domain. [Nedcon(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 in order to maintain safe operations and maintenance of the vessel. Second Officer or Second Mate is the next in rank after the Chief Mate and is the ship's navigator, focusing on creating the ship's passage plans and keeping charts and publications up to date. Apart from watchkeeping, the Second Officer may also be designated to train the cadets on board or to fulfill 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 good 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 main 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" in order to be allowed to take courses and training for AB. Both AB and OS are usually supervised by a Boatswain, who is also a rating, in charge of examining the cargo-handling gear and lifesaving equipment as well. The Boatswain usually holds an AB certificate as well. The structure for the deck department on board merchant vessels is mainly the same on all vessel types. [Nedcon(2013)]

Human factor

At unmanned autonomous vessels the human operator will be replaced by a computer. This means that the duties as described above will be executed by a computer. 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]. Hereby 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 in relation to 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, an decision is being made which results in an action. Changing the system and repeating the whole process. However there are factors which influence the effectiveness of this process. These can be internally or from the environment. Where automation is less prone to environmental factors, will it 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 effective 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

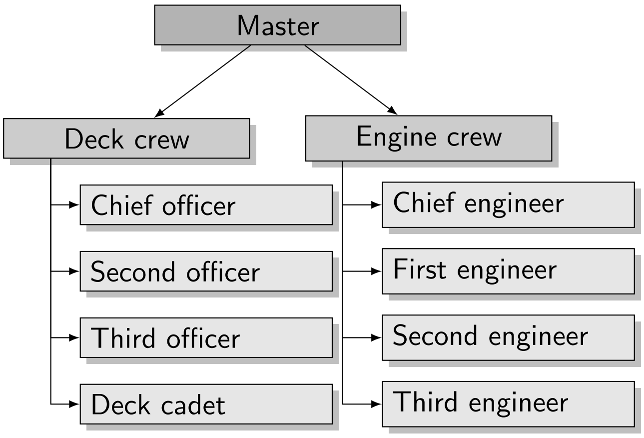


Figure A.7: Basic crew structure organogram

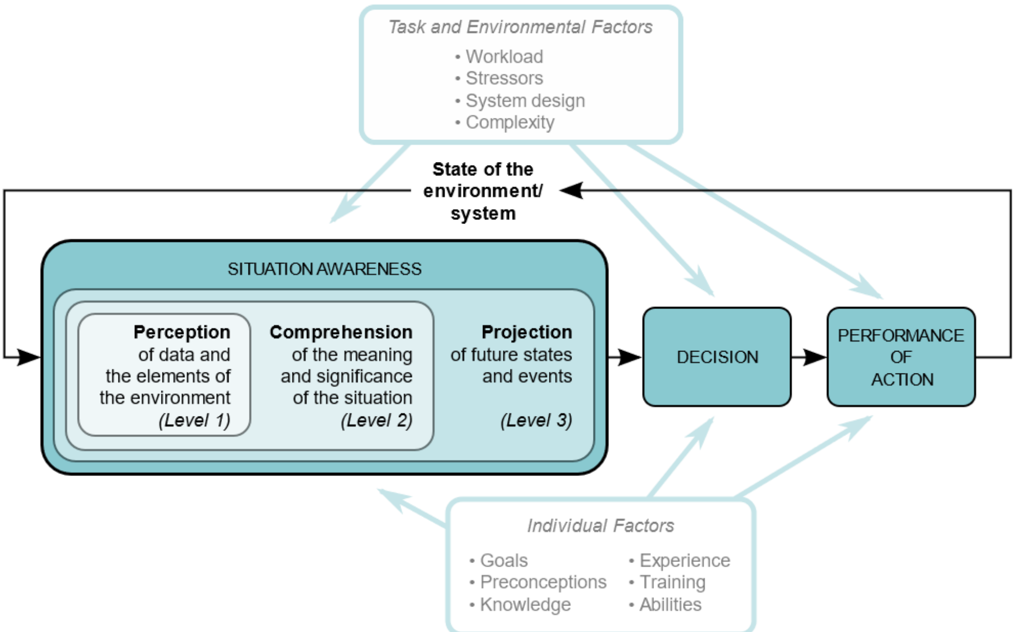


Figure A.8: Endsley model for situational awareness thousands of years of evolution have provided us with a pretty good ability to recognize and make sense of things.

