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Chasing the Perfect Rudder Angle

Evaluating the feasibility of a decision support system. A pilot study.

Bachelor's project in Nautical Studies
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Bachelor's project

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Abstract

The aim of this bachelor thesis was to do a pilot study to test the hypothesis that a support system can aid in increasing safety during navigation. In order to achieve this, a support system needed to be created and experiments carried out.

In order to substantiate the beneficial value of such a support system, accident reports for ships involving grounding, contact and foundering were studied. All vessels involved in the accidents were large and modern ships, and only accidents caused by a failure to properly execute a planned manoeuvre were considered for the thesis. Accident reports show that navigating under demanding weather conditions pose great challenges; the contention is that a support system could assist the navigator in avoiding critical misjudgments.

The first idea was to use matrices to calculate force vectors. This approach was abandoned in favour of using long-established hydrodynamic modelling. The support system was developed for the sole purpose of testing the hypothesis in a commercial simulator using a specific scenario; its use beyond this is therefore extremely limited. Additionally, it was not feasible to facilitate a direct connection between support system and simulator. These factors resulted in the adoption of certain assumptions and limitations early in the development process.

Current and wind were not collected from measurements from simulated instruments, but inserted manually into the support system. As a result, current and wind were identical in simulator and support system. Nor were there any real time updates during testing. No user interface was ever created; in its current form the system requires a basic knowledge of coding to use. Consequently, the system was controlled by the thesis authors, and the results from its calculations presented to the test participants in a format readable by navigators.

Programming was done in Matlab with the Simulink add-on. Test were performed in a bridge simulator in order to optimise an already existing mathematical model. For the optimisation, standard manoeuvre test were performed. Monte Carlo simulations were used to adjust hydrodynamic derivatives, in order to predict ship movements in the simulator. In the experiment, students at the Norwegian University of Science and Technology in Ålesund participated in a simulator test in Vatlestraumen. The ship used for the experiment was a very large crude carrier 305 metres in length.

The difficulty in defining a good manoeuvre led to a simple pass/fail system being used for statistical analysis. The pass criteria was set at successfully navigating through the area of the simulation without making contact with land or touching bottom. A chi-square test was used to analyse this data.

The null hypothesis for the statistical analysis was that there is no significant difference whether the support system was used in the first or second passage with the very large crude carrier. The null hypothesis was rejected at $p < .10$. Despite the lack of statistical significance at $p < .05$, a p-value of 0.0543 cannot immediately be written off as a result of pure chance.

In addition to fewer groundings in tests performed with the support system or after its use, data show that it resulted in a more controlled use of rudder. When the time required to find a close to optimal rudder angle has been reduced or eliminated, the navigator has more time and attention to spare for other critical aspects of navigation. The authors contend that this increases navigational safety.

Further research is recommended to confirm or reject the hypothesis. Tests performed using identical pre-planning for all participants would aid in isolating positive or negative effects of using a support system similar to the one used for this thesis.

For any development of a system for practical use, tests on real ships would be required; the hydrodynamical model used in this thesis should be replaced by a more suitable modern alternative. It is the authors' opinion that the model used for optimisation should be further developed and tested in order to facilitate the building and optimisation of mathematical models during normal ship operations. This would lead to an increased selection of models, aiding research in hydrodynamics.

“If my weakest troops fail to eliminate a hero, I will send out my best troops instead of wasting time with progressively stronger ones as he gets closer and closer to my fortress.”

—The Evil Overlord List – (Anspach 1996, Item 80)

“The pilot initiated the turn using three degrees of port rudder, followed by successive increases to five and 10 degrees’ rudder when he realised the ship was wide in the turn.”
—Azamara Quest accident report – (Transport Accident Investigation Commission 2002, p.5)

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Finally, our most sincere gratitude goes to our supervisor, Rami Zghyer. His assistance has been above and beyond even our wildest expectations. Without him, this thesis would have been a bleak shadow of its current form.

