Introduction

The Maritime industry is tapping into the world of automation and digitalisation. The automation level of vessels is proliferating. Vessels are being connected to the shore by different means. Operational data is becoming available and enriched with other data sets like design data, weather data and maintenance data. These technologies boost the development of autonomous and unmanned vessel designs [Blanke et al. (2017)]. At the same time the Maritime Industry is facing challenges when it comes to crewing and safety [Cappelle et al. (2018)]. Combined with an increasing competition, it is hard to make healthy margins. These trends trigger the Maritime Industry to embrace autonomous sailing technologies to secure a healthy future. These business developments reflect in the significant amount of research and development projects [SMASH (2017)] [Eriksen (2017)] [MUNIN (2016)] [Sames (2017)] [Rolls-Royce (2015)] [Waterborne (2016)]. Each one of these projects tackles one or more challenges in the development of autonomous sailing. However, is the topic of communication between unmanned and manned vessels has not been touched upon [Saarni et al. (2018)]. In chapter 1, these challenges and related projects are discussed. Currently, no solutions are available yet, yet it is necessary to ensure the safety of all vessels: manned, unmanned, remote, automated and autonomous.

This report presents the results of the study on communication between unmanned autonomous sailing vessels and manned vessels. It presents a design philosophy which has been translated into a methodology for handling communication, which then is eventually turned into protocols which are derived based on theory and validated through simulations.

Context

In many situations the Convention on the International Regulations for Preventing Collisions at Sea (COLREGs) is sufficient to determine the intentions of other vessels [IMO (1972)]. They can be seen as ship separation rules, which guide all vessels to make early and correct alterations to their course. It will take more time to assess the situation when using VHF, as there is less time to act limiting the possible strategies. These rules also apply to autonomous ships, and can thus be used when manned and unmanned vessels meet. Examples of such regulations are to stay on the starboard side of the shipping lane and not to cross other ships with a small relative angle. When this does not happen, communication is necessary. When this communication doesn't occur correctly, there is a much higher risk of accidents (appendix C). There are also situations in which regulations are contradictory, such as the accident between Artadi and St-Germain as described in appendix C.2. These contradictions occur more often in complex situations, such as a harbour approach.

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

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

Design philosophy

We developed a strategy to cope with the challenge of communication between manned and unmanned vessels, without the introduction of new systems to the bridge of manned vessels. First, we will try to avoid the need for communication, by staying well clear from other ships. When this is not possible, communication is proved to be necessary, requiring a new protocol to be developed. This strategy can be used as a foundation to build a system for decision-making which ensures safe operation of both manned and unmanned vessels. Different steps must be taken to implement this strategy.

First, the decision model for safe navigation has been analysed in order to determine which factors are required to make a decision. The next step is to learn how these factors influence the decision-process. This can also be used to determine critical situations. In those critical situations it isn't possible to navigate without communication. Identifying situations for a communication protocol necessary. Using the situated Cognitive Engineering (sCE) method, the operational demands, relevant human factors and envisioned protocol could be defined. The current state of the maritime industry is taken into account.

Research questions

The report will touch upon different research domains in more detail: Maritime Technology and Computer Science. The part on maritime technology focuses on the situation where manoeuvring is just enough. While the computer science part will focus on the development of the communication protocol. Answering the following research questions:

> *How do ship manoeuvrability characteristics influence the domain for decision making, to ensure that the chosen strategy will result in a closest point of approach 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 report has four parts. In each part, the challenge of communication between manned and unmanned vessels is discussed. Part I gives a more detailed context of autonomous shipping. This context is used with a decision-model to show why communication is a challenge, and how this challenge can be tackled.

Part II aims to determine how communication can be avoided. To resolve this, it is important first to determine when communication is necessary, which is in case of critical situations. These situations are tested in a simulation environment. The time-domain for decision-making can be determined to ensure safe operation in these simulations. These situations are simulated, using a validated manoeuvring model. Thereby is evaluated that ships need communication in fewer cases if the decision-domain is improved.

