



# MSc Thesis

New TITLE desribing the research

Ingmar Wever (4161041)  
July 31, 2018



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MSc Thesis  
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July 31, 2018

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# Notes

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Supporting why research is relevant. . . . .	2
link structure to chapters . . . . .	2
simplify graphic to make it more relevant . . . . .	6
give extended descriptions of systems . . . . .	7
How is information used. Mention parts on information overload. Thereby also the difference between ships. Officer walking around on big ship, vs small bridge on a tug for example. . . . .	9
Are these really relevant accidents, add more/other? . . . . .	16
Add images of resulting damages . . . . .	16
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Reference to infographic with time-line unmanned/autonomous levels . . . . .	23
change name so all projects are positive . . . . .	23
give more info on projects and why my research has added value to them. . . . .	24
more info on JIP and Soevereign . . . . .	24
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also describe the rules, which might be based on signs . . . . .	33
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## Preface

## **Abstract**

# Glossary

list of  
used  
symbols

## Abbreviations

**AIS** Automatic Identification System

**AMS** Alarm Management System

**ARPA** Automatic Radar Plotting Aid

**BNWAS** Bridge Navigational Watch Alarm System

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

**CFD** Computational Fluid Dynamics

**COLREGs** Convention on the International Regulations for Preventing Collisions at Sea

**CPA** Closest point of approach

**DOF** Degrees of freedom

**DP** Dynamic Positioning

**ECDIS** Electronic Chart Display Information System

**ENC** Electronic Navigational Chart

**GNSS** Global Navigation Satellite System

**GPS** Global Positioning System

**GT** Gross Tonnage

**IEC** International Electrotechnical Commission

**IHO** International Hydrographic Organization

**IMO** International Maritime Organization

**JIP** Joint Industry Project

**MARPOL** International Convention for the Prevention of Pollution from Ships

**no-UI** Non-visual User Interaction

**sCE** situated Cognitive Engineering

**SMCP** Standard Maritime Communication Phrases

**SMNV** Standard Marine Navigational Vocabulary

**SOLAS** International Convention for the Safety of Life at Sea

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

**TEU** Twenty foot Equivalent Unit

**UID** User Input Device

**VDES** VHF Data Exchange System

**VHF** Very High Frequency radio

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# Introduction

Considering the major projects within the maritime industry [SMASH(2017)] [Eriksen(2017)] [MUNIN(2016)] [Sames(2017)] [Rolls-Royce(2015)] [Waterborne(2016)]. It can be assumed that unmanned and autonomous shipping are getting closer. Mitigating human errors can be done by taking out seafarers from the chain of command, however this will introduce new challenges. For example, the communication with other vessels and decision making in unknown situations. Communication is used to share information on the intentions or discuss future actions. This means the safety of all vessels (manned, unmanned, remote, automated and autonomous) can be ensured. The question which should be asked is: When do vessels have to know each others intentions, certainly when only limited communication is possible? This is most relevant when sharing short term intentions which determine the path. As decisions must be made on changes for the path, within minutes or even shorter.

## Context

A computer might like to have as much information as possible. But in case of manned vessels this is not practical, as this will result in an information overload of the crew and communication channels [CCNR(2017)]. Currently is secured in two ways, how intentions of other vessel can be acquired. First and foremost are the Convention on the International Regulations for Preventing Collisions at Sea (COLREGs)[IMO(1972)], rules applicable to all vessels. They can be seen as ship separation rules, which guide 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, thereby is it possible in most cases to program them into a decision model. Examples are to stay on starboard side of the shipping lane and to not cross other ships with small relative angle. However in critical situations such as the entering of harbors or in busy parts of the world, the VHF radio must be used to ensure that intentions are clear, as the COLREGs are not always sufficient anymore in these cases.

To make autonomous shipping possible, autonomous vessels should know how to communicate their intentions. Doing this by behaving in a predictable manner and without overloading the different VHF channels (including AIS). Other options are to develop a new system, or separate autonomous traffic from other vessels. This will be much harder to implement, but even in those cases, the manner of sharing intentions should still be worked out. This is done by making sure that the radio is used correctly, clear signs which can be interpreted from the behavior and data exchange in other ways. Which all ensures that other vessels know enough about the intentions to anticipate correctly, without overloading communication channels.

To solve the problem, different parts should be taken into account, different vessels have different expectations for other vessels, as characteristics which determine the manoeuvrability differ and strategies for specific situations depend on many factors. For example will a cargo ship follow a fairly predictable path. While a small tug boat might move around much more. This means much 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. The first will consider the situation where verbal radio communication is taken out completely. In this case decisions must be made clear earlier and more bold to ensure others are aware of your intentions and can anticipate correctly to this. To ensure an unimpeded voyage this must be done in time. This so-called time-domain for decision making can be determined by taking several steps. First the possible decisions must be determined, these are mapped to possible positions using the manoeuvring capabilities of the ship. Combing these results with similar analysis for surrounding ships, the likely decisions can be determined which will lead to an unimpeded voyage. Where an unimpeded voyage means that no verbal communication via VHF-radio is needed, to ensure a passage without perceived risk.

The second part will focus on sharing information to optimize estimation of the time-domain. Much has been done and is still under development on how to get more information to the seafarer. However more information is not the solution. The right information is more important. In the situation as described in the first part, there will be no verbal communication. Therefor other means of communication are needed. Using for example sensors like radar, communication via AIS or a new system. The raw data from these sources will together form the information needed to create the decision domain. The first step to known which sources are needed, is to know which information is desired. Thereby will be determined what the impact of different information is on the decision making process.

Both parts will model the steps from interpreting information and making strategies based on this information, also known as situational awareness of the vessels. To test these models, a tool is developed. In this tool situations at sea can be simulated. The input will be the different models developed in the above described parts, together with situations and sea. The simulation shows which strategies are chosen by the different sets in different scenarios, when different models are implemented.

## Research questions

The above mentioned models are all steps towards autonomous shipping. This research will be a start, including mostly qualitative research. Eventually it is the aim to use the models to form a register of possible decisions. By looking into which information is most relevant for the different vessels. This will be done from two perspectives within the domains of Maritime Technology and Computer Science. Resulting in two research questions:

*How do ship characteristics influence the time-domain for decision making, to ensure that the chosen strategy will result in a safe minimal distance between vessels?*

*Which information must be shared between vessels, to ensure that likely decisions of other vessels can be predicted correctly?*

Add figure with line with available information, certainty correct decision is being made. Supporting why research is relevant.

## Report structure

Within the project, several steps will be taken. At first more context is given on the current

link structure to chapters

state of the maritime industry in respect to autonomous sailing and ways of communication. Thereby mentioning how the knowledge developed in this research, will help to tackle challenges. Next a more detailed plan of approach for the development of an application is given, showing which factors should be taken into account and how this will eventually lead to an application in which models can be verified and validated.

Followed by two different parts. First on the forming of a time-domain for decision making. Within a simulation environment, a model is formed which is based on the current situation for sharing information. This model is used to form strategies to cope with specific situations which occur while sailing. To validate if it is possible to use this model, different scenarios are defined which are used as test-cases. These scenarios will be tested within the simulation environment. Requirements for this simulation are first defined, which lead to user stories and an implementation. This simulation is finally validated together with seafarers on the quality of the communication and if ships act realistically within the different scenarios. This is used to give an qualitative advice on how to optimize communication, or more specifically which information should be shared.

The next part will use the previously developed model where variation are made to the information which will be shared between vessels. To determine which information should be shared in more complex situations where current systems for sharing information are not sufficient. Thereby is studied what the impact is of varying the information on the previously mentioned strategies to cope with the specific situations.

## **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.

New technologies led to new ways for communication, which subsequently led to safer operation. But new technologies also lead to complexer situations. As ships get bigger and perform more complex operations, resulting in less manoeuvrability. In those situations it is very important to share the right information at the right time. The current situation of the maritime is assessed together with a summary of likely new technologies related to navigational safety.

First the technologies which are currently used to ensure safe navigation of vessels is discussed. This is followed by a description of accidents which occurred, giving insight in the mistakes made and how this can be avoided with improved systems. Which projects on these new systems and unmanned ships are discussed in chapter 3. The development of autonomous and unmanned ships are discussed, as these have advantages when it comes to safety. The last chapter of this part will describe a model to discuss the knowledge which will autonomous and unmanned ships will be safer.

# 1 | Current systems for safe navigation

Before developing new systems and procedures to improve safety, the first step is to know what is currently available. Thereby should be considered how different types of information can be supplied. Nowadays decisions on navigation are taken from the bridge. Thus all information must be available there. To gain insight in a structured way, the bridge is split into four elements as described by DNV-GL. The human operator, procedures, technical system and the human-machine interface. As shown in figure 1.1 [DNV GL(2011)]. In this chapter these elements will first be discussed, how they are in theory. This is followed by a discussion on the differences between this theory and practice. Which results in a conclusion on relevant systems for the communication between manned and unmanned ships.

simplify graphic to make it more relevant

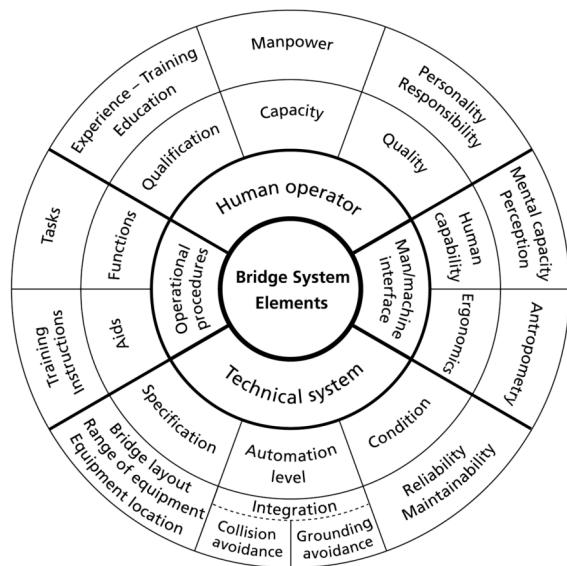


Figure 1.1: Bridge system elements

## 1.1 Technical system

The most straightforward element are the instruments and equipment at the bridge. The different classification societies have lists describing the equipment at the bridge. These are based on the regulations for navigational equipment on board of ships from the International Convention for the Safety of Life at Sea (SOLAS), a modern ship should at least have:

- Magnetic compass
- Gyro compass
- ECDIS
- Transmitting heading device
- Automatic Identification System (AIS)
- Receiver for Global Navigation Satellite System (GNSS)
- Internal communication system
- Bridge Navigational Watch Alarm System (BNWAS)
- Telephone for external communication
- Radar
- Radar beacon
- Daylight signaling lamp
- Speed and distance measuring device
- Echo sounding device

- Rudder, propeller, thrust, pitch and operational mode indicators
- Rate of turn indicator

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

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

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

give extended descriptions of systems

### **Automatic Radar Plotting Aid (ARPA)**

Automatic radar plotting aids are essentially utilized to improve the standard of collision avoidance at sea. Primarily designed as anti-collision radar. which calculations, image

### **Very High Frequency radio (VHF)**

### **Electronic Chart Display Information System (ECDIS)**

### **Automatic Identification System (AIS)**

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

in operation at all times except where international agreements, rules or standards provide for the protection of navigational information.

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

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

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

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

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

- Position report, reports navigational information.
- Standard class B equipment position report, less detailed report for vessels using class B transmitters.
- Base station report, used by base stations to indicate presence.
- Static and voyage related data, gives information on a ship and its trip
- Binary addressed message and acknowledgment, an addressed point-to-point message with unspecified binary payload.
- Binary broadcast message, broadcast message with unspecified binary payload.
- Standard Search and Rescue Aircraft Position Report, used by an aircraft (helicopter or airplane) which is involved with search and rescue operation on the sea (i.e. search for and recovery of survivors of an accident at sea).
- Addressed Safety-Related message and response, used to send text messages to a specified vessel.

- Interrogation, used by a base station to get the status of up to 2 other AIS devices.
- Aids-to-navigation report, used by an (AtN) aid to navigation device (buoys, lighthouse, etc.).
- Multiple slot binary message with communications state, used to transmit binary data from one device to another.

## 1.2 Man/machine interface

Previously all information was plotted by hand on navigational charts. With the developments of integrated bridge systems and for example the ECDIS, this is not necessary. This also means that a digital representation of the environment is already being made. Including calculations, relevant for navigational safety. These also give warnings to avoid collisions or represent information received via VHF. This is done in a way which is more easy to interpret by the officer of watch, as for example AIS, Electronic Navigational Chart (ENC) and the radar are combined. Examples of the different systems can be found in figure 1.2.