Whereas the human operator is more prone to environmental factors. Where workload is a big factor in the ability to concentrate and thus the ability to forecast future states and thus 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 own responsibilities. Research has shown that many of these crews have multiple cultures and nationalities work next to each other. Which often have a 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]. Certainly when conversations happen via a radio with some noise.

A.1.4 Procedures

To become a certified seafarer, different skills and knowledge must be acquired. The IMO has developed several conventions to standardize this knowledge globally, the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW) is leading here. This ensures that ships sailing in international waters have skilled crew which know what they can expect from other vessels. This also means they have navigational abilities such as plotting on a radar. But they also have knowledge of 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.

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.

Prior to 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 various 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 four Annexes containing technical requirements concerning lights and shapes and their positioning; sound signalling appliances; additional signals for fishing vessels when operating in close proximity, and international distress signals.

Where part B is most relevant for this research, with subject like safe speed, obligation to determine risk of collision and take action with all means available, how to act in different situations with other ships, or in 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, so as to avoid confusion and error, there is a need to standardize 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 standardize the language used in communication for navigation at sea, in port-apporaches, 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 standardize 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 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.

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. However this is 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 does include talking in the local language, for example Dutch in front of the ports in the North sea. This was one of the main issues during the collision between AL ORAIQ and FLINTERSTAR, as described in appendix C.1. Another example which occured 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 maps. For example was there a camping between Rotterdam and Dordrecht, which does not exist anymore. However the operators still refer to this bend as the camping. Autonomous systems should be able to interpret natural language and recognize 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 own success. Due to the popularity, more and more information is send over these radio frequencies. Limiting the number of AIS transmissions per ship per minute. Which automatically reduces the accuracy and relevance, as information is older. This make it harder to predict paths on the AIS information, therefor it is obligated to use Automatic Radar Plotting Aid (ARPA). This is however harder to interpret. Combining these would give very good information which can be used by the autonomous system. There is however another problem in this case. As shown by Loodswezen do some ships tweak the AIS information, in order to ensure that the officer of watch uses its ARPA. This can be seen in figure A.9. Here the vessel have an error of 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 organizations, such as International Maritime Organization (IMO). As it will determine which solutions are possible.