Even the most dedicated of helpers cannot eliminate all errors committed during the development of this project. Any remaining mistakes are ours, and ours alone.

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1 Introduction

Manoeuvring a ship is a process of constant evaluation and estimation. There are simply too many variables to keep track of for it to be anything else. A captain may sail the same route every day for decades and never experience the exact same conditions twice. A skilled officer with experience in how his ship behaves uses that experience to estimate correctly – or close enough not to matter – most of the time. Some do it all of the time. When that skill and/or experience is lacking, the likelihood of getting into dangerous situations increases.

To execute a manoeuvre, one must first apply an initial rudder command, then wait for the rudder to affect the ship. Once the effects become observable, one must evaluate whether the chosen rudder angle is the correct one and if not adjust accordingly. The cycle of apply, wait, observe, evaluate, adjust is then continuously repeated throughout the manoeuvre.

Using too little – or too much – rudder in the initial phases of a manoeuvre means that a large correction will soon be needed. If this correction is not done quickly and with a suitable rudder angle, it becomes difficult to execute the manoeuvre as planned. In restricted waters, such errors can have catastrophic results.

It is obviously desirable to choose an initial rudder angle as near perfect as possible. An inexperienced navigator might be tempted to make use of the ship's autopilot. Unfortunately, a traditional Proportional Integral Derivative (PID) autopilot is wholly unsuitable for precise manoeuvres, even if perfectly tuned. It is a system designed for keeping a course and simple course changes. It is also a "dumb" system, where the input is based on a set of standard conditions, and corrections made if it is discovered that the ship is not following the intended course.

At the opposite end of the scale there is Dynamic Positioning, which uses a combination of mathematical models and constant measurements of wind and current. Usually this is used as a means to keep a ship in a fixed position using thrusters, but it can also, to some extent, be used to move.

What all known existing systems have in common is that they are largely reactive. Whether making a first estimation based solely on standard conditions or in combination with wind and current measurements, they all work based on what is happening in the moment.

The authors of this thesis have chosen to look at the problem from a different angle. Instead of an automated system reacting to what is happening, they have sought to devise and test a system to assist the navigator in planning manoeuvres well in advance. Additionally, rather than having the system take control, it remains in an advisory function, leaving decision and execution in the hands of the navigator. This thesis will explore the hypothesis that safety is increased with the assistance of such a system.

1.1 Motivation

The motivation for writing this thesis is quite simple: manoeuvring a vessel affected by external forces is hard. This is a subjective statement; attempts to make it objective are made in Section 1.2.1 – Accident Reports. Some captains might guide their vessels through difficult manoeuvres in adverse conditions without ever feeling anxiety, or doubting the decisions they make. However, unless this is true for *all* people piloting ships all the time, it makes sense to try to solve this problem.

"At any given time, there will be a number of different forces affecting a manoeuvre. It would be impossible and not very relevant to calculate the influence of all these forces at all times in a given manoeuvre. We must therefore assess the situation on the fly – using a master's accumulated experience" (Kjerstad 2017, p.1-1, own translation). It is naïve to seek a simple mathematical solution to something so complex as ship path prediction. Constant changes to one input sends ripples that affect the overall output. Any equation that fails to take account of this will fail at its job. Kjerstad (2017, p. 1-1) writes that at any one time there will be several forces that impact on a manoeuvre. Perfect modelling of all forces would indeed be impossible, at least by today's computers. Much of the idea behind the hypothesis explored in this thesis springs from a disagreement over the irrelevance of trying to calculate those forces. Perfection being unattainable is a poor argument against an effort to create something useful.

Developing something to be of immediate benefit aboard real vessels would be infeasible. Such a project falls well outside both the discipline of nautical studies and the time allotted for the completion of a bachelor thesis. Consequently, focus will be on designing a system with the sole purpose of testing a concept: Will a path predictor that gives ship specific information about the execution of planned manoeuvres increase navigational safety?