These screens are all integrated in some way into the bridge console. Depending on the size of the vessel, the lay-out may differ. Although, there are also regulations for the placement of systems in SOLAS. Examples of these bridge layouts can be found in figure 1.1.

## 1.3 Human operator

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

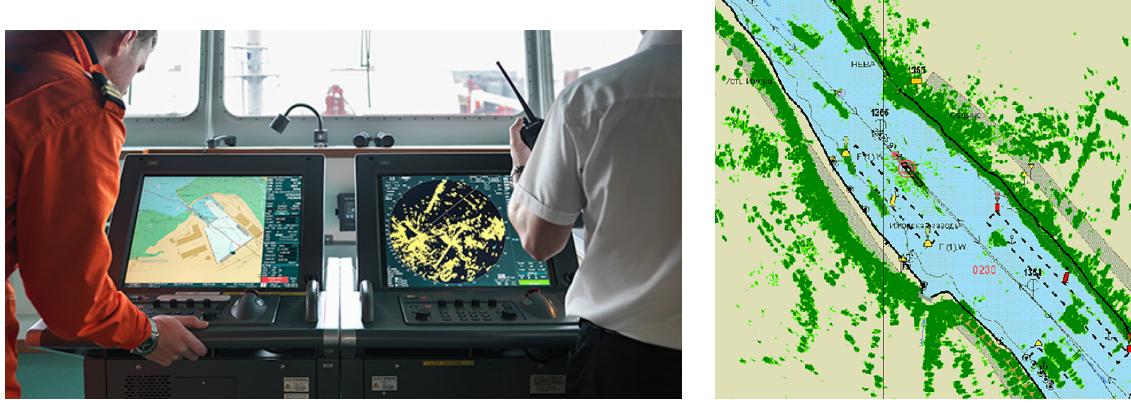
### Role as operator

To give more insight into the different roles on board of a merchant's vessel, is the structure shown for officers in figure 1.4. At smaller vessels, roles are combined where possible. The Navy has in some cases even more operational crew members. Apart from the licensed officers who manage the vessel, does the crew also consist of ratings who have hands-on skills within their own domain. [Nedcon(2013)]

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

The supreme authority on board a merchant's vessel is the Master or Captain. The entire crew is under his command. He is responsible for the safety, use and maintenance of the vessel and makes sure that every crew member carries out his work accordingly. He is also in charge of

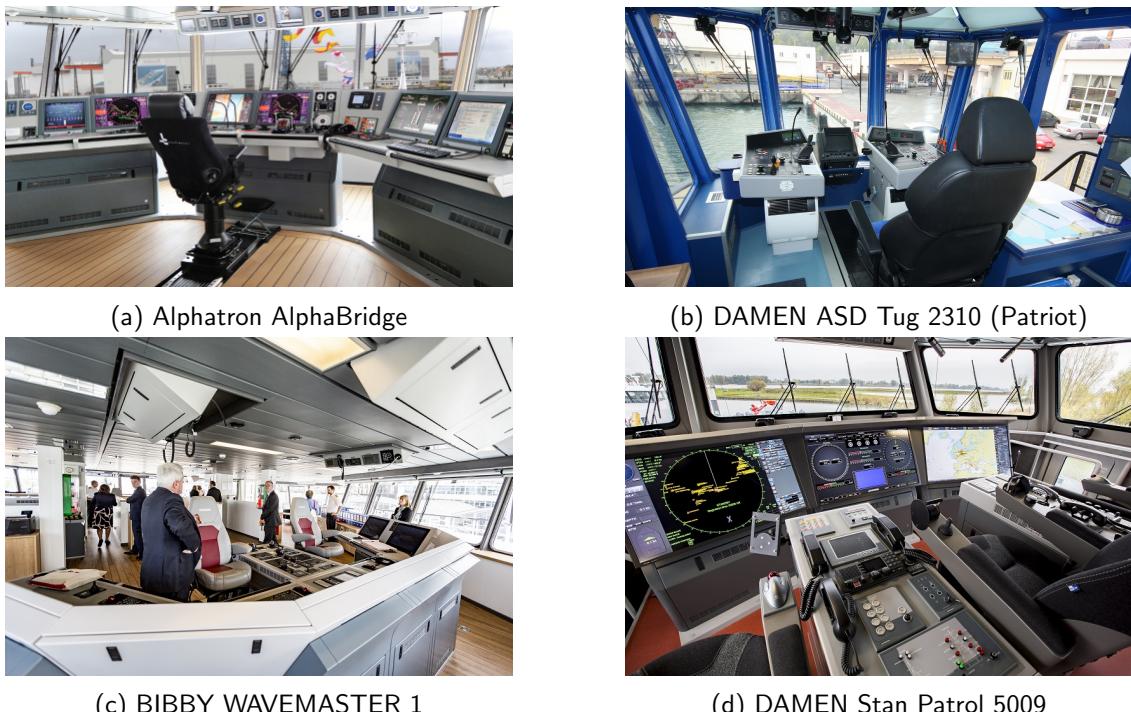
How is information used.  
Mention parts on information overload.  
Thereby also the difference between ships.  
Officer walking around on big ship, vs small bridge on a tug for example.



(a) Separate screens for ECDIS and Radar

(b) Radar overlay

Figure 1.2: Electronic Chart Display Information System (ECDIS)



(a) Alphatron AlphaBridge

(b) DAMEN ASD Tug 2310 (Patriot)

(c) BIBBY WAVEMASTER 1

(d) DAMEN Stan Patrol 5009

Figure 1.3: Various examples of bridge designs

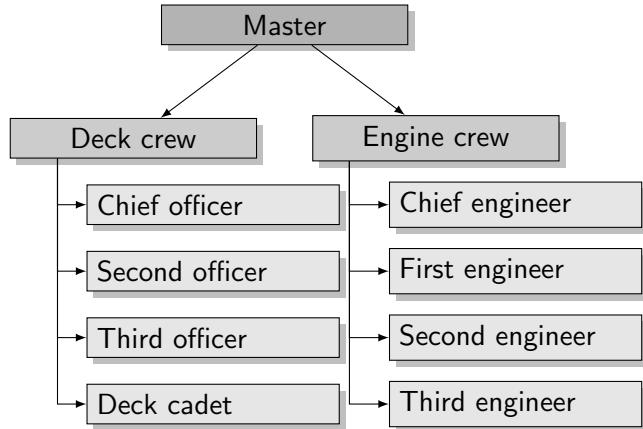


Figure 1.4: Crew structure basic

the following: payroll, ship's accounting, inventories, custom and immigration regulations, and the ship's documentation. In order to become Master, a seafarer must first have several years of experience as a deck officer and as Chief Officer. According to the vessel's hierarchy, the first deck officer and the head of the deck department after the Master is the Chief Officer. He is in charge of the vessel navigation, watch duties, charging and discharging operations. The Chief Officer also directs all the other officers on deck, creates and posts watch assignments and implements the Master's orders in order to maintain safe operations and maintenance of the vessel. Second Officer or Second Mate is the next in rank after the Chief Mate and is the ship's navigator, focusing on creating the ship's passage plans and keeping charts and publications up to date. Apart from watchkeeping, the Second Officer may also be designated to train the cadets on board or to fulfill the rank of security, safety, environmental or medical officer. The Third Officer or Third Mate is the fourth deck officer in command and is usually the Ship's Safety Officer, responsible for ensuring the good functioning of the fire-fighting equipment and lifesaving appliances. He undertakes bridge watches and learns how to become a Second Officer. A Cadet on board a merchant's vessel receives structured training and experience on board and learns how to become a deck officer.

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

### **Human factor**

At unmanned autonomous vessels the human operator will be replaced by a computer. This means that the duties as described above will be executed by a computer. This automation

step has unknown consequences for the ability to observe and decision making. While it has clear advantages when it comes to memory and reduced concentration due to fatigue.

Situational awareness is a model to determine the ability to observe and make decisions. How well humans perform is determined by their (learning) experience [Underwood et al.(2013)]. Hereby is important to notice that situational awareness is not limited to perceiving, but has multiple levels. This is described using the Endsley model (figure 1.5).

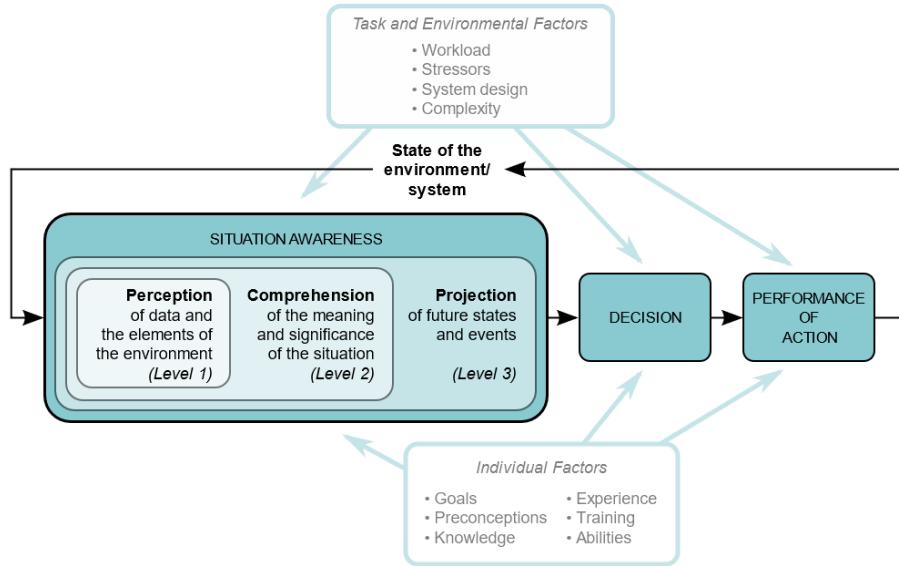


Figure 1.5: Endsley model for situational awareness

The first step is to acquire situational awareness. This is based on three different levels of information processing [Kalloniatis et al.(2017)]:

**Perception** Data is merely perceived.

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

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

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

Whereas the human operator is more prone to environmental factors. Where workload is a big factor in the ability to concentrate and thus the ability to forecast future states

and thus make the right decisions. The workload might be too high due to an overload of information [Speier et al.(1999)], when tasks are too easy [Washburn and Putney(2001)], or when limited attention is desired for a long time, and something unexpected happens [McMorris et al.(2018)].

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

## 1.4 Procedures

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

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

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

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

The COLREGs includes 41 rules divided into six sections: Part A - General; Part B - Steering and Sailing; Part C - Lights and Shapes; Part D - Sound and Light signals; Part E - Exemptions; and Part F - Verification of compliance with the provisions of the Convention. There are also four Annexes containing technical requirements concerning lights and shapes and their positioning; sound signalling appliances; additional signals for fishing vessels when operating in close proximity, and international distress signals.

Where part B is most relevant for this research, with subject like safe speed, obligation to determine risk of collision and take action with all means available, how to act in different situations with other ships, or in restricted waterways.

### Standard Maritime Communication Phrases (SMCP)

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

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

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

**Advice** Stand by on channel 6 - 8.

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

**Warning** Buoy number: one - five unlit.

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

**Question** What are your intentions?

**Instruction** You must alter course to starboard.

**Request** Immediate tug assistance.

## 1.5 Difference between theory and practice

How does it go in practice, experience.

Certainly in inland water or near coast conversations might be in natural language, instead of SMCP.

Mention the problems with ECDIS/AIS (old information, not correct as mentioned bylood-swezen), as I refer to this in snapshots scenario description.

## 1.6 Relevant systems for autonomous shipping

Not everything is relevant to other ships, in order to determine the possible decisions. This is only: information from radar, information available in AIS (where reliability must be considered), warning systems, etc...

- Radio communication
  - Conversational agent using Standard Maritime Communication Phrases (SMCP)
  - Availability on Very High Frequency radio (VHF)
  - Automatic Identification System (AIS) messages
- Visible signals
  - Light signals
  - Flags
  - Mast head signals
  - Heading, position and movements
- Audible signals
  - Horn
  - Speakers
- Distress, urgency and safety signals
  - Flares
  - Smoke

## 2 | Accidents

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

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

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Are these  
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damages

## 2.1 MV AL ORAIQ and MV FLINTERSTAR

During the night between 5 and 6 October 2015 on the Northsea near Zeebrugge, a collision occurred between the LNG tanker AL ORAIQ, sailing under the Marshall Islands flag, and the FLINTERSTAR cargo ship, sailing under the Dutch flag. The FLINTERSTAR sank almost immediately as a result of the collision, an illustration of the accident is shown in Figure 2.1. The captain of the FLINTERSTAR was badly injured in the incident but the other ten people on board and the pilot were rescued out of the water unharmed.