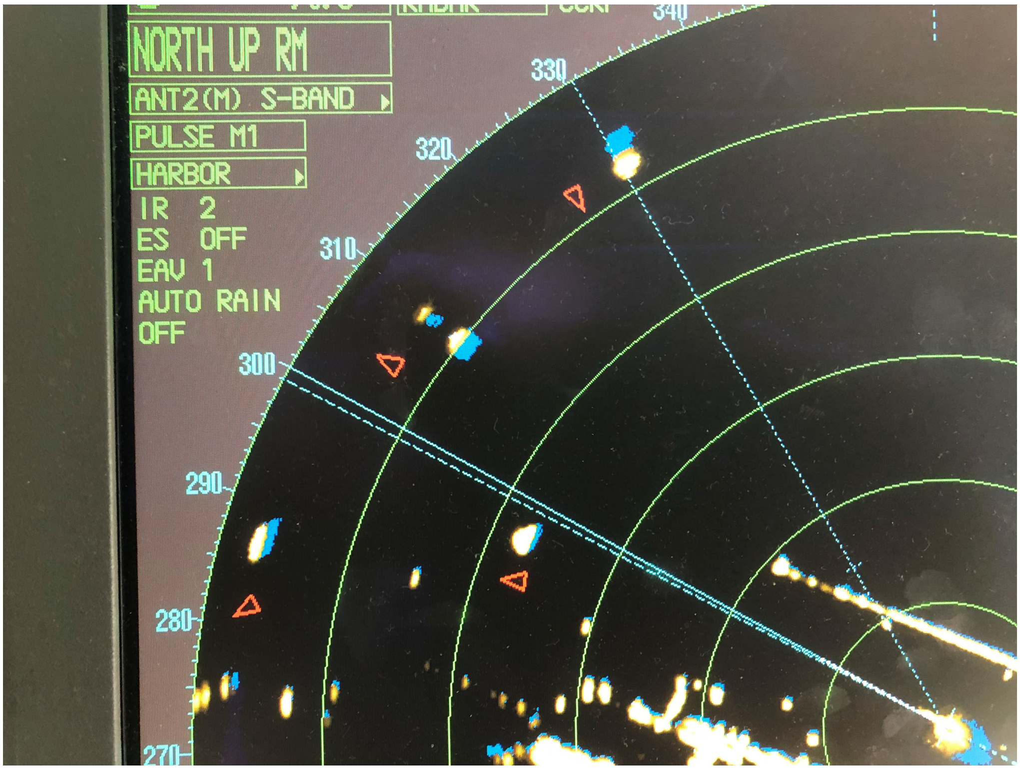


Figure A.9: Wrong AIS input when plotted on ARPA

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

B Simulation environment

This appendix will describe the development process of the simulation tool. This tool will be used to simulate situations and manoeuvers. 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 basic tool, 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 using different modules.

B.1 Foundation

The first step is to set the goals or requirements for the tool. This doesn't mean it is a full description of the tool, but 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 behaviors when turning or changing speed. This can be based on sea-trials and done using a mapping from current speed, current rotation, rudder angle and throttle to future speed and turning speed. This 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 visualized easily. Thereby changing ship characteristics, shared information and other inputs. The third requirement is that it should be possible to predetermine run the simulation with pre-determined actions, paths and manoeuvers.

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 an acceptance criteria this 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*. Object in the map which is used by the simulation. But to work correctly it also had needs for information.

Some examples of those user stories are given below:

- 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 visualized and can be selected to operate.
- As an operator, I want to predefine a path, so that I can test manoeuvers.
  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 manoeuvrer in a realistic way, so that the simulation is relevant for real-life situation.
  Acceptance criteria: Hydrodynamic model is validated.

B.1.1 Software architecture

Based on the above described requirements and user stories, different modules are defined. Using 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 facade.

Simulation The simulation adds processes which are relevant for simulating situations in real-time. This also means that it ensures 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 visualization the simulation will still be able to run.

DynamicObject Here the used ships are 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 is stored how the ships look and their characteristics such as 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 situation and the time-step. It finally returns the new speed, course, heading and location. Thereby does it check if the input values are correct. It does not matter in which world it is, or how it is visualized.

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

For the specific implementation of both parts of this research, two packages are used: Testing manoeuvers (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 visualized. This is acquired by using a module with general functions such as ship creation, manoeuvrer 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 very important. 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 however result 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 have 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 are also the information stored by the simulation about the vessel. These are described in table B.2 and 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 is 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

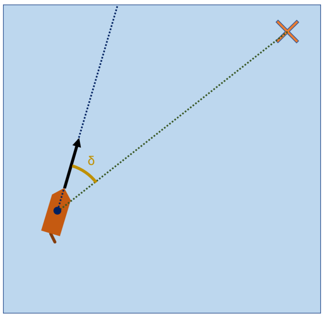


Figure B.1: Calculation of relative angle

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 manoeuvers 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. Ship manoeuvrability is described by the following characteristics:

- 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. However this project will 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 is the following criteria are complied:

1. *Turning ability*. The advance should not exceed 4.5 ship lengths (L) and the tactical diameter should not exceed 5 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 traveled 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.

