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)]. One of the major reasons mentioned is the mitigation of human errors, in autonomous shipping this is done by taking out seafarers from the chain of command, this will however introduce new challenges. One of the less explored challenges is the issue that communication 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

A computer works most efficient when it has all information in a structured way. Humans however are better with limited and unstructured data, to avoid information overload of the crew and communication channels [CCNR(2017)]. This will result in a challenge when manned and unmanned vessels have to communicate. In many situations are 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. As it is safer to make early adjustments to course or speed, than to spend too much time using Very High Frequency radio (VHF), Automatic Radar Plotting Aid (ARPA) or Electronic Chart Display Information System (ECDIS) to make an assessment. 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. However in critical situations such as the entering of harbors or in busy parts of the world, are the COLREGs not always sufficient.

To ensure the safety of all vessels, must decisions be taken well in advance. This depends on the manoeuvrability of the vessel. A cargo vessel will for example, follow a fairly predictable path. While a small tug boat might move around much more. Which results in more false positives on potential collisions with other vessels. The manoeuvrability also means that it is necessary to think ahead several minutes with a long and heavy 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 such as depth, traffic separation schemes and harbor entrances.

Problem statement

This research will be separated into two parts. In those parts, the challenge of communication between manned and unmanned vessels is considered. The first part aims to determine how communication can be avoided, by giving insight into the time-domain for decision making. By looking at the the decision process, critical situation can be selected which are analyzed in more detail. Using manoeuvring models these situations can be simulated to determine the time-domain and determine if this can be improved to ensure that communication is needed in fewer situations.

The second part 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 this is sufficient to ensure the right information is shared. This is done by using the situated Cognitive Engineering (sCE) method to quickly define a new protocol which can be tested in a simulation environment.

Research questions

This research will be a start, to solve the challenge of communication between manned and unmanned vessel. This can be used as a foundation to build a system for decision making which ensure safe operation of both manned and unmanned vessels. The parts relate to different research domains: Maritime Technology and Computer Science. Which resulted in two research questions:

> *How do ship manoeuvrability characteristics influence the domain for decision making, to ensure that the chosen strategy will result in a safe minimal distance between vessels in critical situations?*
>
> *Are existing systems and protocols for communication, sufficient to ensure that manned and unmanned ships can operate side by side safely?*

Report structure

link structure to chapters

Part I

Steps towards safe autonomous shipping

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. Which led to the development of COLREGs.

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.

As discussed in the introduction 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. 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

Research projects funded by the EU should aim at sustainable growth. This means, be competitive while also improving the safety of people working in the industry and reduce the environmental footprint [Eriksen(2017)] [European Commision(2017)]. This research will mainly focus on improving safety at sea within existing projects developing autonomous ships. Most of these project build upon previously developed technologies which are currently already in use. This chapter will first discuss: Why the step towards autonomous and unmanned is taken? Followed by a description of current projects to develop new technologies. To finally identify which challenges will most likely arise in this process.

1.1 Why autonomous and unmanned shipping

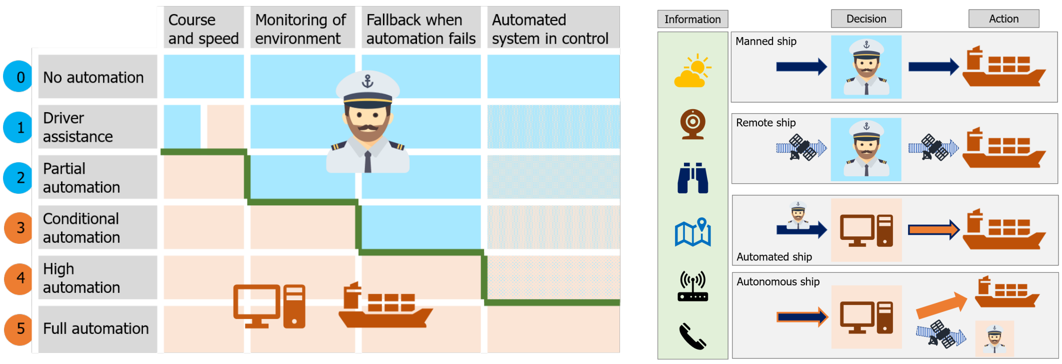
Due to digitalization, ships will become more sophisticated. More data is generated by sensors, improved connectivity and new ways to visualize data. This enables ships to continuously communicate with managers and traffic controllers. At first, this can be used to analyze data and give better advice 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:

- *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*, when there is better usage of data and communication. Thereby comes that computers don't have to work in shifts to go home or take breaks.
- *Improve competitiveness*, as tankers which are traded for example, do not have to enter a harbor to get fresh supplies.
- *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. 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.

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)]

The different projects around the world, working on the transition towards autonomous or unmanned vessel, are mentioned with their current status. Thereby should be considered that the projects are working on different levels of automation. These different levels are shown in figure 1.1a. 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 research project MUNIN has been one of the major projects by a consortium of ship-builders and scientists. 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:

- 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.