In order to test hypothesis, the authors of this thesis set out to complete the following tasks:

- Create a decision support system being able to predict ship movements in a commercial simulator.
- Test this systems on participants in navigator in-the-loop experiments.
- Evaluate results and make a statistical analysis.

1.2 Literature Review

The literature review for this thesis is divided into four distinct parts. The first part mentions accident reports from across the world where, in one way or another, according to the authors, a Decision Support System (DSS) giving information about rudder orders in advance of a manoeuvre could have changed the outcome. Here, the focus has been on finding accidents where the consequence has been grounding, foundering or contact. Accidents that occur because of a misjudgment of the ship's manoeuvrability due to weather forces have been of particular interest. A good search function is a rare occurrence in the world of accident investigation. Because of this, over a hundred accident reports listed as being related to grounding, foundering, or contact were chosen and searched for relevance. All of these were with vessels above 100 gross tonnes.

These articles were then subjected to an elimination process to remove the least relevant. Accidents involving older ships, engine or steering failures, or remarkably poor seamanship were removed. The remaining reports all mention as a contributing factor a failure to properly plan for the effects of wind and current while executing a planned manoeuvre. A brief summary and discussion of how the most relevant relate to the thesis will be given in Section 1.2.1 – Accident Reports.

The second part is a summary of how the rate of turn approach to manoeuvring works. This is one of the more common methods of manoeuvring in restricted waters and the one taught to most students at Norwegian University of Science and Technology (NTNU) in Ålesund. The literature for this section comes mainly from that used to educate and train navigators.

The third part is about a similar work in path predicting decision support systems.

The fourth part covers hydrodynamic sources used in building the DSS. Searches for relevant terms gave many of the articles regarding pivot point and wind coefficients. Books regarding general knowledge about hydrodynamics were found via searches and suggestions by staff at NTNU in Ålesund.

1.2.1 Accident Reports

The following section contains brief summaries of accident reports deemed to be of particular interest for substantiating the usefulness of a system such as the decision support system devised for this thesis.

First report: According to the Marine Accident Investigation Branch (2002), the PI&O Nedlloyd Magellan ran aground at the entrance to the Thorn Channel at around 07:00 UTC on the 20th of February 2001, while approaching Southampton, England. The grounding was in main attributed to an error of judgment by the pilot. Restricted visibility, an incorrectly set electronic bearing line, and the bridge crew not properly monitoring the pilot were listed as contributing factors.

Second report: The Marine Accident Investigation Branch (2015) writes that at 15:15 on the 14th of July 2014, the Commodore Clipper grounded while approaching St Peter Port, Guernsey, UK. At the time of the grounding, the ship was supposed to be following a 220° line. However, tidal currents of 2-3 knots on the starboard beam was setting the ship to port of its intended track.

During the two minutes immediately prior to the grounding, new courses of 222°, 224° and 226° had been ordered in an attempt to get the ship back on the planned track. According to the accident report, "this heading was insufficient to avoid danger; a larger and earlier alteration of course would have been necessary to get Commodore Clipper back into safe water". (Marine Accident Investigation Branch 2015, p.45) The data collected by the accident investigators show that at the time, the course over ground was consistently 4° to port compared to the course being steered.

Third report: Shoji, Kosuda, and Nemoto (2017) say that at about 12:25 local time on the 6th of June 2015, the Shin Heiryu allided with the East Light Buoy in the Port of Singapore, Singapore. At the time, the vessel had been travelling at a speed of 3 knots through the water in order to facilitate the pilot boarding. Unbeknownst to the master, there was at the time a rapidly increasing stern current. At 12:04, it had been approximately 0.5 knots on the starboard quarter; at 12:22 it was later estimated to have been 2.5 knots almost directly astern. The relatively strong current compared to the vessel speed meant that, as the ship turned to starboard to avoid the buoy, there was a large discrepancy between the vessel's heading and the course over ground. At times, this difference was more than 30°, and the vessel failed to make the turn in time.