Emperical model

To describe manoeuvring correctly a hydrodynamic model is needed. Using an emperical 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, in order 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

Using this information, an estimation can be made about the acceleration. An estimate of the forces is used in this case. Where two forces are calculated, propelling force and 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 determine if the ship is able to 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 is 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 input can be adapted. These inputs are validated for some of the used vessels, the resulting values did not differ significantly. This was most notable when running the different sea-trials with variable inputs. The ship characteristics had a much bigger influence. Although the impact of extreme changes in the rudder configuration have been looked into. The full calculation is discussed by Artyszuk [Artyszuk(2016)].

B.2.4 Numerical settings

Quality/Dependency analysis

Add input for numerical setting (dt vs runtime)

Change time for critical evasive manoeuvrer

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. To evaluate this criteria the change time has been tested for multiple vessels. The used criteria is the distance to the side (Y), divided by

Input	Unit	Description
Length	meter	Length of the vessel
Width	meter	Width 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 the advanced distance (X) (as shown in figure 6.3a). This is plotted against the time it took to make the manoeuvrer. From left to right a 140-meter container vessel, a 250-meter Tanker and a 400-meter cargo vessel are used. The results are shown in figure B.2.

switch X/Y in graph to Y/X

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 big as possible, in the shortest time and traveled distance. When looking at the figure can be seen that this is the case around 18 seconds. Where should be noted that larger vessels have a larger optimal change time. This can be explained by the larger inertia of these vessels. A higher speed has a similar result. The effect of these larger change times is however very small 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 manoeuvrer tests. The chosen change time is 18 seconds.

B.3 Build

In this section the final tool will be discussed. Thereby showing 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 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. Here can the user select if he want 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 can be changed. Thereby is it also possible to add waypoints, so the ship will sail automatically. Further some basic information is shown, such as the speed [knots], course [degrees] and rudder angle [degrees]. This can be seen in figure B.3.