Figure 2.1: Illustration map of approximate collision location

The collision occurred because the bridge team on board of the AL ORAIQ wrongly assessed the traffic situation, vessel's speed and distance from the S3 buoy, prior to contacting the nearby vessel Thorco Challenger. After informing the Thorco Challenger, did they pass on the starboard side. On board of AL ORAIQ were coastal pilots which did not receive feedback from the watch keepers, nor was there feedback from other vessels via VHF radio. The communication which went via VHF radio was mostly in dutch, the officer on duty at AL ORAIQ did not request the Coastal pilots to translate. Also did the bridge watch team not assess the situation properly, leading to very little situational awareness. On board of the FLINTERSTAR there was insufficient attention for watch keeping duties. As several VHF radio communications between Traffic Centre Zeebrugge and other participants within the area monitored by Traffic Centre Zeebrugge, concerning or involving the presence of an inbound LNG carrier were missed by the Pilot and other crew at the bridge on board the FLINTERSTAR. The pilots on board of AL ORAIQ did not attempt to work together. Thereby making decisions without consulting the crew, such as overtaking other vessels. Thus the coastal pilot did not act consistently with international understanding, where a pilot is an advisor to the ship's master. Which means mutual understanding for the functions and duties of each other, based upon effective communication and information exchange. The sea pilot on board of the FLINTERSTAR got engaged in a casual conversation with the officer of the watch, drawing his attention away from monitoring the traffic situation. The Sea Pilot was advising the officer of the watch from what appeared to be routine. [Backer(2015)]

## 2.2 USS FITZGERALD and MV ACX CRYSTAL

A more recent well-known collision was between the USS FITZGERALD and ACX CRYSTAL on 17th June 2017. The US destroyer hit the larger Philippines container vessel resulting in the death of 7 US Sailors. An illustration of the accident is shown in figure 2.2. According to the accident report did failures occurred on the part of leadership and watch-standers. There were failures in planning for safety, adhere basic navigational practice, execute basic watchstanding practice, proper use of available navigation tools and wrong responses.

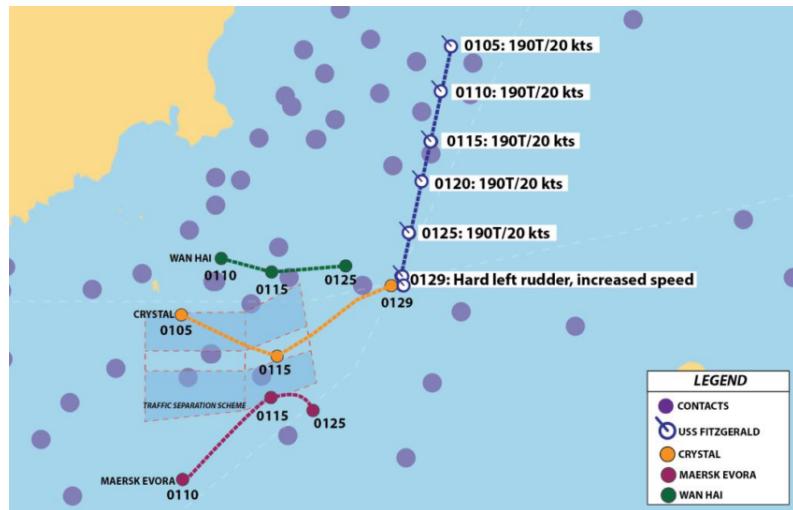


Figure 2.2: Illustration map of approximate collision location

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

## 2.3 USS JOHN S MCCAIN and MV ALNIC MC

Even more recent is the collision between the USS JOHN S MCCAIN and ALNIC MC on 21st August 2017. The US Destroyer hit the Liberia flagged oil and chemical tanker. Resulting in the death of 10 US Sailors. An illustration of the accident is shown in figure 2.3. According to the accident report did the US Navy identify the following causes for the collision: Loss of situational awareness in response to mistakes in the operation of the USS JOHN S MCCAIN's steering and propulsion system, while in the presence of a high density of maritime traffic. Failure to follow the international nautical rules of the road, which govern the manoeuvring of vessels when risk of collision is present. Watchstanders operating the JOHN S MCCAIN's steering and propulsion systems had insufficient proficiency and knowledge of the system.

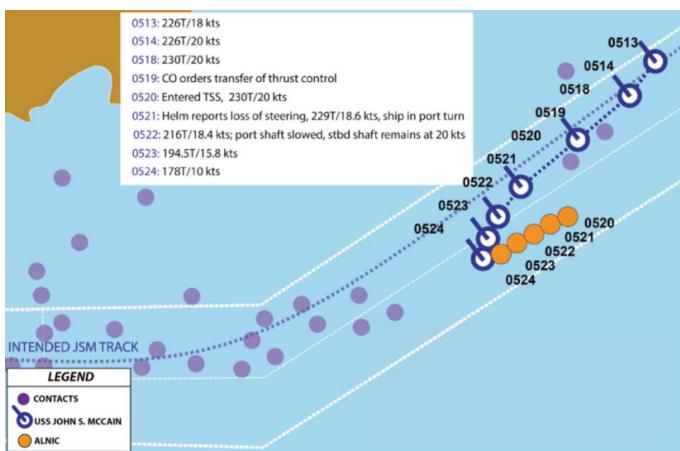


Figure 2.3: Illustration map of approximate collision location

Leading up to the accident did the commanding officer notice that the helmsman had difficulties maintaining course, while also adjusting the throttles for speed control. In response, he ordered the watch team to divide the duties of steering and throttles, maintaining course control with the Helmsman while shifting speed control to another watchstander. This unplanned shift caused confusion within the watch team, which led to wrong transfers of control, where the crew was not aware of. Watchstanders failed to recognize this configuration. The steering control transfer caused the

rudder to go amidships (centerline). Since the Helmsman had been steering less than 4 degrees of right rudder to maintain course before the transfer, the amidships rudder deviated the ship's course to the left. Additionally, when the Helmsman reported a loss of steering, the Commanding Officer slowed the ship to 10 knots and eventually to 5 knots. Due to the wrong transfer did only one shaft slow down, causing an un-commanded turn to the left (port). The commanding officer and others on the ship's bridge lost situational awareness. They did not understand the forces acting on the ship, nor did they understand the ALNIC's course and speed relative to USS JOHN S MCCAIN. Three minutes after the reported loss of steering, was it regained, but already too late to avoid a collision. No signals of warning were sent by either ship, which are required by international rules of the nautical road. Nor was there an attempt to make contact through the VHF bridge-to-bridge communication. Many of the decisions made that led to the accident were the result of poor judgment and decision making of the commanding officer. That said, no single person bears full responsibility for this incident. The crew was unprepared for the situation in which they found themselves through a lack of preparation, ineffective command and control. Deficiencies in training and preparations for navigation were at the base of this. [US Navy(2017)]

## 2.4 MV CONTI PERIDOT and MV CARLA MAERSK

The last accident which will be discussed is the collision between MV CONTI PERIDOT and MV CARLA MAERSK on 9th March 2015. At 12:30 central daylight time, the inbound bulk carrier CONTI PERIDOT collided with the outbound tanker CARLA MAERSK in the Houston Ship Channel near Morgan's Point, Texas. The collision occurred in restricted visibility after the pilot on the CONTI PERIDOT was unable to control the heading fluctuations that the bulk carrier was experiencing during the transit. As a result, the CONTI PERIDOT crossed the channel into the path of the CARLA MAERSK. No one on board either ship was injured in the collision, but an estimated 2,100 barrels (88,200 gallons) of methyl tert-butyl ether spilled from the CARLA MAERSK, and the two vessels sustained about \$8.2 million in total damage. In figure 2.4 the fluctuations in heading can be seen of the CONTI PERIDOT.

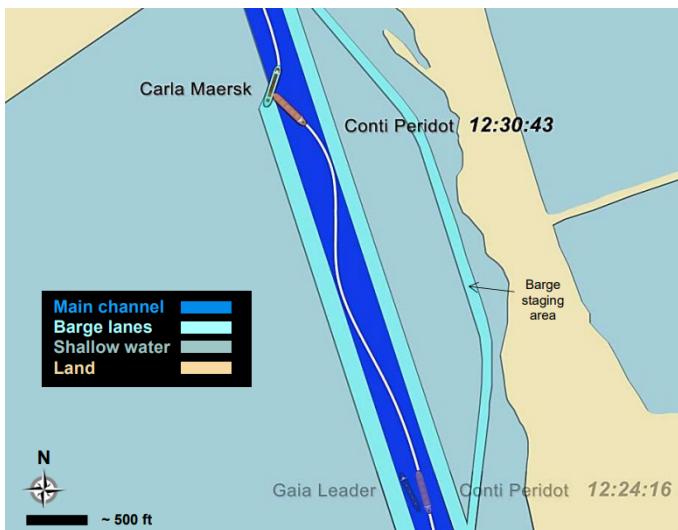


Figure 2.4: Illustration map of approximate collision location

Several safety issues were identified by the National Transportation Safety Board. Inadequate bridge resource management: Despite the pilot's difficulty controlling the CONTI PERIDOT's heading leading up to the collision, he and the master did not work together to solve the problem. The pilot did not involve the master because he was unsure whether the master could do anything to help; the master said nothing because he was likely unaware of the vessel's heading fluctuations and may have been generally reluctant to question the pilot. Insufficient pilot communications: Although the pilot on the CONTI PERIDOT was having difficulty controlling the vessel and had

an earlier near-miss meeting with an oncoming ship, he did not alert the pilots on subsequent oncoming vessels, including the CARLA MAERSK. Lack of predetermined ship movement strategies during restricted visibility in the Houston Ship Channel: On the day of the accident, local pilot associations determined that the increasing fog was significant enough to suspend pilot boardings of inbound ships. However, piloted vessels already under way continued the transit in the fog. Investigators found no existing predetermined ship movement strategy for piloted vessels already under way at the onset of hazardous weather conditions.

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

## 2.5 Lessons learned

For example: Proper bridge resource management is key, warning surrounding vessels if there is limited control is important, strategies for movements in failure modes should be predetermined.

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Summaries  
all  
lessons  
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accidents

## 3 | Steps towards the future

Current projects funded by the EU aim at sustainable growth. This means, be competitive while also reducing the environmental footprint and improve the safety of people working in the industry. [Eriksen(2017)] [European Commision(2017)] This research will mainly focus on improving safety at sea, being connected and able to message instantly is normal nowadays. Thereby also having the information where and when you want it. Many projects are working on manned and autonomous vessels. They have to build upon the previously developed technologies which are currently used. These technologies are mentioned in chapter 1. This chapter will discuss the steps which will be taken in the near future. First, why the step towards autonomous and unmanned is taken. Followed by a description of current projects to develop new technologies. To finally identify that which challenges will most likely arise in this process.

### 3.1 Why autonomous and unmanned shipping

Focusing on the 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 are 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.

Reference to info-graphic with time-line un-manned/au-tonomous levels

## 3.2 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.

### 3.2.1 Visionary projects

Rolls-Royce Marine is involved in different projects which are in some way follow-ups on the MUNIN project. Well-known are the videos of the virtual bridge concept and the Electric

change  
name  
so all  
projects  
are posi-  
tive

Blue vessel, as this was a first clearly drawn 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 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)]. To make these steps they were aware from the start on, that the control room is 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.

Other projects which have clearly published their vision for the future are: - DIMECC with (One Sea)

- AAWA
- ReVolt

Since June 2017 is Rolls-Royce also involved in the unmanned cargo ship development alliance, which is initiated by Asian companies and classification bureaus. In the Netherlands a Joint Industry Project (JIP) has started on autonomous shipping.

Make infographic: combining different roadmaps, such as DIMECC and Rolls Royce, thereby also showing the different levels of automation and unmanned

give more info on projects and why my research has added value to them.

more info on JIP and Sovereign

Make infographic

### 3.2.2 Industry projects

Beside the visionary projects mentioned before, some companies are also coming with real results. 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. 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)].