Fourth report: According to Transport Accident Investigation Commission (2002), the Azamara Quest allided with Wheki Rock in the Eastern entrance of the Tory Channel on the way to Picton, New Zealand on the 27th of January 2016, at about 09:20, local time. At the time, the pilot had been aboard for 20 minutes.

The entrance to the channel is less than 0.5 nautical miles wide and has a 75° port turn. At the time of the incident, there was a projected following current of 6 knots in the centre of the channel. According to the accident report, the turn was started some 20 seconds later than intended. The master had informed the pilot that the ship would "turn on a dime", and that a 3° rudder angle would suffice to start a "good" turn. It soon became apparent that 3° was insufficient, so it was increased to 5° and 10° in quick succession, followed by 20°.

With no time to become familiar with the ship, the pilot only had the master's assessment to go by. A following current is likely to make it more difficult to assess how much rudder is needed, as it increases the speed over ground and decreases the effectiveness of the rudder with regards to distance over ground.

Fifth report: The Marine Accident Investigation Branch (2017) writes that on the 22nd of August 2016, at 00:32 local time, the CMA CGM Vasco de Gama ran aground at the entrance to the Thorn Channel, Southampton, UK. The Marine Accident Investigation Branch lists several reasons for the grounding, some of which are:

- The vessel approached the approximate 140° starboard turn from 260° to 037° too far to the North, resulting in a narrow turn being required.
- The combined effects of 20 knots of wind from WSW and a rising spring tide resulted in the vessel being unable to maintain the necessary Rate Of Turn (ROT) to complete the manoeuvre. Despite the rudder angle being increased to 35° from the initial 10° and engines set at full speed ahead, the ROT decreased as the turn progressed.

After the grounding, several simulator tests were carried out. Under the conditions that existed at the time, the turn as planned and executed by the pilot resulted in a grounding every time. However, when approaching from further south and thus allowing for a wider turn, the passage was successfully completed.

Sixth report: The Australian Transport Safety Bureau (2018) writes that at about 22:20, local time, on the 12th of February 2017, the Aquadiva nearly ran aground while leaving Newcastle, Australia. In order to make a port turn in excess of 90°, the pilot wanted a rate of turn of about 13° per minute. To do this, he first ordered 10° rudder. When it became apparent the ship was not turning fast enough, this was increased to 20°, and then later to hard over.

Eventually, nearby tugs managed to prevent the ship from grounding. The investigation concluded that not enough rudder angle was used, and used too late.

Common causes:

In addition to the items highlighted above, most of these accident reports mention the failure of applying proper bridge resource management as a contributing factor. This becomes particularly critical when there is a pilot involved. There is then a situation where the pilot knows the local area and its dangers, and the regular crew knows their ship and how it behaves. Combining these pieces of knowledge into a whole is crucial, but often made difficult by language problems and lack of time.

Reading these and other accident reports, it is common to see rudder command issued in 5° and 10° intervals. This is natural, as ships are commanded by humans, and humans tend to like round numbers. However, there is nothing inherently magical about a 10° angle. Sometimes it is indeed optimal, other times 8° or 13° would have been better.

In situations like the ones listed above, a DSS using accurate hydrostatic data could be useful in several ways. During the planning stage, it could provide exact wheel-over points, instead of relying on estimations by a pilot who might be wholly unfamiliar with the manoeuvring characteristics of the ship in question. It would be able to suggest more precise rudder angles to use; instead of a human guessing whether to use 5° or 10°, the system could calculate that, for example, 8° would allow the ship to follow the planned track.

If provided with live input from sensor data, the DSS could then adjust its initial assessments as the manoeuvre progresses. Should a projected 2-knot current from SW turn out to be 2.2 knots from WSW, small changes could be applied. The operative word here is "small". Properly adjusted and fed the best data available, the suggestions from a working DSS should never be too far from the optimal values.