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 will be done in 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

Make own info-graphic

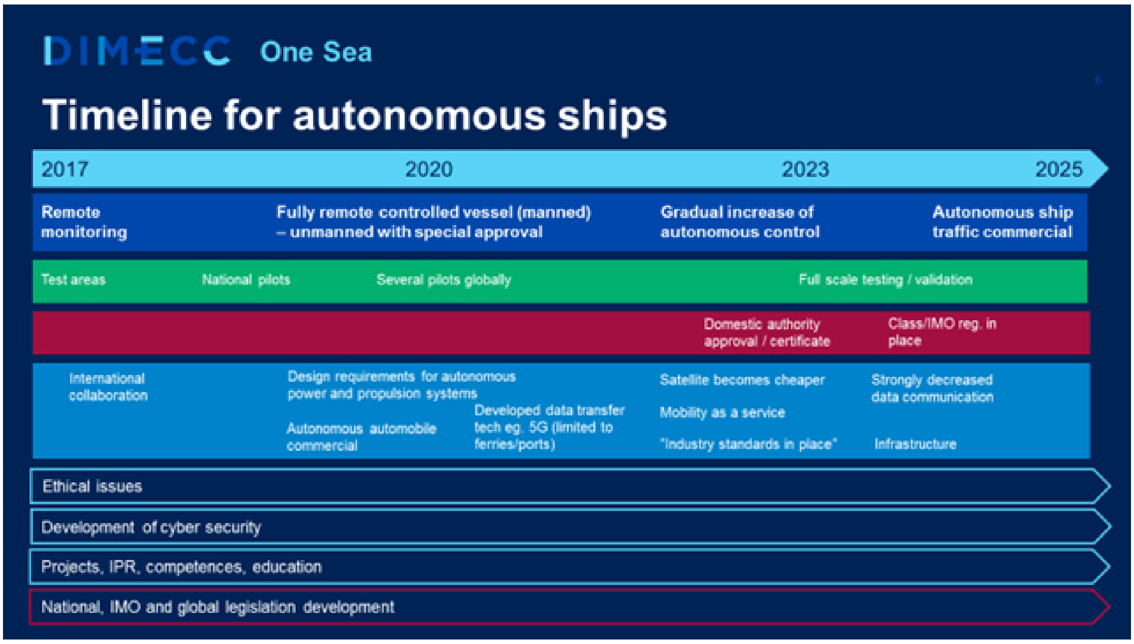


Figure 1.2: EXAMPLE-infographic: Timeline for autonomous ships by DIMECC

Rolls-Royce Marine is involved in different projects which are in some way follow-ups on 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 Twenty foot Equivalent Unit (TEU) feeder. 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 the way towards autonomous, will it start with a virtual bridge, housed below the containers. Utilizing the opportunities of sensors for safe navigation, employing radar, camera, IR camera, lidar and Automatic Identification System (AIS). The roadmap for 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. Combing the roadmaps of these projects, it is known when sub-systems should be developed. In figure 1.2 the timelines of different projects such as One Sea, AAWA and UCSDA are shown.

Update with correct projects in time-line

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 TEU container ship. 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. This will help to steer ships remotely, enable intelligent exchange of information and optimization of waterway maintenance. Good examples are the new vessels from Nedcargo, the Gouwenaar 2 and 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)].

Also did a Joint Industry Project (JIP) start on autonomous shipping under the name Sovereign. 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 Amasus.

more info on JIP and Sovereign

add renders/artist impressions of vessels

Based on the above mentioned projects, can the following be seen as possible use cases:

- Local transport between factories and terminals
- Short sea shipping

- 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 incorporate autonomous vessels in their frameworks. For them the exploratory projects are very important, as this will help to know for which ships codes should be developed. These codes include information on autonomy levels and how to certify unmanned vessels.

The next group 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. Thereby are there companies from other industries, which see opportunities for products they already developed for planes or automotive, which could also be used on unmanned vessel. For example to connect ships, computer vision and protocol for testing systems.

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.

add model from sovereign

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. The challenge of safe operation for unmanned vessels is one of the most important. This is mostly relevant when manned and unmanned vessels meet. As technologies for communication are costly to develop, the aim is to avoid communication when possible. To accomplish this, the first step is to adjust the operational strategies for unmanned ships to avoid complex situations where possible. This means a strategy should be developed on how these ships can avoid complex situations. The most easy way is to take decisions well in advance 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.

In the next chapter factors are discussed which influence the decision making process. This is based on challenges from above mentioned projects and current research.

2 | Decision model

In the previous chapter, several projects are discussed, which gave insight in the challenges towards unmanned and autonomous shipping. To solve the challenge of safe operation in a structured way. First insight is gained on where this is placed within the decision making process. This is done using a model for decision making. 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 talents differ for 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)]. In appendix A, the systems which are used currently at manned vessel to form a correct mental model are discussed. For this research only the result of this step is relevant: Is the acquired knowledge sufficient to identify the situation correctly, or is more information desired via communication? The sensors which in the future will be used is not within the scope of this research, nor how that is combined into 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 is defined by the lay-out of the waterway, other nearby vessels, relevant regulations, etc.