### 3.3 Other stakeholders

State of Lloyds and IMO, developing codes for autonomy level and certification of unmanned vessels.

update  
with  
info from  
IRYOON

### 3.4 Possible use cases

Summarizing the projects, based on this what would be likely use cases:

- Tugs as extra actuator in DP-like system

- Local transport between factories, terminals, etc.
- Crude oil tankers which are traded while at sea
- Short sea shipping (most pilots)

### 3.5 Changes in communication

Describe the impact on the different facets of the bridge (Technical system, man/machine interface, procedures, human operator). e.g: VDES

### 3.6 Challenges when combining unmanned and manned vessel

For unmanned vessels a new system for communication must be developed, as human speech is very hard for computers. The cost of development for this new system depends on the amount of situations it has to cope with. By adjusting the operational strategies for unmanned ships to avoid complex situations as much as possible, these situations can be kept to a minimum. The challenges which have to be tackled are therefore how these ships can avoid complex situations. This means that they have to take decisions well in advance so others are aware of their intentions. Still some challenges are open, as not all complex situations can be avoided. For these cases still must be thought about which information should be shared to make the right decision. Which is related to the question, which systems are needed to share this information.



Figure 3.1: EXAMPLE-infographic: Timeline for autonomous ships by DIMECC

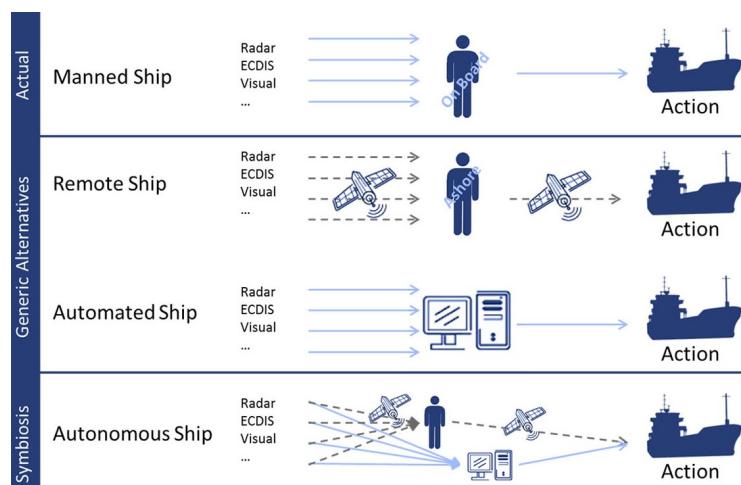


Figure 3.2: EXAMPLE-infographic: From manned to autonomous ships

## 4 | Abstract model

To gain more insight in the steps which should be taken towards unmanned and autonomous shipping. An abstract model is used, this model shows from which domains knowledge is needed or should be developed.

To form the set of possible decisions, different factors should be taken into account. To get insight in these factors, an abstract model is developed. This abstract model will link the creation of a mental model to the physical world, which is key in creating situational awareness. From this model different subjects can be derived, relevant to making the right decision at the right time, which result in the correct strategy to cope with the specific scenarios. In figure 4.1 a visual of the abstract model is shown. In this chapter different parts of the abstract model will be discussed in more detail.

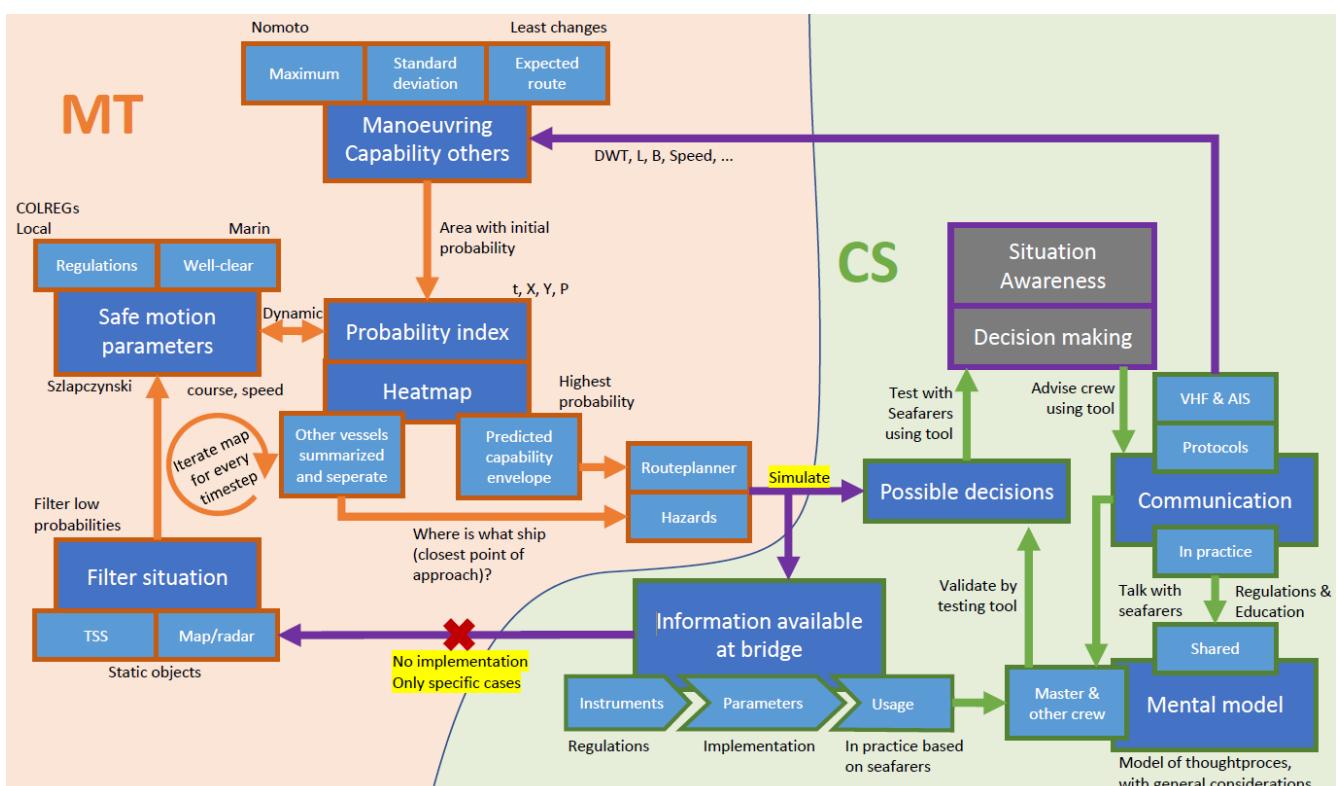


Figure 4.1: Abstract model

### 4.1 Ship characteristics

The main block on manoeuvring capability depends on the ship characteristics. Where there is an influence on both feeling of safety, and the physical limitations. For example a ship crossing another vessel could keep sailing straight as long as possible and than make a hard turn, but it rather changes its course earlier in a way where less loss of speed occurs. With a small ship these hard turns are much easier and will most likely occur more often.

Therefore the capability of the ship is split up in three categories, expected location, likely

change of course and physically possible route based on physics laws. As a full CFD simulation is hard to do for every ship which is encountered, models will be used to make estimations quickly. Thereby it is important to notice that a high accuracy is not necessary, as those extreme movements have a very low probability to occur. Being a bit conservative here will help to allow for all different scenario's to be tested.

## 4.2 Influencing factors

The same goes for the safe motion parameters. There are regulations on minimal passing distances and how close you should come to others. But good seamanship would be to make intentions clear earlier, so that critical situations can be avoided. Applicability of rules depends on the ship characteristics. Just as with the natural laws, the probability of getting into the extreme situations where regulations are followed but still problems might occur are not likely. The model from Szlapczynski is used, to set the estimated safety domains for each ship. Leading to courses and speeds which are safe to sail [Szlapczynski and Szlapczynska(2017a)]. While also incorporating COLREGs and arbitrary distances for well-clear, which is the distance where everyone feels safe. The COLREGs are also relevant in areas around ports, where traffic separation schemes are used. These should be followed by different types of vessels. This will influence the most likely position for a vessel to be. Incorporating information from traffic controllers will thereby lead to the most likely expected route. The same goes for areas with multiple objects on the map, where ships should follow lanes marked by buoys, and avoid quays, fishing area's, no-go zones, etc. Combining this with ship characteristics will lead to a map where for each vessel is shown, where another ship will likely be. When looked at the highest probability this will show the most likely route for each vessel. Which can be used to advise on the route planning of the own vessel. As the probabilities combined with a threshold will result in a set of possible decisions.

## 4.3 Information and communication

Already mentioned is the impact of other vessels and objects on the probability that a ship will be at a specific location. But to know this impact, information has to be gathered from different parameters. Thereby should be looked if the current parameters are sufficient and can be trusted, or if other equipment or instruments should be installed.

Currently vision and radio communication are very important ways to gather information. These types of information are difficult to gather using computers, currently many researches happen on for example Lidar and other methods. Therefore this research will focus on what information is needed, not how it is gathered. Although developments within technologies to gather this information will be taken into account to develop eventually the strategies. For example related to AIS, VHF Data Exchange System (VDES) and different protocols.

## 4.4 Situational awareness

When combining information, communication, characteristics and possible decisions an image of the situation can be formed. This will be interpreted in a way which enables the right decision making for route-planning. This planned route can be used on autonomous vessels,

or be used to advise the crew which decision they should make and what information they should share with others. Mental models will be used to validate if indeed the different vessel have the right information and if enough information is shared. The results from these blocks will be verified with seafarers to validate that the theory corresponds with operations.

## 4.5 Focus of this research

This research will focus on criteria for choosing a specific strategy automatically. And in cases this strategy does not work, what kind of interface is needed between crew on other ships and an autonomous ship.

## **Part II**

# **Relevance of criteria for decision making**

The previous part described the context and the steps needed towards autonomous shipping. This chapter will focus on the decision making process. This is currently done by captains, on autonomous ships this should be automated. To accomplish this, criteria must be known on which these decisions can be based.

To determine the criteria, a ship will have to identify the situation and specific scenario first. These determine which criteria are relevant. For different possible strategies these criteria are evaluated. Based on this evaluation, the right strategy can be chosen. A model in which all this is incorporated is John Boyd's OODA loop [Boyd(1987)]. This model is used in many similar cases, but mostly in military command and control situations [Arciszewski et al.(2009) [Kalloniatis et al.(2017)].

The first steps within this model are to observe, orient, decide and act. Within this part a description is given how this applies to choosing the right strategy in common maritime encounters. The first step describes what can be observed in order to identify the situation. In the orientation phase the situation is evaluated using different criteria. This will result in a decision on the right strategy. To form the decision model using the identification and evaluation, first there will be case studies, where all steps in the decision making process are discussed. Which results in a rule-based time-domain decision model.

This model is consecutively implemented into a tool to test if ships act as expected. By more varying the scenario's, gaps in the rule-based model can be found. Some might be possible to tackle by extending the database with more strategies or criteria. When this is not possible, ships will have to communicate to find the right solution. What should be communicated is not part of this research, how this is done will be discussed in part III.

This part will also include the design of the tool which is used to evaluate the model and test new strategies to improve navigational safety. The tool will include different modules to make sure a realistic simulation can be done. These modules contain for example a manoeuvring model and traffic controller.

<https://www.artofmanliness.com/articles/ooda-loop/>

add picture of OODA loop

## 5 | Identify the existence of a problem

Different situations and scenarios can be identified. This identification is used to develop a decision tree. Using the OODA-loop different steps for decision making can be separated. The first step is to observe the situation, this is done by classification based on the path of nearby vessels. The next step is to orient, thus to determine the possible strategies. Next step is to decide which strategy is the right one, by evaluating criteria. Finally you must act on this decision. In this chapter the first steps classification the situation, based on observations is discussed. Followed by the steps taken in the orientation phase to form strategies.

ref to  
ooda-  
loop

### 5.1 Situation identification

Based on the observations different situations can be classified into four types, the different types are described below:

- *Passing*. Ships do get close, but the paths are not crossing
- *Crossing*. Paths of ships are crossing
- *Merge*. Two ships from different directions, heading in the same direction, strategy might lead in many cases to a take-over.
- *Take-over* Two ships following the same path with different speeds.

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 can be written as:

[current position, direction]

Combining paths of two ships will describe a situation. Using the system to describe paths. The situations can be written down as:

(path own ship | path other ship).

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 5.1. The boundaries are based on COLREGs and shown in figure 5.1.

use  
colreg  
bound-  
aries in  
junction  
and ter-  
minology  
(head-on,  
overtak-  
ing, etc.)