1.2.2 Traditional Manoeuvring Practices

"For larger vessels sailing in narrow waters, it is absolutely necessary to plan which turn circle to follow. Depending on which radius is selected, the point at which you start the turn, the Wheel-Over Point (WOP) will differ from where the WayPoint (WP) itself is located." (Kjerstad 2017, p.2-17, own translation).

On large ships, it has become common in recent years to navigate by Rate Of Turn (ROT) (Kjerstad 2017). In navigator education courses, students are trained to work with physical charts where they set out waypoints, course lines, turn circles with predetermined radius, WOP and more. When the courses are drawn on a map, it is common to leave these at a WP where it is planned to change course. When this happens in narrow waters, it is beneficial to monitor the turn with a constant radius. This is illustrated in Figure 1. Due to inertia, there is a delay from when a rudder command is given to when the vessel has worked up a rotation. The rudder command thus needs to be issued before the vessel reaches the WP; this is called the WOP. The distance between the WOP and where the ship starts turning is called f. This distance has to be compensated for during the planning phase to secure the voyage.

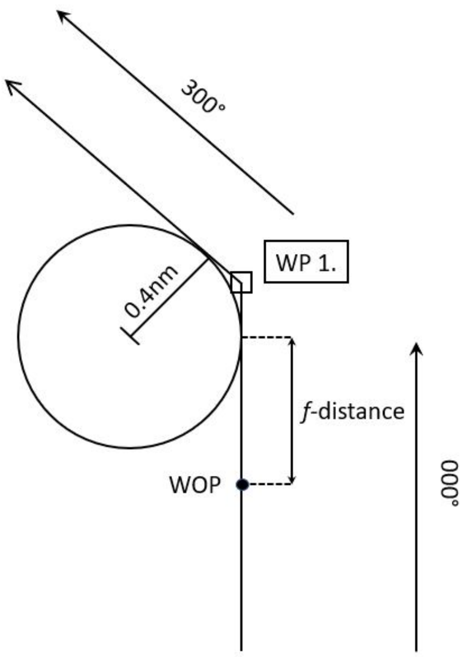


Figure 1. Turn using constant radius.

The f-distance will vary by ship type, rudder type, control system and current. If the f-distance is unknown it can be found on manoeuvre diagrams; those familiar with the vessel will often be able to make an estimation from experience. As a rule of thumb the f-distance is a ship's length; the size of f does not change with the selected turn radius. In addition to any uncertainty with the distance of f, another error factor will be that most ships lose speed while turning. This means that keeping a constant ROT will result in a smaller radius than if the speed remains constant (Kjerstad 2017). The vessel will also be subjected to external forces such as wind, tide and current, which must be compensated for while manoeuvring. In shallow waters, the shallow water effect, channel effect or general bottom topography will also affect the vessel's manoeuvrability.

For each manoeuvre, the navigator will try to work up a ROT when the vessel reaches its WOP. With the vessel speeding through the water, the rudder is put over in the direction of the desired turn. Inertia will cause a delay of varying length before the vessel starts to rotate, also known as turning. As mentioned earlier, there are several influences and external forces that affect the rotation of the vessel; thus it is difficult to know exactly how much rudder angle one must give to get the desired rotation. Accurate estimations, testing, accumulated experience, and/or luck determine whether one has given the right rudder command so that the vessel follows its intended path. If the correct rudder angle for the desired ROT is not found on the first try, it has to be compensated for by giving more or less rudder.