Part III will focus on critical situations where communication is a must. Currently, a communication protocol between manned and unmanned vessels has not been part of any known project. Communication is necessary in cases where there is a lack of trust, missing information or the time-domain for decision-making becomes critical. To ensure a fast implementation of the communication protocol between manned and unmanned vessels, it will be 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.

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

Part I

The problem of communication for unmanned vessels

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

– Peter F. Drucker [Moyers (1988)]

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

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

Many projects are working on unmanned autonomous ships. Chapter 1 starts to describe why steps are taken towards autonomous and unmanned shipping, including the economic and social incentives. Followed by a description of projects, showing the technological push factor. This description will give more insight into the challenges as seen by others, for the introduction of unmanned vessels, which explains the relevance of research into the communication between manned and unmanned ships. We make a separation between the more exploratory projects, aimed to form a vision of the future, and the applied projects intended to develop prototypes in the short term. Chapter 2 relates these challenges to the decision model for ships. This decision model 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 safe unmanned shipping

This research will focus on improving safety at sea by mitigating the risk which comes with communication between manned and unmanned vessels. This challenge has not yet in the scope of the major projects. This chapter will first show why this transition is happening, thus what the social or economic incentives are. Followed by the technological drivers in the form of projects who work on autonomous shipping. 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 and deserves attention.

1.1 Why autonomous and unmanned shipping

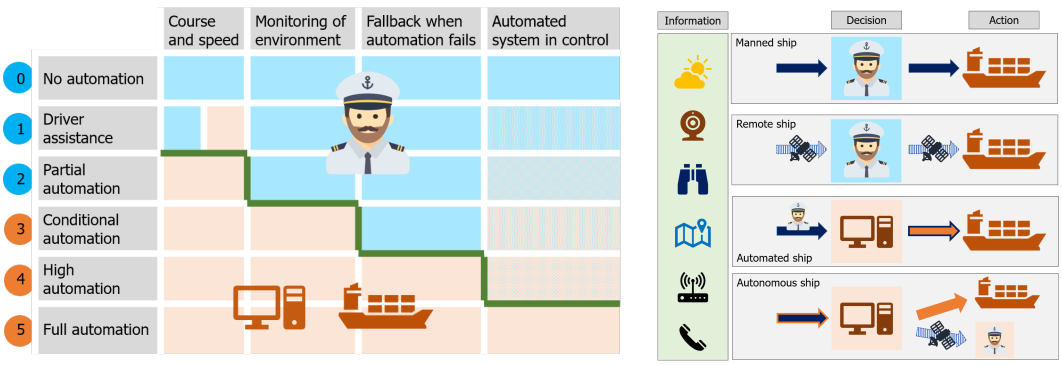
Due to digitalisation, ships will become more sophisticated. Sensors generate more data, improved connectivity and new ways to visualise data. These enable ships to communicate with managers and traffic controllers continuously. At first, this can be used to analyse data and give better advice based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

- *Improved safety*, as human errors cause most accidents. Moreover, unmanned ships will result in less crew at sea. Thus less crew is at risk when an accident occurs.
- *Lower cost*, as insurance goes down due to improved safety. Thereby is manning a large portion of total cost. More automation will result in less crew, which have to be schooled better.
- *Higher productivity*, as the utilisation rate of ships, can be improved, by using technological developments in connectivity. Thereby comes that computers do not 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 seafarers required to operate the vessels. At the same time, European shipping faces a lack of seafaring personnel already today [Cahoon et al. (2014)]. An often cited reason for this lies in the unattractiveness of seagoing professions, especially for youngsters. This unattractiveness is caused to so some extent, by seafaring's inherent problem of lacking family friendliness and the high degree of isolation from social life that comes along with working on a seagoing ship. The current trend towards slower sailing speeds justified by ecologic and economic considerations increase 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 labour market for seafarer as it would enable, at least partly, to reduce the intensity of ship operation. Routine tasks on board would be automated and only the demanding but interesting navigational and technical jobs will be transferred from the ship to a shore-side operation centre. Making "seafaring" jobs more attractive and family friendly than today. Furthermore, economic and environmental benefits when implementing unmanned shipping are expected. [MUNIN (2016)]