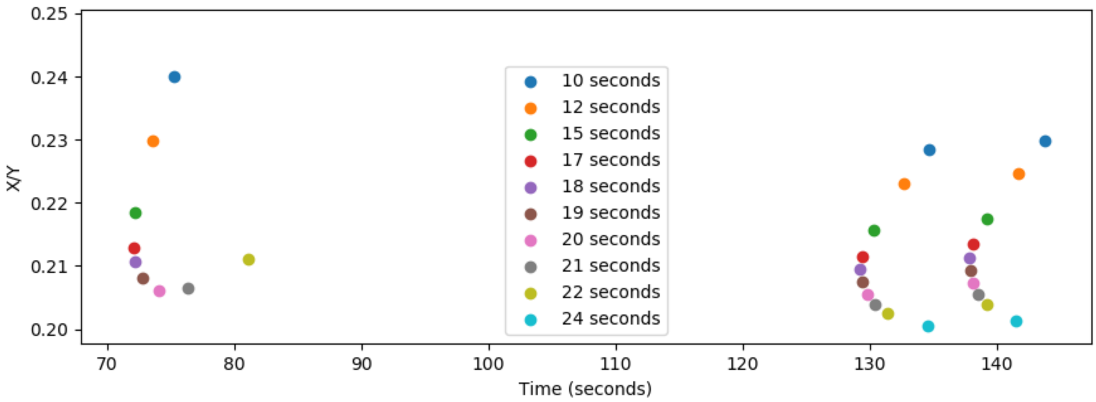


Figure B.2: Change time during evasive manoeuvrer for different ship types

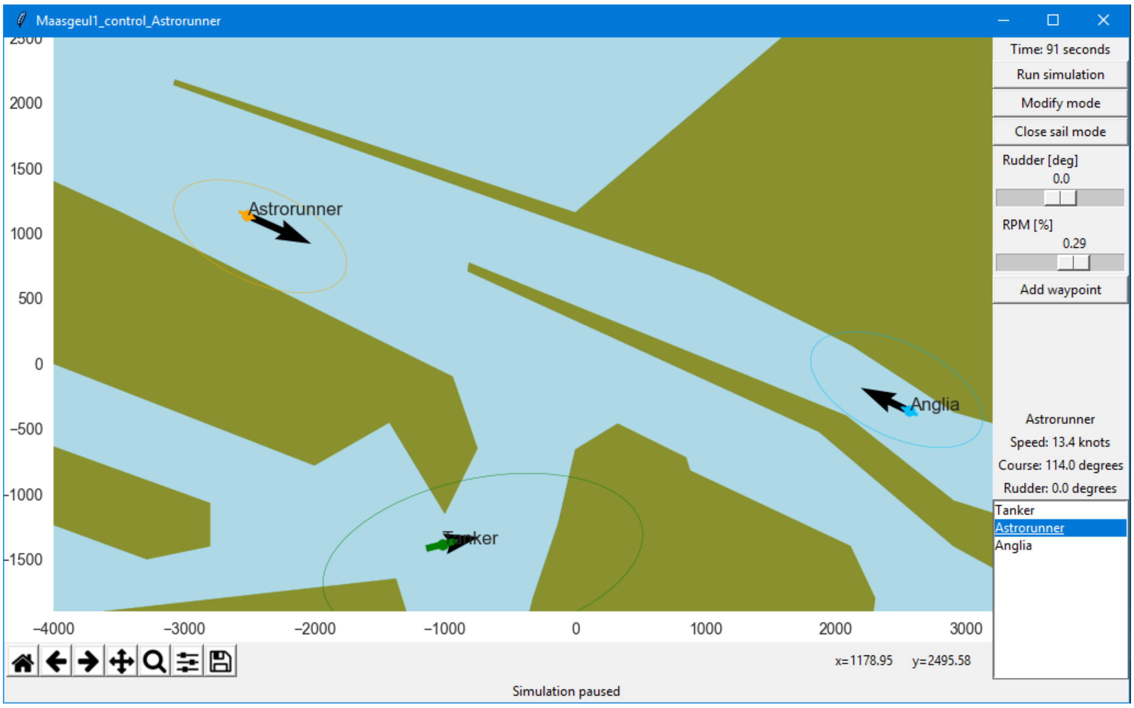


Figure B.3: Simulation environment

B.3.2 Output

Besided simulations within this GUI, it is also possible to execute them without showing the map. This will limit the computational time. To visualize these results, different outputs are stored. These are logged during the simulation. The outputs are stored in a dictionary, so they can be labeled 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 manoeuvers many times with small variances. The configured tests are described in table B.7.

B.3.3 Level of intelligence

Currently is a hydro model implemented, you are able to steer the ship or use waypoints and a background image can be used to show the map.

Currently implemented (level of intelligence)

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 manoeuvrer
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: Different manoeuvring tests

Name	Goal
Sea-trial	Execute zig-zag and turning circle test
Rudder test	Test performance of rudder and how it responds
Evasive manoeuvrer	Compare behavior for different angles
Change time	Test correct moment to start rotating rudder
Timestep	Compare the quality of simulation using different time-steps
Random	Determine effectives of evasive manoeuvrer to increase the crossing distance and CPA

Table B.7: Different manoeuvring tests

C | Accidents

In the last centuries much have changed to improve the safety of vessel and decrease the risk for 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 still accidents occur. To get insight what could 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 in 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, prior to contacting the nearby vessel Thorco Challenger. After informing the Thorco Challenger, did they pass on the starboard side. On board of AL ORAIQ were coastal pilots which did not receive feedback from the watch keepers, 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. Also did the bridge watch team not assess the situation properly, leading to very little situational awareness. On board of the FLINTERSTAR there was insufficient attention for watch keeping 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 is 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, did the accident occur.