1.2.3 Path Prediction Practices

Path prediction systems are to some extent already common aboard ships. One example of this is vectors showing speed over ground or speed through the water on radars and chart machines. The most common versions are ground velocity vectors showing only ship speed or a curved line including rate of turn. The length of this line can be changed to show estimated tracks for different lengths of time. The ground velocity vector is not a helpful tool for turning, because it is hard to get an accurate reading of how a turn is developing from a straight line showing direction of travel at a given moment. The curved line taking rate of turn into account fails to adjust for decreasing speed because of sway movement. In addition, because it is based on the speed and ROT in that exact moment it is not a good path predictor. It is entirely possible for the path predictor to show the ship heading for the starboard bank of a channel when, in reality, port rudder applied means that the ROT is increasing at such a rate that – unless the rudder is immediately changed to starboard – the ship will hit land on the port side. The accuracy of both these systems was thoroughly tested by van Breda and Passenier (1998). They compared conventional path predictors, a relatively simple mathematical model, and path prediction based on an accurate hydrodynamic model. They also compared results in accuracy in navigation with conventional methods such as parallel-indexing and ground velocity vectors. Simulator tests conducted showed significant reduction in positional error between planned and actual track when path predictors took both speed and rotation into account. The greatest reduction was seen in the path predictor which used fast iterations of input to the mathematical model. This effect was most notable with larger course changes.

One negative side of this approach is that it is purely reactive. In some cases a wrong decision can lead to an unrecoverable situation where, regardless of how advanced the support system used, there is not enough time to make corrective measures.

1.2.4 Hydrodynamic Models

The Marine Systems Simulator (MSS) is a toolbox that uses the Matlab add-on Simulink Perez et al. (2006). It was created by merging previous systems developed to provide aid in the implementation of mathematical models of marine systems. Fossen (2011) has collected new results in hydrodynamic modelling and explains concepts with reference to tools found in the MSS. This has been an irreplaceable resource and an excellent introduction to hydrodynamics. It is safe to say that this thesis would not have existed without this book; if by chance anything of importance for the field is found in the following pages, it is because of work adapted from these sources.

A comprehensive study on the manoeuvrability of large tankers was done by van Berlekom, Goddard, and The Society of Naval Architects and Marine Engineers (1972). The purpose of this was to investigate the manoeuvrability of new ship designs during the design stage. A mathematical model was created for tankers of the Osaka class and tested against existing vessels for its capability in predicting ship movements. This mathematical model was incorporated into the MSS toolbox by Trygve Lauvdal in 1994 and revised by T. Fossen in 2001 and 2004. Because of the similarity of the Osaka class to the vessel chosen for testing of the DSS in the commercial simulator, this model was chosen for optimisation to match the trajectory of the commercial simulator vessel. The article gives a comprehensive description of what the hydrodynamic derivatives are and their meaning and importance in the mathematical model.

For an increased understanding of how hydrodynamic models are created and the values of hydrodynamic derivatives calculated, Lewis (1989) wrote about how tank tests can be used to gather information about forces acting on a model hull and then use the data gathered to predict the ship's motion. In an effort to better understand hydrodynamic equations, the lecture notes of Zaojian (2006) have been of considerable help and the explanations are adapted from these two sources.

In order to understand the tools for wind coefficients included in the MSS toolbox, source material for these programs has been consulted. Isherwood (1972) used a method of multiple regression techniques in order to fit calculated coefficients into experimental data. Blendermann (1994) used a method based on *Helmholtz-Kirchhoff* plate theory. Both methods need only the size of the windage areas and the general shape of the vessel to compute coefficients. Blendermann uses a list of parameters that differ for different types of vessels while Isherwood's formulas produce generic coefficients.

Problems with the moment lever arm led to literature regarding the pivot point and its impact on manoeuvring. Capt. Cauvier (2008) points out that the concept of the apparent pivot point is often misunderstood. This point is in fact not a point to be used to understand moments acting on the vessel. This topic is also covered by Jeong (2012) and Seo (2017). A mathematical method to estimate the apparent pivot point is given by Tzeng (1998), whose method uses the rotation of the vessel and sway speed in its calculation.