In the next sections are different projects around the world discussed, which work on the transition towards an 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. It 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 are responsible for the mentioned activity. Beside these levels of automation, are there also different types of automation, each with their 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 Ongoing 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 initial research between 2013 and 2016. Figure 1.2 illustrates how MUNIN focussed on different elements of an autonomous concept, this included among other things:

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

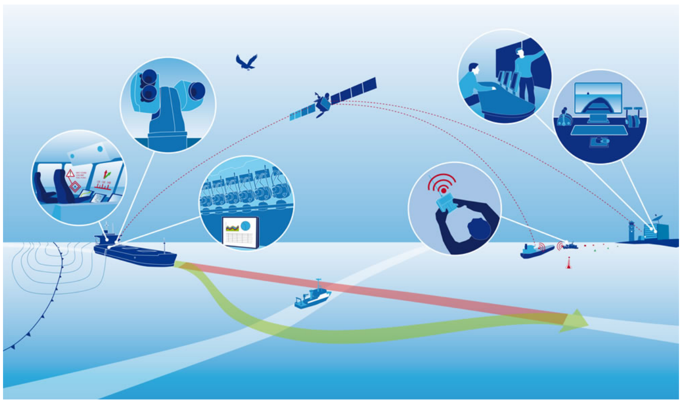


Figure 1.2: Illustration of MUNIN vision

They were thereby taking into account the feasibility of the developed solution, including legal and liability barriers for unmanned vessels. They concluded that unmanned vessels could contribute to the aim of a more sustainable maritime transport industry. Especially in Europe, shipping companies 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 MUNIN admits in their results that they have had a limited scope within the project [MUNIN (2016)]. They have shown the importance of developing a method to determine the intentions of other vessels and systems which are needed. However, did not yet make the step towards developing such a method, which is the scope of this report.

1.2.1 Exploratory projects

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

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

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

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

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

1.2.2 Industry projects

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

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

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

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

Figure 1.3: Render of Electric Blue

Figure 1.4: Render of Yara Birkeland

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

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

1.3 Stakeholders

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

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

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

1.4 Challenges when combining unmanned and manned vessel

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

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

2 | Decision model for safe operation

In the previous chapter, several projects are discussed, which gave insight in the challenges towards unmanned and autonomous shipping. To gain insight into the challenge of communication is a decision model used. This model shows which factors influence the decision-making process and how relevant research support this. The steps in this decision process are the same for manned and unmanned ships.

The decision process within the model is based on Boyd's OODA loop [Boyd (1987)], Endsley model for situational awareness [Endsley (2013)], and combined with models used in the projects as mentioned in chapter 1. The OODA loop has different phases: Observe, orient, decide and act. Similar to Endsley's model: Perceive, comprehend, project, decide and act. The combined model describes how this applies to, choosing the right strategy for safe operation, and relates to external factors and relevant theory. In figure 2.1 a visual of the decision model is shown which is used in this research, this model shows multiple phases in the decision process. The first step describes what can be observed, to form a mental model. The next step is to orient, which is split into the identification of the situation and future hazards. This step will result in a set of strategies, which will be evaluated using different criteria, resulting in a decision. After this decision, the operator administers an action. Which finally results in a new situation, observed in the next iterative step. This chapter will discuss these phases in more detail and how they relate to the challenge of communication, by discussing external factors and relevant theory.