Predict future states and decide on strategy

Based on the situation different strategies are possible. These strategies have to be evaluated. This 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 formulas in common ARPA systems. Using non-linearized methods with for example a Bézier curve, will already result in a smaller error. Simulations would improve this even more, however do simulation with correct hydrodynamic models cost much more computational time. In chapter 5 the linearized and non-linearized methods are described. The simulation method can be done with the tool as described in appendix B, but this tool is not optimized for such calculations, and will therefore not be able to do these calculations in real-time. The hydrodynamic model used in the simulation also described in appendix B.3.3. 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 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 trough the decision process and end-up at the right strategy depends on the situations. This situations is mostly influenced by the environment. In some cases this environment is too complex to make a mental model for, just based on static sensors and should information be retrieved by request. 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.

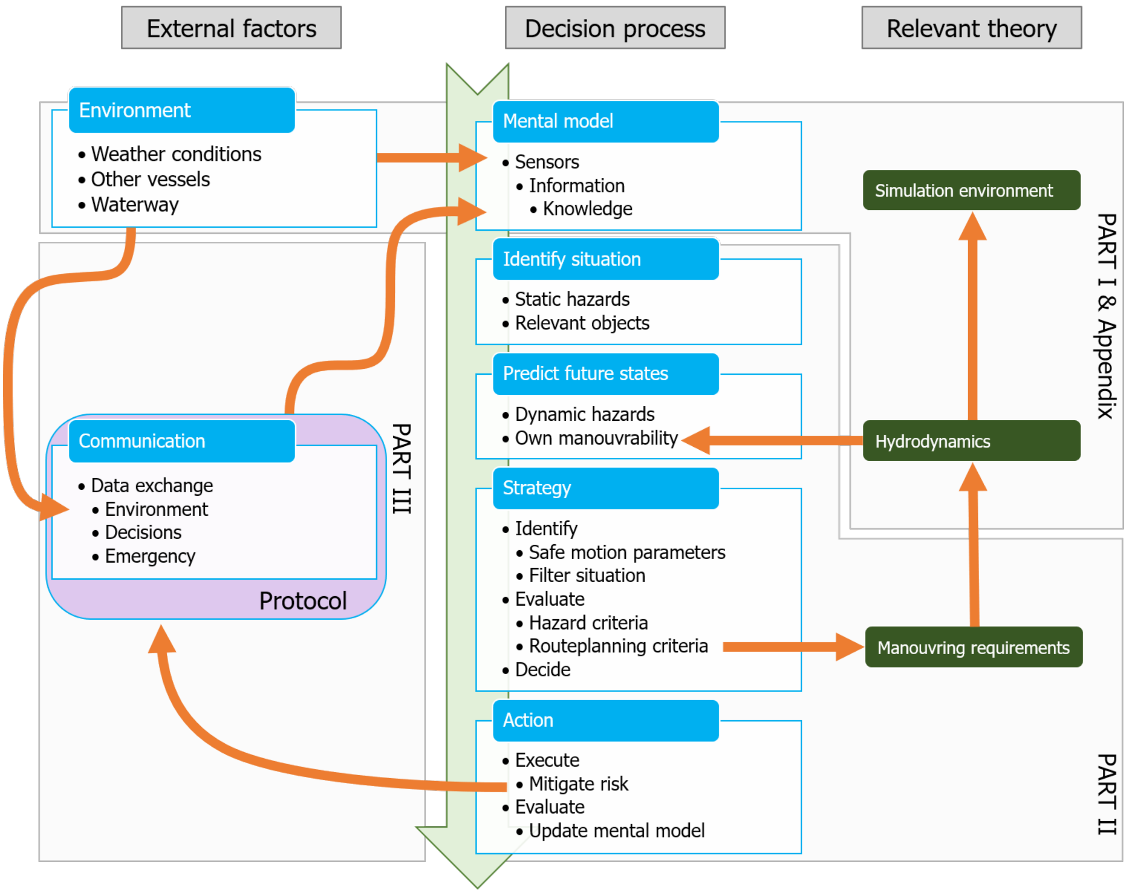


Figure 2.1: Decision model

Part II

Relevance of criteria for decision making

The previous part described the context of this research and showed steps towards autonomous shipping relevant for this research. This part will focus on the limits due to manoeuvrability in the decision making process. However, the steps taken to get to the right decision are similar, as shown in the model from chapter 2. The insights acquired from the decision process can be used to determine manoeuvrability requirements.

The first phase of observation starts with updating the mental model and is followed by a phase where different chunks of information are connected. This means 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 this can be used to determine the right strategy. While the 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 is used. These are also used to run 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 manoeuvring requirements and moment when decisions should 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 depends for example on the manoeuvring characteristics, speed and type of manoeuvrer.

3 | Decision making process

Using a rule-based time-domain decision model, can a general decision process be defined to make insightful: What the situation is and what problem might occur. Nodes in the decision tree are described with keywords to work in a structured way. This white-box approach will cover as much as possible, however is it likely to use machine learning in the final design of a decision algorithm for autonomous and unmanned ships. First the decision phases are described. Followed by lists of nodes used to identify scenarios and situations. Combining this with the rules, will result in the decision model. Also the criteria necessary to go trough the steps are discussed. The aim of this decision model is gain insight in the decision process to show what critical situations are when you want to try 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.