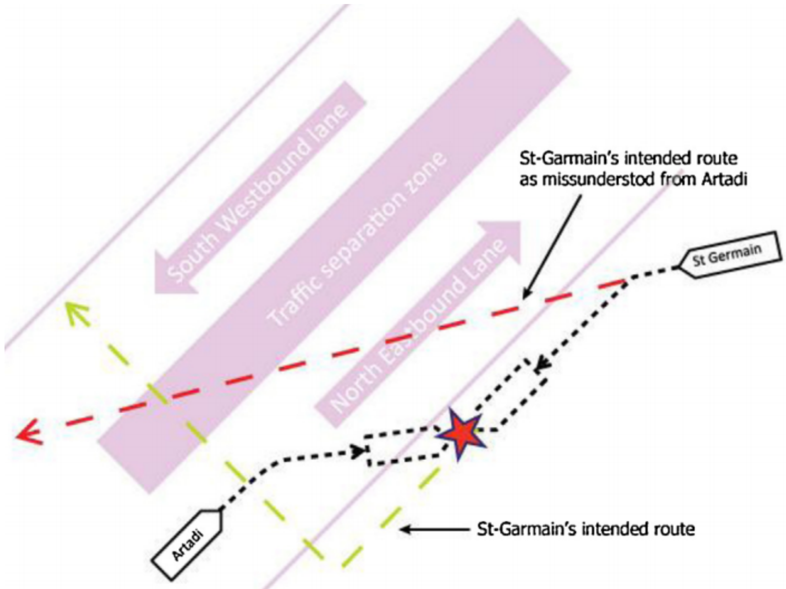


Figure C.2: Illustration of collision between MV ARTADI and MV ST-GERMAIN

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 boarder 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.

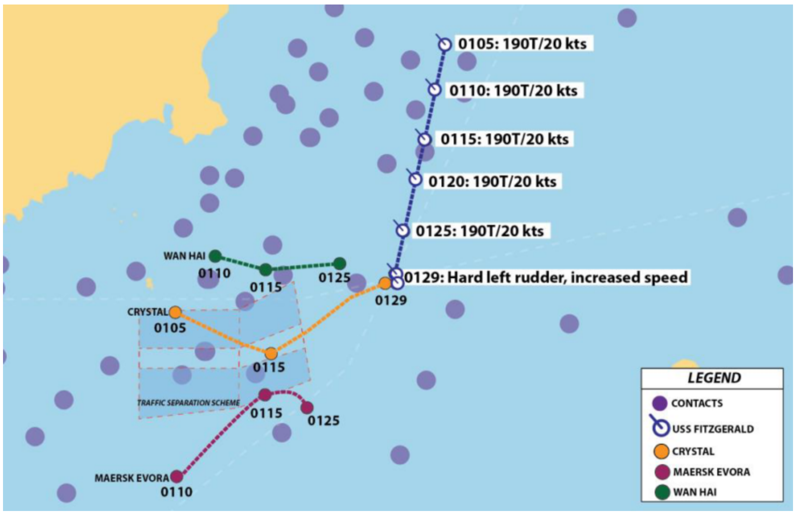


Figure C.3: Approximate collision location USS FITZGERALD and MV ACX CRYSTAL

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, till 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 prescribed 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. Thereby were key supervisors 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 used properly. [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 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 caused confusion within the watch team, which led to wrong transfers of control, where the crew was not aware of. Watchstanders failed to recognize 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 wrong 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 send by neither ship, which are 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 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 spilled 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.

Several safety issues were identified by the National Transportation Safety Board. 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 been generally 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 under way 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 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)]