1.3 Educational Background

The following is a brief overview of the parts of the three-year curriculum that are directly related to navigation. This is included for two reasons. It describes how the competence attained through the course of the studies relates to the writing of this thesis. Furthermore, it demonstrates the experience of the participants used for the experiment (see Section 2.1.1 – Participants).

During the first semester, students receive training in Navigation 1. This subject includes collision avoidance rules, astronomical navigation, terrestrial navigation and simulator training. In the simulator, students are trained and tested in the aforementioned subjects to verify that they have understood the theory and can use it in practice.

In the second semester, the students receive training in Navigation 2. This subject mainly consists of theory about the navigation systems; the theory is tested in both desktop and bridge simulators. During the semester, students are expected to familiarise themselves with RAdio Detection And Ranging (RADAR) and use of Automatic Radar Plotting Aid (ARPA), compass and gyro systems, satellite- and earth-based navigation systems, Automatic Identification System (AIS), and different electronic chart systems.

The third semester contains no elements directly related to navigation techniques.

The fourth semester is demanding, both when it comes to theory and practice. The previous semesters lay a foundation, so now students are expected to dive in-depth into the complexity of marine operations. The focus of the academic content is divided into several small topics, which merge into a large one. It includes how to read and understand nautical publications such as sea charts, pilot guides, tidal tables, current maps, beacon lists and several more. The use and limitations of the Electronic Chart Display and Information System (ECDIS) and advantageous usage of ROT and Parallel Indexing (PI) to secure the voyage is covered, along with the advantages, disadvantages and limitations of the practical use of manoeuvring characteristics and standard manoeuvre tests; also how to operate a vessel in narrow waters and canals, and how the shallow water and channel effects will affect the vessel.

Students must have in-depth knowledge of mooring and anchoring arrangements, including offshore systems, as well as towing and use of tugs. They are taught how to operate the vessel in harsh and icy conditions. Voyage planning includes planning of overseas and coastal voyages, risk assessments, as well as the assessment of necessary margins for safe sailing. For the administrative parts, there is establishing watchkeeping and bridge routines, and logging and documenting the voyage. Use of the Vessel Traffic Service (VTS) and their reporting points and working with a pilot are important aspects the students must become familiar with. They will also learn how to act in case of war or emergencies with the help of the Naval Co-operations and Guidance for Shipping (NCAGS). The Navigation 3 course covers the theoretical knowledge requirements in the STCW (International Convention on Standards of Training, Certification and Watchkeeping for Seafarers) Chapter II, section A-11/2.

In the fifth semester, students start with the last part of the navigation subjects. Maritime communication contains topics on the Global Maritime Distress and Safety System (GMDSS). Medium-, high- and very high frequency transmitters and receivers, Digital Selective Calling (DSC) and satellite communications. It also includes the use of emergency equipment such as Emergency Position-Indicating Radio Beacon (EPIRB), Search and Rescue Transponder (SART) and Search and Rescue Device (SARD). The settings, practical use and testing of the equipment is of great importance in this subject. Protocols and proper procedures for emergency and safety traffic are described in Admiralty List of Radio Signals, vol 5. At the end of the course students receive a General Operators Certificate.

Maritime communication is intertwined with the Navigation 4 course. In Navigation 4, there is great emphasis on bridge resource management with a focus on human factors and leadership. It includes an introduction to how the rescue service in Norway is structured, as well as other countries' similar services. There are mandatory exercises in Search and Rescue (SAR) operations on the bridge simulator, where both management and general execution of theory is used. This course covers the theoretical knowledge requirements in STCW Chapter II Table A-II / 1-2.

Students also have the opportunity to take the elective course position and survey system during this semester. This is more in-depth on how global navigation satellite systems work. An introduction to several position reference systems is given.

During the sixth and final semester, there are no mandatory navigational courses. Apart from courses not relevant to navigation, this semester focuses heavily on bachelor thesis writing.