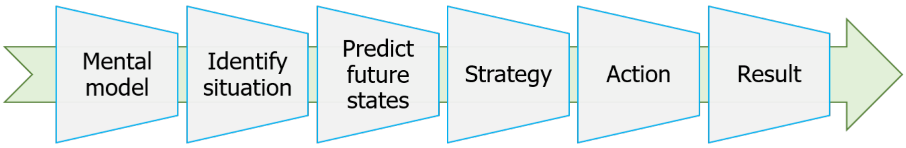


Figure 3.1: Decision process

Class	Description
Mental model	Acquire knowledge about the situation, not part 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	The second step is to determine 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 amount 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 is 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 differs, but they do cross.
Over-taking	The paths of both ships are the same but at different speeds.
Merge	The final direction of both ships 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 what kind of problem there is.

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 determine 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.

Tag	Description
Follow planned path	By doing planned actions
Move away from other path	Change path, in order to increase CPA
Stay parallel for longer	Change path, to sail parallel to other vessel
Adjust speed	Slow-down or speed-up
Abort over-taking	Lower speed and stay behind other vessel
Move away from other position	Check if this is to starboard, otherwise communicate
Communicate	If other (also) has to take action to avoid a problem

Table 3.4: Tags for different strategies

Possible actions

From the chosen strategy, different actions will follow. These action are a combination of an action type, and a moment to execute action. In table 3.5 and 3.6 these are described. The criteria to determine if an action is possible are described in 3.7.

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
Change 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 3.5: Types of actions

Tag	Description
Now	When action can be undertaken as soon as possible
In ... minutes/seconds	Wait for a period of time to ensure bold movement
After action ...	Wait with action till you or other has done another action

Table 3.6: Time-domain for action

Tag	Evaluation
Closest point of approach	Good; Too close
Time till problem	... minutes/seconds
Distance till problem	... meter

Table 3.7: Criteria to determine if action is possible

Result

Using the evaluations from the action phase, can the eventual solution be evaluated. Herein is the human factor on board of other vessels taken into account, in the form of perceived risk. Evaluations and criteria are shown in table 3.8.

Tag	Evaluation
CPA	Good; Too close
Perceived risk	Safe; Uncomfortable; Close encounter; Too close
Safe situation	Yes; Uncomfortable; No
Communicate	Yes; 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. For specific situations and scenarios the eventual decision tree is much smaller than a tree covering all possibilities. Although a generalized model of the tree is drawn, based on the previously described nodes. This model is shown in figure 3.2. Where the purple show decision and grey 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. In appendix C different examples of sub-trees are shown. Using identification and evaluation criteria several common critical paths can be identified . These paths will be identified and evaluated in the next chapters.

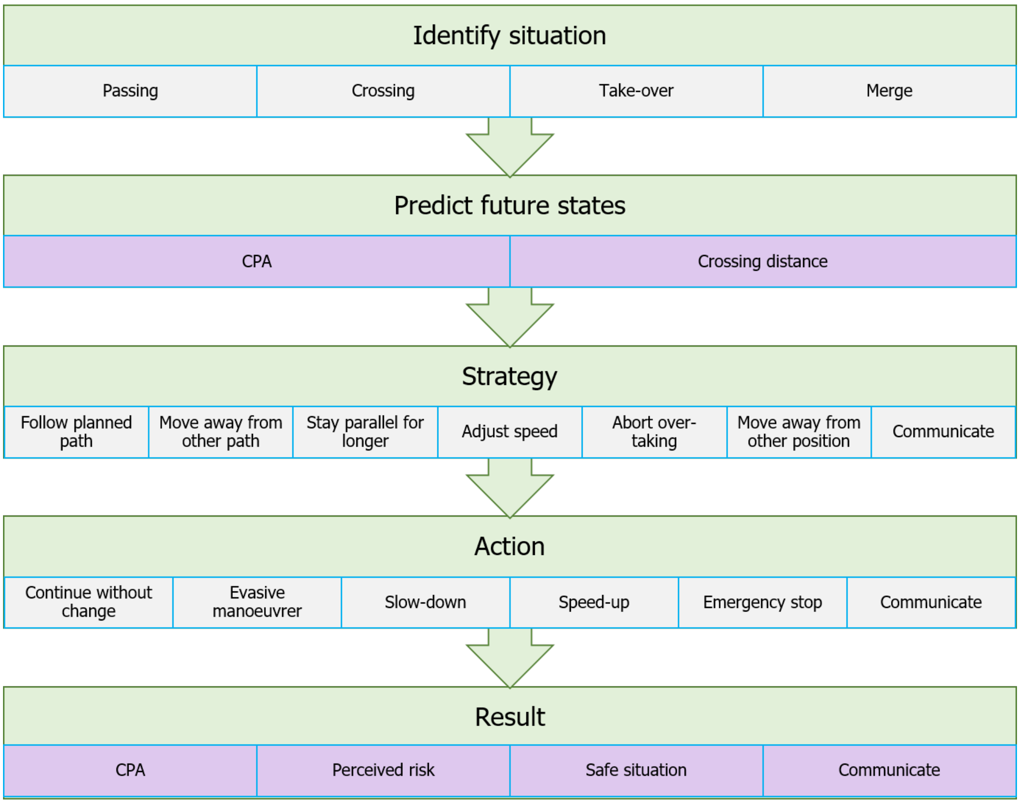


Figure 3.2: Generalized model for decision tree

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. In this chapter, the first steps of classifying the situation are discussed. Followed by the steps taken in the orientation phase to form 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

Based on the environment, can situations be classified into four types. These are also discussed in chapter 3, as these are the same as the nodes in the decision tree:

Passing Ships do get close, but the paths are not crossing

Crossing Paths of ships are crossing

Over-taking Two ships following the same path with different speeds.