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 5.1: Standardized paths for situations

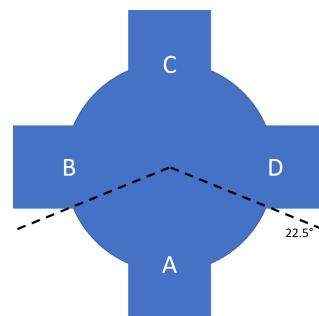


Figure 5.1: Path description

## 5.2 Strategy orientation

Before criteria can be evaluated, more detailed information is needed. Below different types of information are discussed and their consequences on the strategy.

### 5.2.1 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.

---

### 5.2.2 Actors

The second step is the identification of the dynamic objects. This are all objects which are moving. Most important 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 be considered, such as floating containers.

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.

add definition of static hazard and more examples, to make link to evaluation tool and tags

also describe the rules, which might be based on signs

add more examples to describe consequence on strategy

add more examples to describe consequence

### 5.2.3 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 do 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.

## 6 | Definition of criteria

?? To determine which strategy works best, 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. First the criteria which are true or false are discussed, followed by the current and proposed algorithms to calculate the other criteria.

### 6.1 Conditional criteria

#### 6.1.1 COLREGs

How is the path based solely based on COLREGs, without taking into account other ships

Most important rule of COLREGs, is that you are allowed to deviate from any rule if it will increase the safe operation. This is only the case when others also expect you to deviate.

use this <https://www.myseatime.com/blog/detail/8-colreg-rules-every-navigating-officer-must>

#### 6.1.2 Relative speed

#### 6.1.3 Bold movement

Combine paths to ensure bold movements

### 6.2 Calculations based on current systems

Within ARPA and ECDIS the criteria are often already calculated, using linearized algorithms. Below these calculations are discussed for the Closest point of approach (CPA) and crossing position.

#### 6.2.1 Closest point of approach (CPA)

Code snippet :

```
xA = shipA.location[0]
yA = shipA.location[1]
VA = shipA.speed
UxA = math.sin(shipA.course)
UyA = math.cos(shipA.course)

xB = shipB.location[0]
yB = shipB.location[1]
VB = shipB.speed
UxB = math.sin(shipB.course)
UyB = math.cos(shipB.course)
```

convert  
to nice  
latex  
math

```

if (shipB.course == shipA.course) and (shipB.speed == shipA.speed):
    distance = math.sqrt( (xB-xA)**2 + (yB - yA) ** 2)
    print('%s and %s parallel: %d meter apart' % (shipA.name, shipB.name, distance))
    return [distance, 0]

distance = math.sqrt((
    yA * VA * UxA - VA * yB * UxA - yA * VB * UxB + VB * UxB * yB - xA * VA * UyA
    UxA ** 2 * VA ** 2 - 2 * UxA * UxB * VA * VB + UxB ** 2 * VB ** 2 + UyA ** 2 *
    time_s = (((-xA + xB) * UxA - UyA * (yA - yB)) * VA + VB * ((xA - xB) * UxB +
    (UxA ** 2 + UyA ** 2) * VA ** 2 - 2 * VB * (UxA * UxB + UyA * UyB) * VA + VB *

```

### 6.2.2 Crossing distance

Code snippet :

```

locA = np.transpose(np.matrix(shipA.location))
locB = np.transpose(np.matrix(shipB.location))
p = locA - locB

UA = np.array([[math.sin(shipA.course)], [math.cos(shipA.course)]])
UB = np.array([[math.sin(shipB.course)], [math.cos(shipB.course)]])

d = np.concatenate((UB, -UA), axis=1)
n = np.linalg.inv(d) * p

crossing = locB + n[0, 0] * UB
relativeSpeed = n[1, 0] / n[0, 0]

```

convert  
to nice  
latex  
math

## 6.3 Proposed algorithm based on planned path

Using the planned path of the vessel, better estimations can be made for the closest point of approach and crossing distance. As this planned path is not available for other ships, without introducing new systems, an estimation is made for the likely path. 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.

Disadvantage: heavier computation and less accuracy due to numerical solve

### 6.3.1 Closest point of approach (CPA)

1. Check if something has changed since last calculation
  - (a) No, check out
  - (b) Yes, continue
2. Use waypoints to determine expected path for own ship (Bezier 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 points for each time-step, compare to stored CPA
    - (a) If smaller than stored CPA, update stored CPA with calculated CPA
- 

### 6.3.2 Crossing distance

### 6.3.3 Passing distance

use  
pseude-  
code  
with loop  
to skip  
timesteps,  
speeding  
up the  
calcula-  
tion

## 7 | Decision-model

In the previous chapters are ways to identify and evaluate a situation discussed, including a case study. This means the first two steps of the OODA loop are taken, observe and orient. The next step is to decide on the right strategy. Deciding on the right strategy also includes the moment this strategy should be executed. This is done using a rule-based time-domain decision model. First an ontology is defined. Followed by a database of scenarios and situations as defined in the previous chapters. Combining this with the rules will result in the decision model. Thereby is the aim of this decision model to avoid communication.

### 7.1 Decision phases

To describe the different phases in the decision taking process. An ontology is defined to describe these phases. Thereby is shown in figure [how these steps relate in a process diagram](#).

add process diagram

Class	Description
Situation	The first step is to identify the encountered situation, to determine which criteria are relevant.
Problem identification	The second step is to determine if there is a problem, as there is only a change in strategy needed when this is the case.
Strategy	If there is a problem, a new strategy can be chosen, this is based on the evaluation of the criteria.
Action	From this strategy, different actions will follow.
Result	Finally the result is evaluated, in a similar manner to the problem identification.

Table 7.1: Ontology used in decision model to describe phases

### 7.2 Tags for decision making

#### Encountered situations

This is the first step to limit the about of steps needed to get to the right strategy. The identification process is described in table 7.2 and section 5.1.

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.
Merge	The final direction of both ships is the same.
Over-taking	The paths of both ships are the same but at different speeds.

Table 7.2: Tags for different situations

### Identification of problem

To identify if there is a problem, different criteria are being evaluated. These criteria are described in chapter ???. In table 7.3 the nodes and branch tags 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 (CPA)	Good; Too close
Crossing point	In front; Behind
Crossing distance	Good; Too close
Relative speed	Faster; Same speed; slower

Table 7.3: Tags used for identification of a problem

### Possible strategies

Tag	Description
Follow planned path	
Move away from other path	
Stay parallel for longer	
Adjust speed	
Abort over-taking	
Move away from other position	Check if this is to starboard, otherwise communicate
Communicate	

Table 7.4: Tags for different strategies

### Possible actions

To execute a strategy, different actions are taken. These action are a combination of an action type, and a moment to execute action. In table 7.5 and 7.6 these are described.

Tag	Description
Continue without change	
Starboard	
Portside	
Slow down	
Speed-up	

Table 7.5: Types of actions

Tag	Description
Now	
In ... minutes	
After action ...	

Table 7.6: Time-domain for action

**Result**

Tag	Description
CPA	
Perceived risk	

Table 7.7: Tags for safe situation criteria

Tag	Description
Safe situation	
Communicate	

Table 7.8: Tags for results

**7.3 Decision trees**

Static analysis to identify the problem can be found in figure 7.1-7.4.