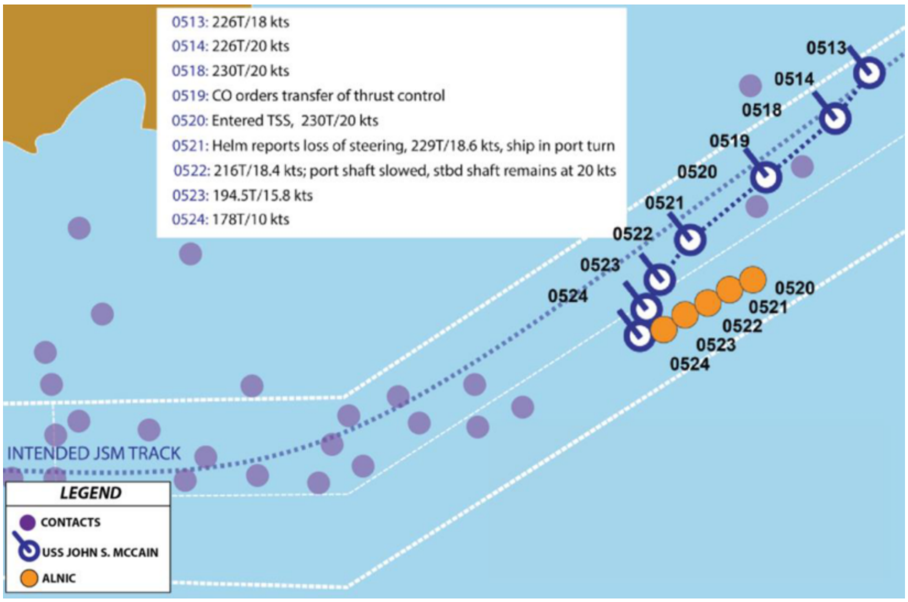


Figure C.4: Approximate collision location USS JOHN S MCCAIN and MV ALNIC MC

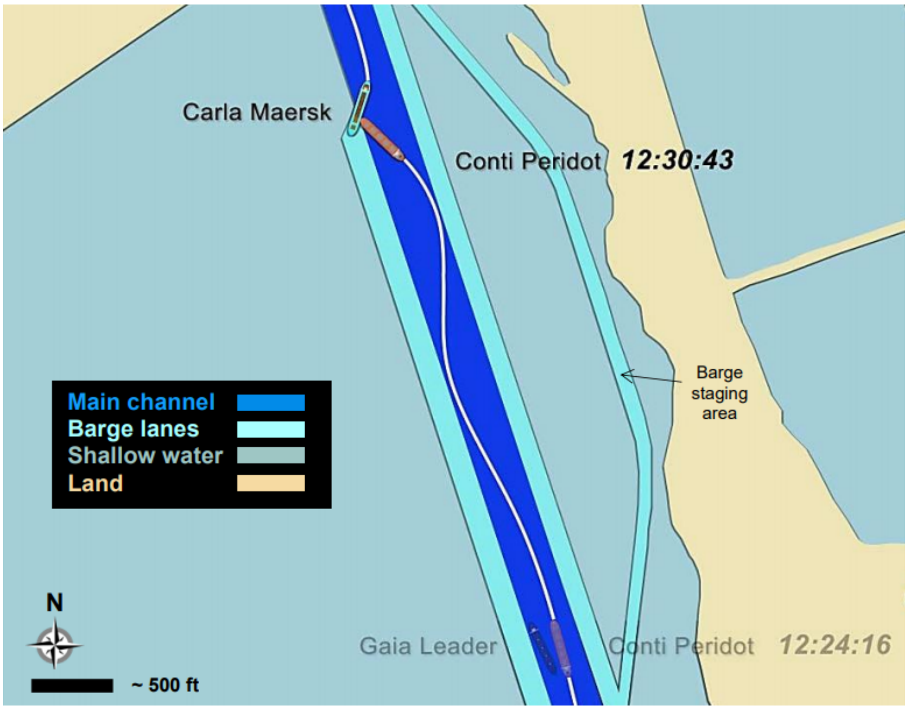


Figure C.5: Illustration of collision MV CONTI PERIDOT and MV CARLA MAERSK

C.6 Lessons learned

In all of the above described accidents, mistakes were made. But in all cases was there not sufficient communication, to warn the other vessel. If this would have happened, they could have taken actions to avoid the collision. In order to achieve effective communication, there should be an universal protocol. This protocol should be used under all circumstances. Thereby is it important that all seafarers understand this protocol, and are able to 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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