Merge Two ships from different directions, heading in the same direction, strategy might lead to an over-taking or crossing situation, depending on the relative position.

It depends on the type of waterway which situation is likely. To determine this, 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 4.1.

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 4.1: Standardized paths for situations

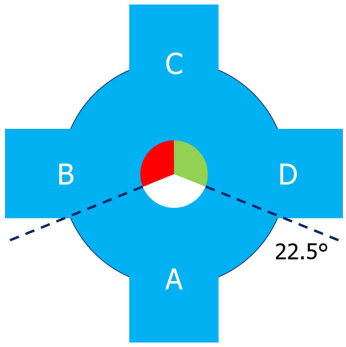


Figure 4.1: Path description

The boundaries to determine if the other ship comes from direction A, B, C or D are based on COLREGs. 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 the color of the light will be white. The other situation which might be difficult is when a ship comes from the front with an angle. 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.

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 Type of waterway

To determine which strategies can be chosen. The type of waterway is the first to consider. As this might restrict the area where can be sailed, which influences the possible strategies. 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. This means 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 bridges, buoys, forbidden zones, quays, port mouth 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. Or more directive signs on obligated directions or speed limits. This is mostly 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 off course other ships which do 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. The major difference between static hazards are of course that the 'forbidden zone' around these objects changes over time. Which makes it harder to determine if you are operating safely.

To predict the path, 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 while in operation. Ferries in inland waters which have priority over other shipping traffic. Other ships with limited manoeuvrability or forbidden zones around them. As these all could force to act on a specific strategy.

4.3 Scenarios

Using the information on type of waterway, location and actors, the scenario can be identified. 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 as described by Szlapczynski [Szlapczynski and Szlapczynska(2017a].

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 first step of the decision tree 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, which do not predict the closest points of approach and crossing distance correctly while turning for example, often resulting in many dismissed alarms. The different methods to evaluate criteria are discussed. First the current and proposed algorithms to calculate the Closest point of approach (CPA) and crossing distance. 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 already being 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. Below these calculations are discussed for the Closest point of approach (CPA) and crossing position. How this is implemented in the simulation tool is discussed in appendix B.

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 5.2. Where P and Q are the moving points, with corresponding direction vectors u and v, which include the speed and direction.

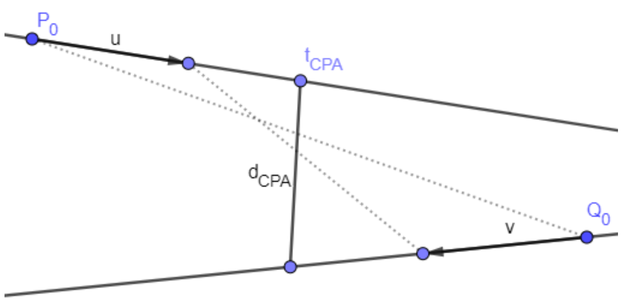


Figure 5.1: Example for Closest point of approach (CPA)

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:

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

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

Since d(t) is a minimum when $D(t) = d(t)^2$ is a minimum:

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

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

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, else it is in the future.

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).

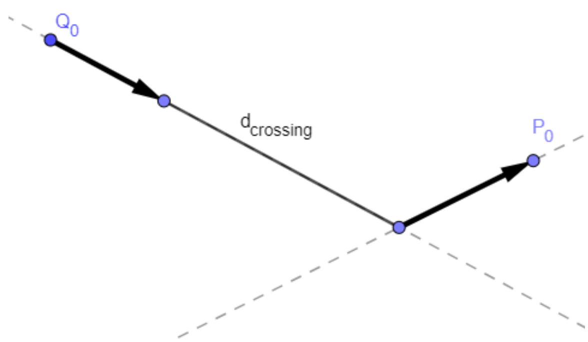


Figure 5.2: Example for crossing point and distance

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

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

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

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

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

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, using the probability that another ship is choosing a specific strategy.

Although it will result in better evaluations, is the disadvantage that much heavier computations are needed, while also introducing uncertainty with the numerical solver. Therefore a combination can be made based on the expected route to use the linearized or non-linearized methods. The calculations have to be done for every combination of your ship and another ship which is nearby.

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 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 Bézier curve thus used for making a representation of own vessel, while other vessels are represented with the linearized function as described earlier.