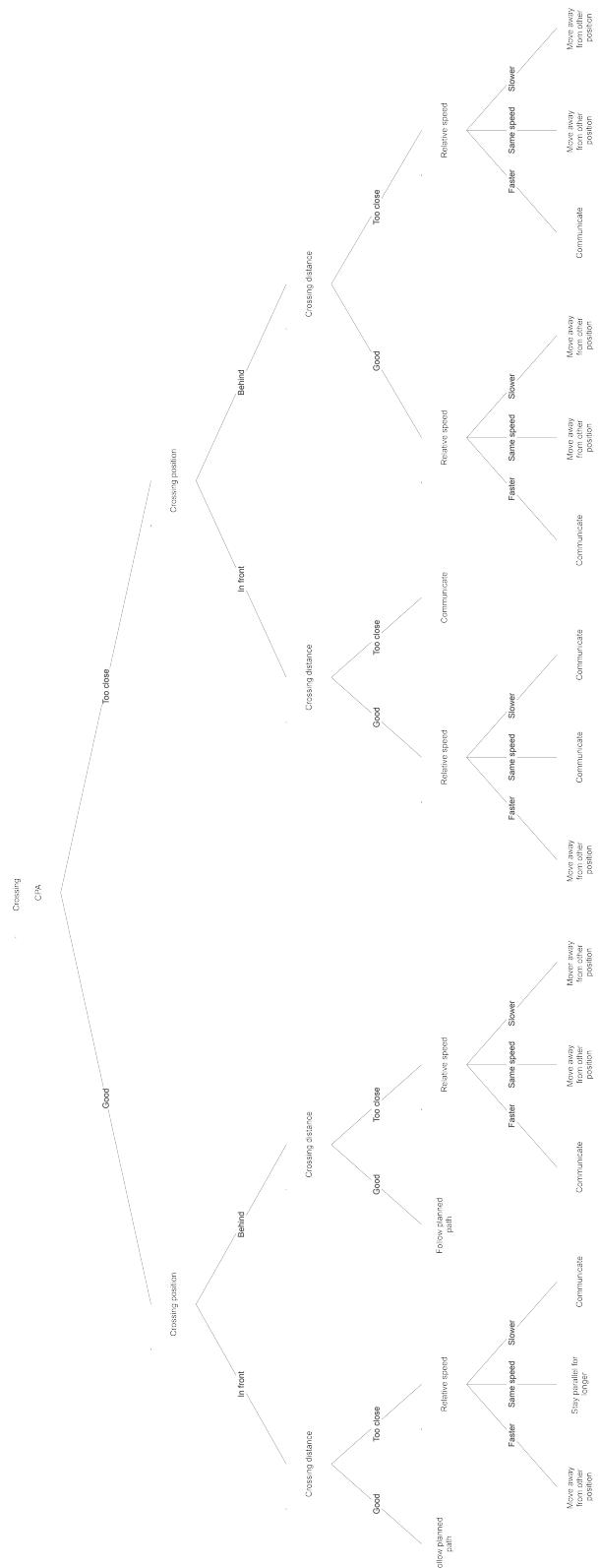


Figure 7.1: Decision tree when crossing

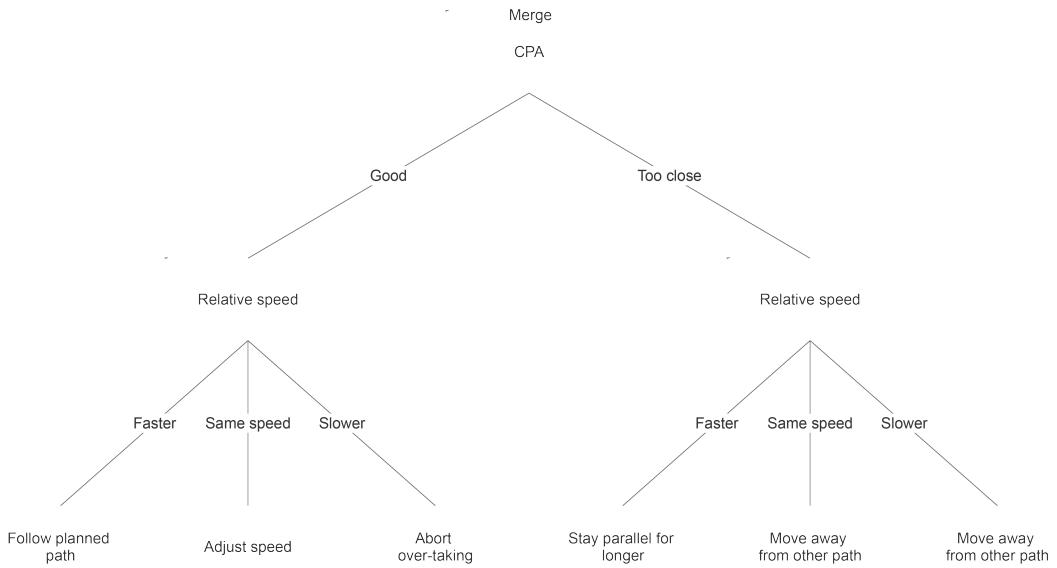


Figure 7.2: Decision tree when merging

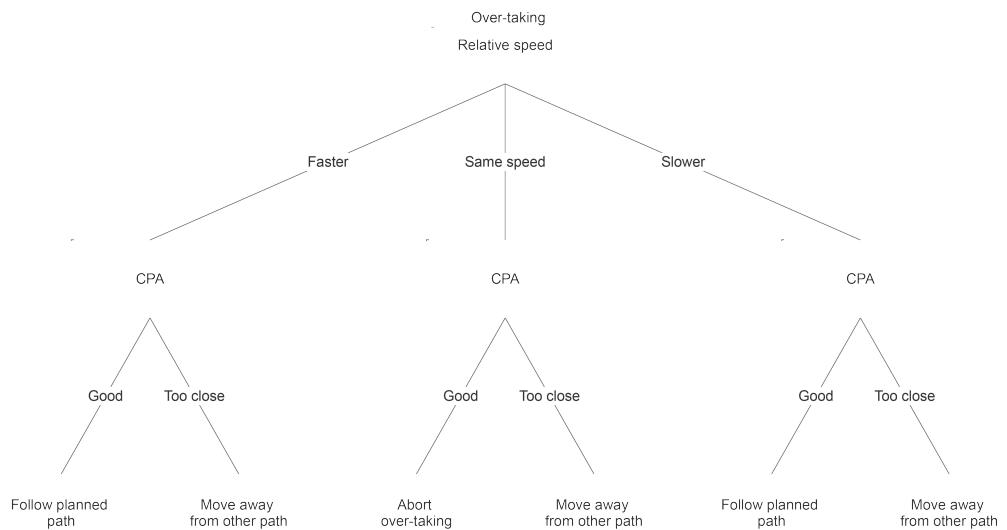


Figure 7.3: Decision tree when overtaking

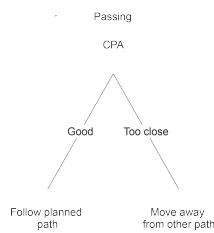


Figure 7.4: Decision tree when passing

## 8 | Analysis of scenarios

Example scenarios will be discussed in this chapter. This is done to determine the relevance of criteria in different situations and scenarios. The same steps as described in the previous chapters will be taken to determine the right strategy. Situation sketches are used to support the descriptions. The results will be a list of tags for the specific scenarios, which can be used to identify a situation. These tags can than be linked to the different criteria.

### 8.1 Entering Maasgeul towards North Sea, Rotterdam

The first scenario which will be analysed, is from the viewpoint of a crude oil tanker, which will leave the port of Rotterdam. To enter the traffic lane towards the Maasgeul, it has to cross the path of another vessel coming from port-side. While taking another ship from starboard into account, which is already heading towards the Maasgeul.

The decisions which have to be taken are to change course and/or speed. This must be done multiple times. Different snapshots are taken throughout, including information on criteria which the crew uses to make their decisions. This example case is made up, but is based on real situations as described by pilots and AIS-recordings. First a description of the situation is given, which is the starting point of this example. The aim of this description is to enable the reader to understand the situation. Next relevant rules are discussed which should be taken into account when deciding on the strategy. Followed by the different snapshots, which will give insight in the decision making process and relevant criteria. This is concluded with a calculations for the relevant criteria.

#### 8.1.1 Situation description

The location of the situation is the junction between the Beerkanaal, Maasgeul, Nieuwe Waterweg and Callandkanaal. A map with more details is shown in figure 8.1. Quays restrict the possible paths ships can sail to avoid each other, there is however no traffic separation scheme. In this example case there will be three vessels involved.

**GULF VALOUR** 249 meter crude oil tanker. Coming from the Yangtsekanaal, heading to the Maasgeul, via the Beerkanaal. Just rounding the pier of 8e Petroleumhaven with 7.8 knots.

**ASTRORUNNER** 142 meter container ship. Coming from the Maasgeul with 13.4 knots heading towards the Calandkanaal.

**ANGLIA SEAWAYS** 142 meter ro-ro cargo carrier. Leaving Rotterdam via Nieuwe Waterweg towards the North-Sea with 10.3 knots.

All ships have licensed pilots on board, thereby do traffic controllers monitor the traffic and might give directions.

In order to classify a situation, tags are used. Example tags for this situation are: *junction, harbour, restricted waterways, multiple vessels, traffic controller*

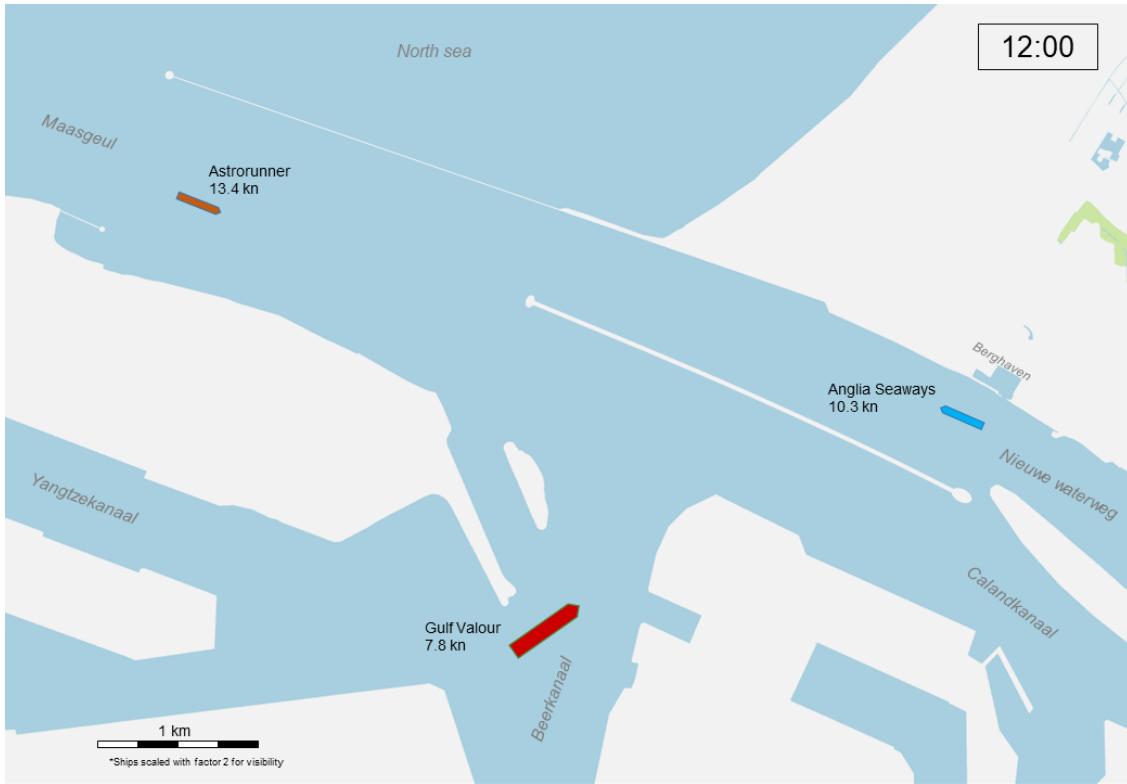


Figure 8.1: Situation sketch 12:00, with area which can be observed by Gulf Valour

### 8.1.2 Relevant COLREGs

The rules relevant for the situation are discussed, these should be taken into account during the decision making process, ordered in a chronological manner, on the moment it becomes relevant.

*Rule 7a: Every vessel shall use all available means appropriate to the prevailing circumstances and conditions to determine if risk of collision exists. If there is any doubt such risk shall be deemed to exist.*

This is particularly relevant in this case, as both ships can't be observed by the Gulf Valour by sight or radar at the start, due to port terminals and landmasses.

*Rule 19d: A vessel which detects by radar alone the presence of another vessel shall determine if a close-quarters situation is developing and/or risk of collision exists. If so, she shall take avoiding action in ample time, provided that when such action consists of an alteration of course, so far as possible the following shall be avoided:*

(i). an alteration of course to port for a vessel forward of the beam, other than for a vessel being overtaken;

(ii). an alteration of course towards a vessel abeam or abaft the beam.

Determining the 'ample time' for different scenarios is the purpose of this research.

*Rule 9a: A vessel proceeding along the course of a narrow channel or fairway shall keep as near to the outer limit of the channel or fairway which lies on her starboard side as is safe and practicable.*

This might limit the options to avoid a collision, or an exception should be made and com-

municated.

*Rule 15: When two power-driven vessels are crossing so as to involve risk of collision, the vessel which has the other on her own starboard side shall keep out of the way and shall, if the circumstances of the case admit, avoid crossing ahead of the other vessel.*

It should be determined if the Gulf Valour indeed crosses the Astrorunner in a way, such that this rule applies. It might also be that the Beerkanaal is ranked lower and therefore not really a crossing.

*Rule 13c: When a vessel is in any doubt as to whether she is overtaking another, she shall assume that this is the case and act accordingly.*

This is mostly relevant when the Gulf Valour comes close to the Anglia Seaways.

### 8.1.3 Snapshots

To get insight into the decision making process, the first step is to know the situational awareness at different moments in the process. Snapshots are taken from these moments. Giving a summary of the information based on observations and communication. This is used to validate or form strategies and eventually take decisions. Thereby is discussed which criteria are most important and example tags are used to identify the situations.

Communication, Observations, Strategy based on current information, Key criteria

#### 12:00 Start

The traffic controller has radar images of the whole harbour. He uses them to inform all ships about the position and intention of other ships. In this case the Gulf Valour is told there are two other ships. One at the Nieuwe Waterweg heading for the Maasgeul and one at the Maasgeul heading for the Calandkanaal.

The crew at the Gulf Valour sees both vessels on the ECDIS. However is not sure where the ships are exactly, as was mentioned in section 1.6, is the ECDIS not reliable enough. Due to the height of the bridge, it is possible to look over the land a bit, to make an estimation of the position of the other vessels. The ARPA has however too much noise to make the desired calculations.

Currently there is not enough information available to decide which strategy works best. There are no hazards nearby, thus the planned path will be followed. Where the Gulf Valour will make the turn into the Beerkanaal, which will reduce the speed.

*Tags: missing information, restricted waterways, multiple vessels, turning*

#### 12:03 Ships are visible by sight

To avoid an overload of the communication channels, the communication between ships is kept to a minimum. The most important communication comes from the traffic controller. As the situation did not change significantly, no updates are given.

Both vessels are now also visible on the ARPA and by sight. A closest point of approach is calculated, however this is based on the current heading and speed. As the Gulf Valour is still turning, this information is not of any use. Based on the speed of both vessels, it is possible though to make an estimation where the closest point of approach will occur.

Based on this estimation, a strategy can be chosen. The first choice which should be made is if a thight or wider turn is made through the Beerkanaal. As COLREGs prescribe to keep starboard, and thus a wider turn. Might it be more convenient to end in the middle or even at port side, by making the turn more tight. As there is no traffic coming into the Beerkanaal. But will make it more easy for the Gulf Valour to pass behind the Astrorunner, considering the Gulf Valour will slow down due to the tighter turn. To determine the right strategy, several key criteria are relevant. The first to consider is the moment both ships enter the crossing, relative to each other. The Gulf Valour can influence this by reducing the speed. This will also influence the path taken during the long turn trough the Beerkanaal. If it is better to make a tight turn on port side, or make it wider to end at starboard side of the Beerkanaal. In this case both enter at a similar time, therefor is chosen to have contact with traffic control. They decide to reduce speed a little bit more, by reducing engine speed and making a tight corner.

*Tags: restricted waterways, junction, crossing, turning*

### 12:06 Crossing with Astrorunner

At this point the strategy determined at the previous snapshot is executed. Thus the Gulf Valour passes the Astrorunner first startboard-starboard, and crossing the path at stern side. This means they deviated from the standard COLREGs, but with consent of the traffic controllers.

As the Gulf Valour passes at the stern side, it is easy to have a low rate of turn while crossing. This means a good estimation on relative speed to the Anglia Seaways can already be made by sight and via the ARPA.

Thereby should be considered which speed the Gulf Valour has to travel according to the schedule, which is higher than the current speed of the Anglia Seaways. This means the Gulf Valour has to act like it is overtaking the Anglia Seaways, while also entering the Maasgeul shipping lane. They have to move to starboard side of this shipping lane, to avoid head-on-head colissions with oncoming future traffic, which is not part of this example. Thus the final strategy is to go to the planned speed of 16.2 knots. While sailing in the centre of the shipping lane, leaving enough room to have the Anglia Seaways between the Gulf Valour and the Pier.

add  
screen-  
shot of  
simula-  
tion

*Tags: restricted waterways, junction, traffic-lane, crossing, over-taking, turning*

### 12:11 Under control

After crossing behind the Astrorunner the path is continued to the middle of the Maasgeul. To ensure a safe overtaking manoeuvrer around the Anglia Seaways. While overtaking the situation is under control and the Gulf Valour is underway to its next destination, without having the risk for close encounters. A few miles further out the pilot will leave and contact with traffic control is not necessary anymore.