2.1 Decision process

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

Mental model

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

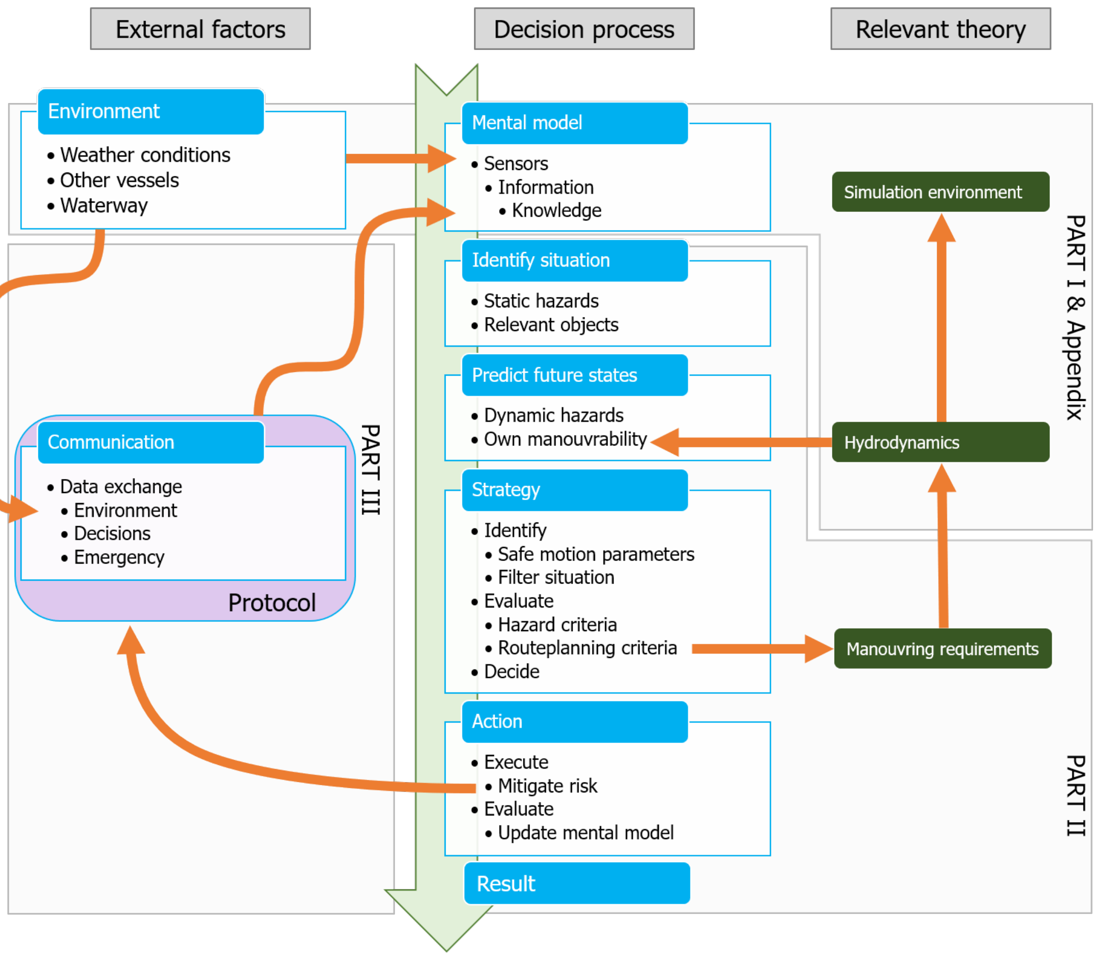


Figure 2.1: Decision model

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 the manned vessel, to form a correct mental model. For this research, only the result of this step is relevant: Is the acquired knowledge sufficient to identify the situation correctly, or is more information needed? Future technologies and sensors are not within the scope of this research, nor how their outputs result in useful information.

Identify situation

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

Predict future states and decide on strategy

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

2.2 External factors

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

2.2.1 Environment

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. The wind and waves might limit the manoeuvring capabilities of a vessel. These are also the reason some vessels are not allowed to enter a port when wind or waves are too high. If such repercussions are necessary, depend on the layout of the waterway. Due to currents, operations (e.g. maintenance and fishery) or limited depth, might some area's be restricted. Operators acquire this information via communication channels, but communication channels which only allow receiving and not sending, such as Navigational text Messages (Navtex).

The same goes for standard information on other ships. They might send their location and speed via AIS, but still key is the ARPA. Due to weather conditions, these systems 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 the whole decision process itself is optimised to avoid communication. The same goes for communication with shore-based stations such as traffic controllers or in the future remote pilots. Sensors or current systems are not able to retrieve this information. Such as a place and time to berth or pick-up a pilot.

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

2.2.2 Communication

As described are there still cases in which communication is necessary. We discuss in part III the case where communication between manned and unmanned vessel is needed. Using the situated Cognitive Engineering (sCE) method a protocol is defined, based on existing systems and protocols. Thus using AIS to send written messages, or VHF and 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.