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 manoeuvrability on decision criteria

The criteria as described in the previous chapter are aimed to determine if there is a problem. In the case there is a problem. Different actions can be undertaken to mitigate the risk. To determine which actions are feasible different criteria are used. As these manoeuvers are complex is it usefull to develop a database with thresholds upfront. To determine these thresholds, simulation are performed for different ships and scenario's. In this chapter is described how these thresholds are calculated, using the simulation environment as described in appendix B.

6.1 Manoeuvrer descriptions

The COLREGs prescribe to have single bold movements, thus alterations of course or speed, should be clearly observable. To acquire this, do strategies often result in actions which can be categorized in different types of manoeuvers. Most common in critical situations are the evasive manoeuvrer and emergency stop. The time needed to do these manoeuvers depends on the manoeuvring characteristics. These characteristics are measured using different types of manoeuvers. Most relevant in this case are the zig-zag test and turning circle of the ship. In this section these different manoeuvers are described.

6.1.1 Sea-trial

Manoeuvring capabilities of a ship are determined during the sea-trial. Using the same manoeuvring tests and metrics as currently used by ship designers, will make the results most relevant. 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 zig-zag test, turning circle and emergency stop. In this section these will be described. The resulting metrics are discussed section 6.2.

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 path for a 140m cargoship is shown in figure 6.1, together with the given rudder and resulting acceleration and drift during the first part of the test.

Zig-zag test

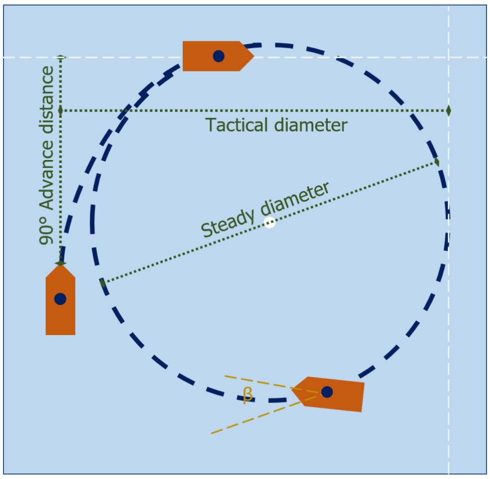
The second test is the zig-zag test. Herein is the overshoot tested when changing course. This is done by putting the rudder at an angle of 10 or 20 degrees to port side, till the course change is also 10 or 20 degrees, than the rudder is changed to starboard side. This is repeated several times to get 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. 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 larger the overshoot, the better the yaw checking ability, but this will result in a lower path changing-ability. Using this metric can be validated how well the manoeuvring model works, compared to existing sea-trials with the same ship using for example the trial database of Damen.

Emergency stop

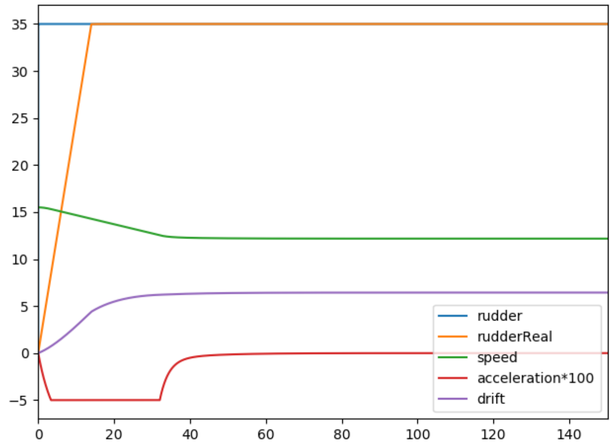
Not yet imple-mented

6.1.2 Evasive manoeuvrer

The evasive manoeuvrer aims to increase the Closest point of approach (CPA). Based on COLREGs is there a stand-on and give-way vessel. The stand-on 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 and the crossing situation is perpendicular. 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.

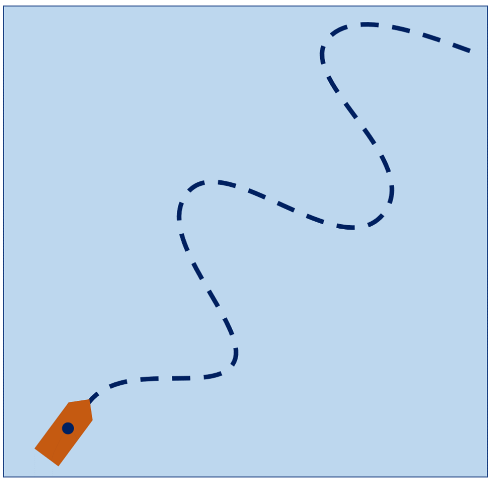


(a) Illustrative path

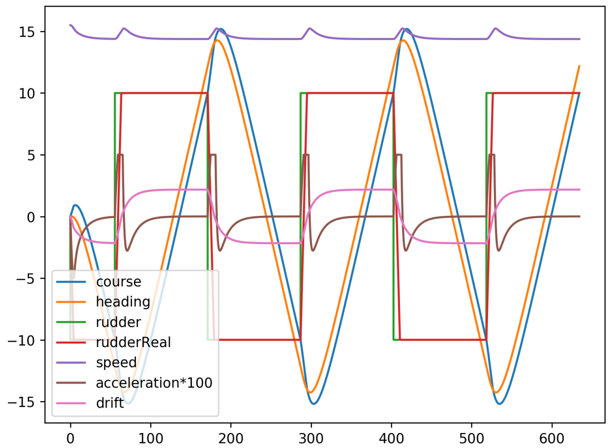


(b) 15kn with 140m cargoship

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

6.2 Trial results

During the tests as described in the previous section, different results can be acquired. Using the simulation tool as described in appendix B different metrics can be calculated. These results depend on the following input variables: Ship manoeuvrability, starting speed, speed other vessel, crossing angle. These can be related to the criteria which determine if a vessel can safely act in a specific situation. The metrics acquired from the manoeuvring tests are:

Describe why this evasive manoeuvrer (90 deg) is most common critical

- Sea-trials
  - Advance distance
  - Tactical diameter
  - Steady diameter
  - Steady drift angle
  - Overshoot angle
- Evasive manoeuvrer
  - Closest point of approach (CPA) or passing distance
  - Time needed for manoeuvrer
  - Distance before problem occurs

Results of trials showing the dependency of passing distance on distance till CPA and current speed are shown in figure 6.4 on page 37.

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.

Also other the course change, time to execute and advance distance are plotted. But less conclusions can be drawn from this. Examples are shown in figure 6.5 on page 38. From this plots can be concluded that the distance before the accident and current speed influences the maximum passing distance. Where should be considered that the line also shows where the previously mentioned asymptote is.

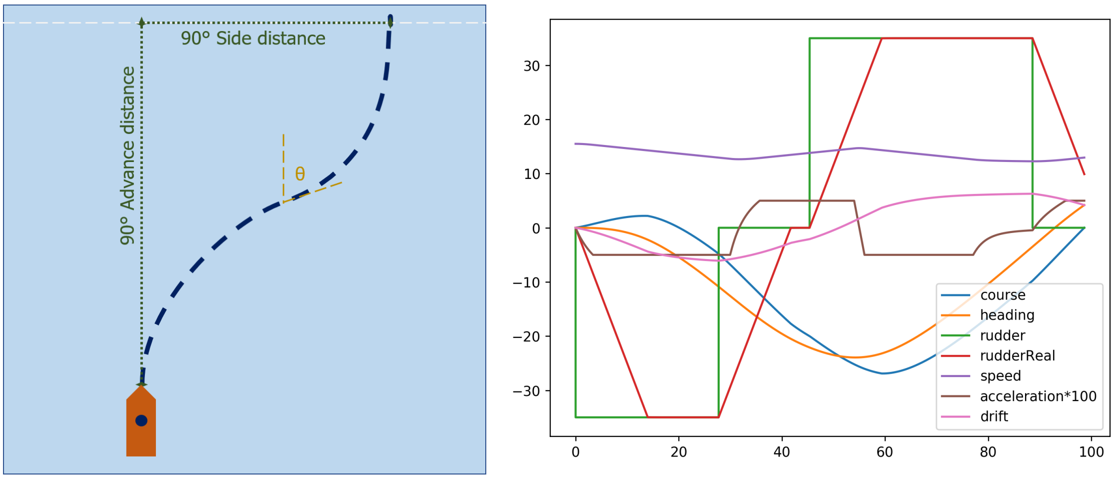
6.3 Dependency analysis

Result of varying input: Ship manoeuvrability, starting speed, speed other vessel, crossing angle. –¿ Common critical situation

Variables relevant for simulation model

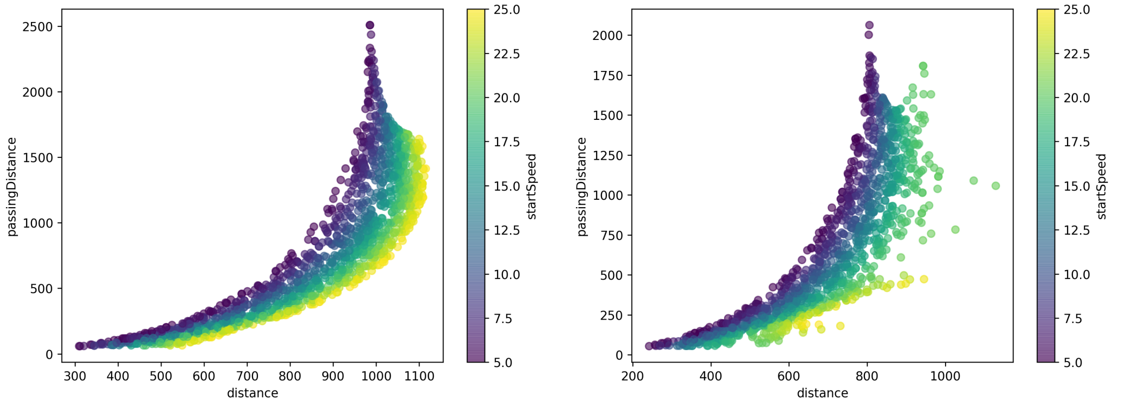
- Time used to limit overshoot (changetime)
- dt