*Tags: shipping-lane, over-taking*

#### 8.1.4 Criteria check

At every step, several criteria determine the strategy. At the different snapshot moments these criteria are calculated, in order to validate them. The results are shown in table .

make  
table

### 8.2 Second scenario

discuss  
another  
scenario

### 8.3 Relevant lessons

summarize  
relevant  
lessons,  
and what  
NOT  
should be  
forgotton

## 9 | Development of testing environment

A tool is developed in which can be tested how well decision model works.

### 9.1 Basic design

To test the different scenarios a tool will be build. This tool will be able to simulate the scenarios to get more insight why decisions are made. Full scale testing will cost much more money, time and effort, as it is harder to control. Small scale testing will introduce many unknown factors. Therefore is chosen to build an application in which models can be tested. The development will be based on the principles of the Agile Manifesto, as this has proven to result in effective software. This means there will be a start with a basic tool, which will continuously be improved. Changes in requirements might appear through out the whole process, to deliver a better tool. Thereby must be kept in mind that working software is the primary measure of progress. This is only possible when the software is sustainable and thus easy to maintain and improve, which is only possible with a good design. Keeping it simple will be key in this process. Thereby reflective moments are needed to check if the chosen path is the right one, or if the direction should be adapted. [Agile Manifesto(2001)]

#### 9.1.1 Requirements

The first step is to set the goals or requirements of the software. This doesn't mean it is a full description of the software, but features it should at least have to be able to answer the research questions. The most important requirement is that ships within the simulation behave similarly to ships in reality. This does not necessarily mean that all hydromechanics should be known. But ships should have similar ways of turning and changing speed. This can be based on sea-trials and done using a mapping from current speed, current rotation, rudder angle and throttle to future speed and turning speed. The second requirement should be that it is flexible, in a way that different scenarios can be added and tested easily. Thereby changing ship characteristics, shared information and other inputs. Thirdly, it must be possible to show the register of possible decisions for the different vessels. To be able to validate this with seafarers. Meaning it will be a white box model.

#### 9.1.2 User stories

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

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

- *Operator*. The person who sets up the simulation and fills in the different properties for the ships and specific scenario.
- *Viewer*. Someone who uses the application to view a specific scenario. Thereby trying to answer the research questions.

- *Ship*. Object in the map which is used by the simulation. But to work correctly it also had needs for information.

Some examples of those user stories are given below. All users stories can be found in appendix XXX..

- As an operator, I want to add vessels to the map, by selecting them in a list, so that they become part of the simulation.

Acceptance criteria: Ship visualized and other ships start receiving information.

add user stories to appendix

- As a viewer, I want to be able to get the belief state, intention and next action of a ship, so that I can verify if it is what I expected it to be.

Acceptance criteria: Belief state, intention and next action are shown.

- As a ship, I want to be able to predict the path of other vessels, so that I can make my decisions based on this.

Acceptance criteria: correctly updated belief state about other vessels.

### 9.1.3 User interactions

What should be done in the different modules

### 9.1.4 Minimum viable product

Considering the above mentioned requirements and user stories. Not everything is within the scope, and thus shouldn't be developed and implemented. Examples of possible features which are not implemented are: ... There must also be considered that several assumptions are made to create a system which works in a practical manner, as not all input data is available or calculations might be very hard and slow down the simulation too much. The assumptions made are: ...

Thereby should be kept in mind that the acceptance criteria for the application is: The ability to insert a model for decision making for a ship, which depends on information collected from other ships closeby, its own ship characteristics and the environment it acts in.

Extent the acceptance criteria for the full application

## 9.2 Manoeuvring capability model

Estimation of relation between throttle, loss of speed while turning. Thus a mapping from current speed, current rotation, rudder angle and throttle to future speed and turning speed

## 9.3 Probability index

what should the polygons show

## 9.4 Radio

The area in which situations are tested are not larger than the radius of an VHF radio (about 20 NM - IMO regulations)

[http://solasv.mcga.gov.uk/m\\_notice/mgn/mgn324.pdf](http://solasv.mcga.gov.uk/m_notice/mgn/mgn324.pdf) - p8

Therefore a ra

## 9.5 Controller

Based on the waypoints there is a simple controller to adjust the rudder angle. This controller steers based on the relative angle between the waypoint and the current position. This is done in the *adjustRudder* function. The distance and relative angle is calculated, this is used in a simple decision tree to decide on the rudder angle, which is similar to a so-called "proportional controller". For this simulation it will give enough accuracy. For a better result, a "PID-controller" could be implemented:

Relative angle (°)	Rudder angle (°)
25-180	35
10-25	25
0-10	Relative angle * 8/10

Table 9.1: Rudder angle based on relative angle

## 9.6 Estimation of characteristics

Deadweight to displacement for example

## 9.7 Application design

Building and verification including description of the architecture. Model-view-controller architecture, for easy modification as there are less dependencies between modules.

### 9.7.1 Design patterns

Push-pull listener

### 9.7.2 Model and classes

Use list from excel, make simple drawing how they link and talk to each other. Based on model-view-controller.

### 9.7.3 Methods

Full list in appendix XXX, describe important methods and how design patterns are used.  
Push-pull for example

### 9.7.4 User interface

Some screenshots of the application with a description what can be controlled and seen.  
Implementation of models is not relevant yet.

## **10 | Manoeuvrability requirements for safe operation**

### **10.1 Critical scenarios**

### **10.2 Criteria**

Turning circle Advance distance Tactical diameter

### **10.3 Resulting design matrix**

## 11 | Lessons learned

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

### 11.1 Factors not taken into account

Germans for example do sometimes alter the off-set of AIS to avoid confusing with radar image. As captains should use radar instead of AIS information to navigate. AIS is not reliable enough, but with small errors captains still do it, so giving it a large off-set will force captains to use radar.

other factors equipment, flagstate, origin of crew, etc.

### 11.2 Result

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

## **Part III**

# **Protocol to enable teamwork between manned and unmanned ships**

In the previous part a decision model is described which tries to avoid communication between vessels by taking the right decision at the right moment to ensure an unimpeded voyage. However this is not always possible. This is often the case due to missing information, or a lack of understanding about the intentions of other vessels. With manned ships, verbal communication via VHF is used to acquire the missing information or discuss strategies with other ships. Thus to have unmanned vessel sail between manned vessel, a protocol is needed.

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

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The communication which currently happens between vessels is mostly when COLREGs are not followed, or when intentions are not clear. Other communication which will not be within the scope of this research, such as the communication with traffic controllers and how conversations are interpreted by other vessels. Thus this research is a starting point to develop a full protocol needed for the acceptance of unmanned vessels.

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

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

## 12 | Foundation

The foundation segment in the sCE methodology describes the design rationale in terms of (a) operational demands, (b) relevant human factors knowledge, and (c) envisioned technologies. Together, these three constituents describe (1) the problem to be solved, (2) the existing knowledge on ways to solve the problem, and (3) the technology needed to implement that solution.

### 12.1 Operational demands

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

#### 12.1.1 Problem scenario

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

However, as shown in the previous parts, are COLREGs not always sufficient to decide on the right strategy. For example due to missing information. In those cases the VHF radio can be used for verbal bridge-to-bridge communication. Leading here is the Standard Maritime Communication Phrases (SMCP). The primary task of this protocol is to diminish misunderstanding in safety related verbal communications. Beside this verbal communication, non-verbal communication might be used, such as light signals, sound signals and semaphore signing.

The reason safety related verbal communication is needed, when you will deviate from the rules, deviant behavior is registered, or more information is needed to take the right decision. Cases where this occurs is when there is no visual. For example due to bad weather, obstacles like bridges and terminals, or the information received via AIS is not reliable.

Marker words are used to introduce the content and purpose of the communication. Below for each of the marker words an example is given.

**Advice** Stand by on channel 6 - 8.

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

**Warning** Buoy number: one - five unlit.

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

**Question** What are your intentions?

**Instruction** You must alter course to starboard.

**Request** Immediate tug assistance.

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

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

When using the current systems in a way they are not designed for. This might result in information overload of the crew and communication channels. Resulting in misunderstanding and problems with communication. As the VHF can only be used in one way. As it is a receiver or a transmitter, but can't be both at the same time.

### 12.1.2 Problem analysis

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

#### Primary actors

The focus of this research will be on bridge-to-bridge communication. This means the most important actors can be divided for the unmanned and manned vessel:

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

He wants to avoid information overload, while being aware of the situation. This is only possible when he stays concentrated, to acquire this, the tasks must be challenging and he needs to have a form of autonomy.

- *Helmsman and lookout*. Both monitor the situation and execute commands from the officer of watch. A risk for them is information overload, which could result in information overload.

- Unmanned vessel
  - *Controller agent*. This agent is responsible for situational awareness. Thus getting safely from A to B. It will decide on the navigational strategy, it will do this based

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ence

on the information it can acquire via all different means. Including newly developed communication protocols. His duties are similar to the duties of the officer of watch as described for the manned vessel.

- Other vessels
  - *Crew and pilots on nearby vessels.* They might want to know the intentions of other vessels to base their strategy on. However do not want to receive all discussions. As this will result in an information overload.

### Secondary actors

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

- Only recipients
  - Crew on vessels which are not traveling.
  - Shipowners of unmanned vessels, monitoring vessel from other location.
- Not within scope of the research
  - Vessel traffic controllers
  - Crew which are in distress and require assistance

### Goals

The main goal is to ensure reliable sharing of information, without the risk for information overload or misunderstanding. Such that manned ships will trust unmanned ships to choose the right strategy. As manned ships can be informed, using natural language describing the reasoning of unmanned vessels.

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

Using the same philosophy, it might be possible to develop also a protocol for communication with traffic controllers in later iterations. This is certainly relevant it is also not feasible for them, to have new systems to communicate and instruct unmanned ships.

### Infeasible solutions

The easiest solution for unmanned ships would be to just install a new system. This is however not feasible as mentioned before. To implement this it would mean that all ships which could encounter an unmanned ship will have to install this too. It might be possible to make it obligatory via regulations, this will however cost a lot of time and money. Making the introduction of unmanned ships less likely. This is also the reason to use a Non-visual User Interaction (no-UI), as a GUI will require new screens or changes to the ECDIS which are only possible when regulations are changed.

## 12.2 Human factors

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

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

The three constituents important to the human factors analysis are: (a) the human factors knowledge, (b) measures, and (c) interaction design patterns.

### Human factor knowledge

Human factors knowledge describes available knowledge coming from previous research about how to solve the problems that have been identified in the problem analysis.

- Which information is needed to have situational awareness? [Rothblum et al.(2002) [Breda and Passenier(1999) [Prison et al.(2013) [Hodgetts et al.(2015) [Porathe et al.(2014)]
- When does information overload occur? [Arimura et al.(2001) [Neerincx(2008)] [Schutter(2016)] [Porathe et al.(2014)]
- What is more effective to ensure a feeling of autonomy? [Feys et al.(2016)]
- How is information perceived if it is being pushed or pulled? Thus listen to radio with continuous information (repeating), or only send message when asked for
- What are the expectations of a human from an unmanned ship?
- Do people trust automated systems in emergency situations? [Neerincx(2008)] [Walliser(2011)]
- Is there an uncanny valley for chatbots?
- ...

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### Human factor measures

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

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- Is the system used correctly?
- Does the protocol act as expected?
- Will it solve the problem of missing information?
- Do people perceive it as easy to use and useful?

- What is the impact on attitude towards unmanned ships?

### **Interaction design patterns**

Interaction design patterns (IDPs) focus on the human-computer interaction, such as usable interface design and control options. IDPs offer generic solutions to recurring HCI design problems that have been proven to be effective. IDPs are often made available in repositories.

- Radio communication
  - Usage of message markers
  - Conversational agent
- Visible signals
  - Light signals
  - Mast head signals
  - Flags
- Audible signals
  - Horn
  - Speakers
- Distress, urgency and safety signals
  - Flares
  - Smoke

### **12.3 Envisioned technology**

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

Using only existing systems to develop a Non-visual User Interaction (no-UI). Different systems which are currently used, are described in chapter 1. Below different systems and protocols are mentioned which can be used to design the new protocol. Using these already existing systems will shorten de development, learning and implementation time.

- Radio communication
  - Conversational agent
  - Negotiating agent
  - Usage of message markers
  - Availability on VHF

- Natural language variations on SMCP
- NATO phonetic alphabet and numbing
- Addressed AIS message to exchange information or interrogate
- Visible signals
  - Light signals
  - Mast head signals
  - Flags
  - Heading, position and movements
- Audible signals
  - Horn
  - Speakers

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

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

## 13 | System design specification

The system design specification describes the solution to the problem in the form of a system design that makes use of the identified relevant human factors knowledge and the envisioned technology. The system specification consists of design scenarios, use cases, requirements, claims, and ontology.

### 13.1 Design scenarios

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

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

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

Trust in autonomous ships is formed, as the information is reliable, the interaction is similar to the interaction with other manned ships. This resulted in acceptance of unmanned ships on the general waterways. Where the risk for collisions and perceived risk reduces, or at least does not increase.

#### Information extraction from problem scenario

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

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

### Envisioned effect of system implementation

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

1. The system will send only on demand or when it has tried any other solution. This will reduce the probability for information overload. As a threshold to check if the system is successful in solving the problem of information overload, the current amount of communication can be used.
2. The protocols which are currently used by the officer of watch are the same. The purpose is to make it more easy to get information. This means that the situational awareness will minimally be affected by the system on board of the manned vessel. Also here the current level of situational awareness can be used as a threshold.
3. By introducing an negotiating agent, decisions can be made in a similar manner to current ships. Using the decision tree it will have a favorite strategy, but it might be possible to use others if this is better for the encountered manned ship. This will ensure that the officer of watch at the manned ship, still has a feeling of autonomy, similar to that of the current situation.
4. Although the current systems are not designed to be used by unmanned vessels. Are there major developments on conversational agents in the last few years. This means that voice communication is starting to become more easy to develop. Certainly when considering that a lot of radio conversations are recorded. Thus it will be more easy to train the agent. Thereby must still be considered the importance of transparent communication. Thus also being open about being a robot.
5. Using addressed AIS messages and a conversational agent at unmanned vessels. Manned ships will be able to ask for support or information at all time. It is even likely they will receive the information faster compared to manned-manned ship communication.
6. The conversational agent is most relevant for unmanned ships when they want to ask for support or information. As addressed messages are not often used at the moment. They will use the SMCP in a similar way to how it is currently used. So not much will change compared to the current situation for manned ships.

## 13.2 Use case

Scenarios are used to create more specific descriptions of step-by-step interactions between the technology and its users (i.e. use cases). Use cases include actors, to specify which stakeholders/agents are interacting with each other in a given action sequence (use case).

The use cases provide a detailed description of the interactions between the technology and its user. Use cases make the design scenario more concrete by describing exactly how the technology makes sure that the problem is solved. Use cases are informed by human factors theories (described in the system's foundation).

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

Tags: *Intention*

add more tags

A 26 meter autonomous fast crew supplier (FCS2610) is heading towards a wind farm at the north sea with a speed of 22 knots. To get there, she has to cross a busy traffic lane. There she will pass a 150 meter container ship (Reefer), sailing at 14 knots. The FCS2610 will pass in front of the Reefer with a distance of 900 meter or 0.5 Nautical mile. Which is just accepted according to the safety domains [Szlaczynski and Szlapczynska(2017b)]. To ensure the Reefer understands the intentions of the FCS2610, communication is necessary. This is done in the following manner:

- The AIS, masthead and flags are showing the vessel is sailing autonomously, without interference from crew and listening to the VHF.
- A conversation is started by the FCS2610, by calling the station on board of the Reefer and updating status in AIS.

Reefer, C-6-Z-G-7

Reefer, C-6-Z-G-7

This is unmanned FCS2610, 2-F-F-P-4

Unmanned FCS2610, 2-F-F-P-4

Switch to VHF channel seven-two

over.

- The FCS2610 waits for a response from

Unmanned FCS2610, 2-F-F-P-4

This is Reefer

Agree VHF channel seven-two

over.

- At VHF channel 72, FCS2610 communicates her intentions.

Reefer, C-6-Z-G-7

This is unmanned FCS2610, 2-F-F-P-4

Intention. I intend to pass in front with a distance of 0.5 Nautical mile.

over.

- At VHF channel 72, Reefer confirms intention.

Unmanned FCS2610, 2-F-F-P-4

This is Reefer, C-6-Z-G-7

Intention received. You intend to pass in front. Distance is 0.5 Nautical mile.

over.

- Close communication and pass in front.

Reefer, C-6-Z-G-7

This is unmanned FCS2610, 2-F-F-P-4

Nothing more. Have a good watch.

Over.

Unmanned FCS2610

This is Reefer

Thank you.

Over and out.

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

### Fishery vessel gets close to traffic lane with unmanned VLCC

Tags: *Question*

NB: Use cases do not specify the way in which the technology enables the described interactions. For example, the interactions may take place through voice commands and audio, but could also be text-based, be instantiated with the use a drop-down menu, or even by a human operator sitting on the other side of the application, listening and responding to the events taking place. No assumptions are made about the level of automation or the current capabilities of the technology in mind. A use case simply describes the behaviour of the system, regardless of the technology required to produce that behaviour. Because the sCE method describes an iterative process of specifying the system's design, at later stages some behaviours may prove to be infeasible or not viable. This may result in alternative use cases that may be better aligned with the available technology. But it may also be the case that one ends up with a slightly different version of the technology that in fact is able to produce the ideal behaviour described in the original use case. The main goal of iteratively refining the system specification is to gather all the alternative design solutions, compare them in systematic evaluations, and converge to one design solution that is effective, reliable, affordable, etc

## 13.3 Functional requirements and claims

In the sCE method, use cases are used to derive functional requirements and claims, i.e. specific functionalities the technology should provide to its user followed by the system's objectives, and the hypotheses to be tested during system evaluations. This is accomplished by annotating all functional requirements with their underlying objectives (called claims).

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

### Actors

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

- Officer of watch
- Unmanned vessel
- Nearby vessel

### User stories

- As an officer of watch, I want to know if there are unmanned ships in the area, so that I know if I have to adapt my way of communication. AIS shows if ship is manned, and what its status is.
- As an officer of watch, I want to validate if information received via AIS is correct, so that I can base my decision on correct information. When officer of watch asks unmanned ship via VHF, the answer should be reliable and based on current information.
- As an officer of watch, I want to make my intentions clear towards all other ships, so that they can anticipate to this. Shared intentions should be incorporated into the decision making process of unmanned ships.
- As an officer of watch, I want to be able to make small mistakes when following a protocol, so that I can still act fast when I do not know the exact SMCP sentence. The unmanned vessel should understand the message, even if its not exactly the SMCP sentence.
- As an officer of watch, I want to use existing protocols, so that the extra effort to communicate with unmanned vessels will be kept to a minimum. Current seafarers should be able to understand what they should be doing without an explanation on the protocol.
- As an unmanned vessel, I want to initiate communication, so that I can exchange information or ask questions to another specific ship. The unmanned ship needs situational awareness based on a digital model of the reality to know which ship sails where and what the interactions could be in order to make the right decision.
- As an unmanned vessel, I want to validate if acquired information is correct, so that I can base my decision on correct information. Check via communication if digital model is correct.
- As an unmanned vessel, I want to be able to check if they understand my intentions when other ships do not act as expected, so that I know if I should change my strategy. The communication should be incorporated in the decision making process and unexpected actions by others ships should be registered.
- As a nearby vessel, I want to receive only information which is relevant to me, so that the risk for information overload is limited. By switching VHF channels for full conversations this is similar to the current way of working.

---

add more user stories

### 13.4 Ontology

Lastly, the sCE method prescribes the construction of an ontology, i.e. a vocabulary describing a common language to be used throughout the system specification to avoid miscommunication, misunderstanding, and inconsistencies. Furthermore, the ontology can serve as the basis for the technology's data structure. By specifying important concepts in the ontology and also choosing to use only one word instead of various ambiguous synonyms, communication

becomes clearer and misunderstandings can be reduced to a minimum. The terms specified in the ontology are consistently used throughout the entire project.

Status:

**Listening** . Listening to the radio without taking action.

**Waiting** . Waiting for a response by other ship.

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

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

<http://www.segeln.co.at/media/pdf/smcp.pdf>

Types of messages:

**Call** Start of conversation, in which a ship only requests contact with another ship. It might also be necessary to introduce as an unmanned vessel (why does google assistant do this?)

**Acknowledge** Accept invitation for conversation.

**Message** Starts with "marker word", followed by the actual message and ended by a request for confirmation. In the SMCP the following marker words are used:

- *Advice*
- *Information*
- *Warning*
- *Intention*
- *Question*
- *Instruction*
- *Request*

**Respond** Response to the previous message or response.

**Close** End conversation with greeting.

## 14 | Design evaluation

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

### 14.1 Artefact

The artefact is an implementation or prototype that incorporates a given set of requirements, interaction design patterns, and technological means.

### 14.2 Evaluation method

The evaluation method can take many forms, such as a human-in-the-loop study, a use-case-based simulation, or an expert review.

Question if it should pass turing test, which Human Factor measures are possible.

### 14.3 Evaluation results

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

## **Part IV**

### **Wrap-up**

## **15 | Results**

Describe results when both researches are combined. Do they support each other.

## **16 | Conclusion**

### **16.1 Answers to research questions**

### **16.2 Recommendations for future research**

## **Part V**

**TEMPORARY: Old text**

## Manoeuvring capability

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

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

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

## IMO standard

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

1. *Turning ability.* The advance should not exceed 4.5 ship lengths (L) and the tactical diameter should not exceed 5 ship lengths in the turning circle manoeuvre.
2. *Initial turning ability.* With the application of 10° rudder angle to port or starboard, the ship should not have traveled more than 2.5 ship lengths by the time the heading has changed by 10° from the original heading.
3. *Yaw-checking and course-keeping abilities.*
  - (a) The value of the first overshoot angle in the 10°/10° zig-zag test should not exceed:
    - i. 10° if L/V is less than 10 seconds
    - ii. 20° if L/V is 30 seconds or more
    - iii.  $(5 + 1/2(L/V))$  degrees if L/V is between 10 and 30 secondswhere L and V are expressed in m and m/s, respectively.
  - (b) The value of the second overshoot angle in the 10°/10° zig-zag test should not exceed:
    - i. 25° if L/V is less than 10 seconds
    - ii. 40° if L/V is 30 seconds or more
    - iii.  $(117.5 + 0.75(L/V))$  degrees if L/V is between 10 and 30 seconds
  - (c) The value of the first overshoot angle in the 20°/20° zig-zag test should not exceed 25°.

4. *Stopping ability.* The track reach in the full astern stopping test should not exceed 15 ship lengths. However, this value may be modified by the Administration where ships of large displacement make this criterion impracticable, but should in no case exceed 20 ship lengths.

## Limits

These standards give guidance during sea trials, but won't help much. What are maximum values for manoeuvring capability. Based on trial run are values found for Nomoto (other theories?)

Wat is constant? Versnelling / vertraging of de afgeleide daarvan

Clarke, D., Gedling, P. and Hine, G. (1983). The application of manoeuvring criteria in hull design using linear theory. The Naval Architect, pp. 45–68

## Desired capability

What are normal movements for a ship of a specific size

## Expected route

Ship will most likely keep sailing straight and on same speed

## Input

Nomoto, more detailed is Norrbin equation

## Detailed capability

Key equipment for the manoeuvrability are rudders, fixed fins, jet thrusters, propellers, ducts and waterjets. However it is not practical to determine this for every ship which is nearby. Therefore a more statistical approach is taken using comparable ships.

describe formula to determine crossing-point of line  
CPA calculation

## Prediction with limited data

Own vessel input comes from sea-trial, other vessels based on received information via AIS. DWT, L, B, speed, etc.

## **Filter situation**

Input from static objects shown on the map

## **COLREGs**

most important COLREG criteria are:

- minimal crossing angle
- minimal distance starboard
- minimal distance portside
- minimal distance rear
- voorkeur port-port side crossing

## **Traffic separation schemes**

input from local authorities

## **Navigational aids**

map/radar/etc.

## **Accepted probabilities**

Which probabilities can be ignored to speed-up calculation

## **Other filters**

Significant wave height/ weather/ windspeed

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