- hydro input values

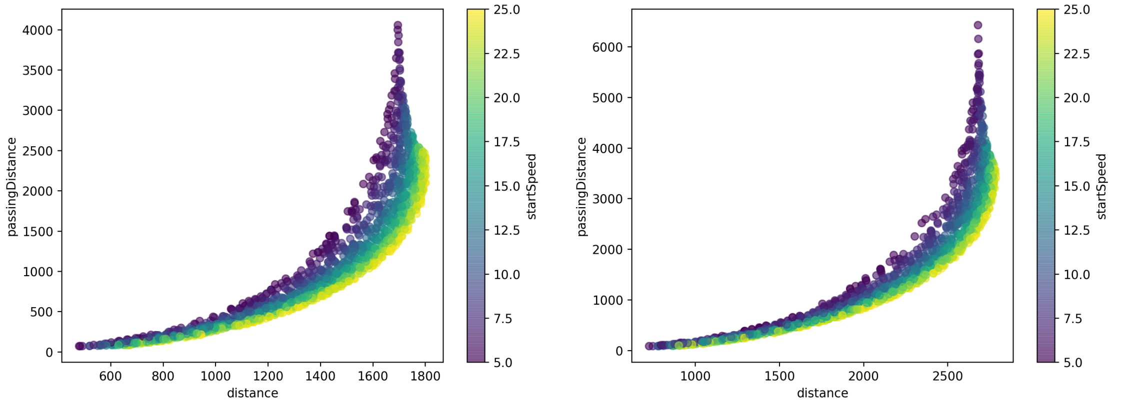


(a) Illustrative path (b) 20 degrees at 15kn with 140m cargoship

Figure 6.3: Evasive manoeuvrer

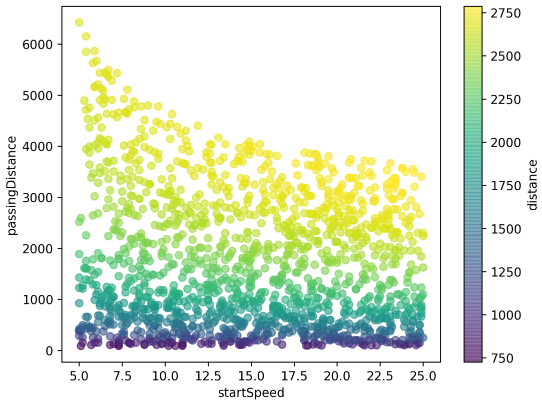


(a) Astrorunner (140m cargoship) (b) DAMEN Combi freighter 7200 (118m freighter)

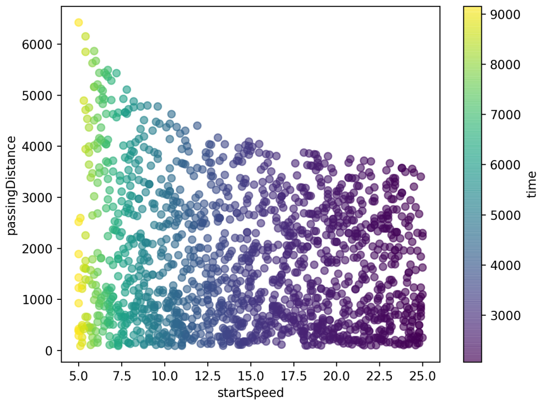


(c) Gulf Valour (250m tanker) (d) Emma Maersk (400m containership)

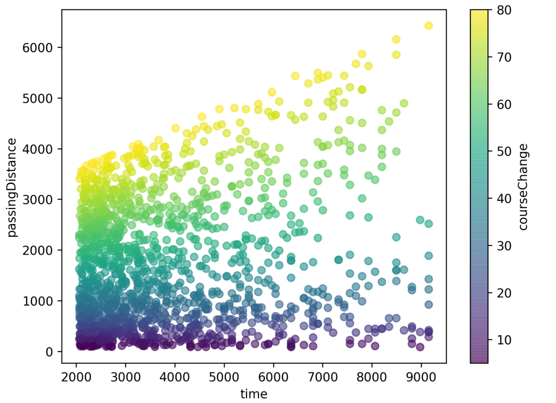
Figure 6.4: Dependency of passing distance on distance till CPA and current speed



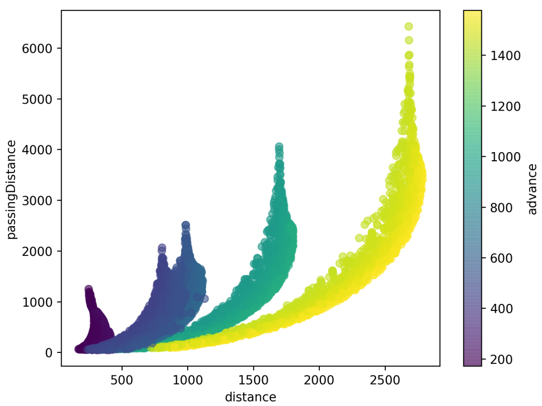
(a) Emma Maersk - Start speed, passing distance and distance till accident



(b) Emma Maersk - Start speed, passing distance and time



(c) Emma Maersk - Time needed, passing distance and course change



(d) Advance based on distance and passing distance

Figure 6.5: Other plots