2 Method

Method is divided up in three parts. The first part details the experiment carried out as part of this bachelor thesis and the second part focuses on the use and creation of the DSS. The last part concerns the choice of statistical method used for analysis of data.

2.1 Experimental Setup

The experiment was carried out using the commercial simulator at NTNU in Ålesund. Participants were picked from the fourth semester nautical school course Navigation 3. This course contains a simulator exercise that with little modification could be used for an initial test of the hypothesis: a decision support system similar to the one devised for this thesis improves navigational safety. As an added benefit, mandatory participation secured a good number of participants. Ideally, these would have been people with experience as deck officers, such as the teaching staff in nautical sciences. However, the larger sample size obtained by using second year students was deemed to far outweigh the use of less experienced participants.

The vessels used for the experiment are listed in Table 1.

Table 1. Vessels used for experiments.

Ship name	Vessel 1	Vessel 2	Vessel 3
Ship type	LNG carrier	Very large crude carrier	Container vessel
Length overall	295m	305m	399m
Beam	45.8m	47m	59m
Displacement	101800t	214943t	249931t
Draught fore	11m	19.8m	16m
Draught aft	11m	17.6m	16m
Block Coefficient	0.71	0.68	0.69
Rudder type	Normal	Normal	2 Normal
Max rudder angle	45°	35°	35°
Max rudder rate	3.6°/s	1.4°/s	5.3°/s
Top speed	20.5kn	16.0kn	19.0kn
Propeller	Fixed pitch	Fixed pitch	2 Fixed pitch
Propeller rotation	Clockwise	Clockwise	Clockwise

2.1.1 Participants

As already mentioned in Section 2.1 – Experimental Setup, the participants for the experiment carried out in this thesis were students in their fourth semester. See Section 1.3 – Educational Background for further details. At the end of the fourth semester, students have completed all courses related to navigational techniques in their nautical education. Their next step in regards to navigational techniques will be aboard ships as deck cadets. With no navigational courses involving sixth semester students, fourth semester students were the best option available in sufficient numbers.

Each class is divided into two groups. Approximately one half of the class have taken the academic route, qualifying for the course through a diploma earned at the end of thirteen years in school. The other half have spent two years at a maritime high school, followed by two years as deck trainees aboard ships, qualifying as able seamen.

In the beginning of the first semester, each student completes a Carl Gustav Jung personality test several times. Students are then paired based on their educational background and the personality test results. One student with an academic background and one with an able seaman background are put together based on the results of this test. This pairing lasts throughout the three years and usually does not change.

The trials for this study were held in the middle of the participants' fourth semester, when they were already familiar with the instruments needed to complete the experiment. They worked in their regular pairs, to simulate a real world environment where two navigational officers have spent considerable time together.

3 weeks prior to the experiment students signed a consent form. The form stated that data about ship movements would be collected and used for the purpose of this bachelor thesis. It also mentioned that no video or pictures of the participants would be included and that the logged data would be saved and kept confidential. Consent could be revoked until the 27th of February 2020, the day before the experiment.

All students in the fourth semester signed the consent form and no one revoked the right to used their data prior to the deadline. The consent form can be found in Appendix A – Consent Form (in Norwegian).

2.1.2 Manoeuvre Tests Using Desktop Simulators

In preparation for the experiment, manoeuvre tests were carried out by the participants on desktop simulators. The desktop simulator consists of two regular computer screens, with a keyboard and mouse for each screen. One screen has a working ECDIS, the other has radar, autopilot and a first person view from the command bridge.

Once a week, students have four hours of desktop simulation and two hours of bridge simulation. The laboratory work is important and a large part of their one-day-a-week practical education. The participants had been doing manoeuvre tests for several types of vessels during the course.

Two weeks prior to the experiment students were given a mandatory exercise. Their task was to do manoeuvre tests of Vessel 2 from Table 1. The setup was identical to manoeuvre tests done previously during the semester, with the addition of a zigzag test. At this point, the students were unaware that this vessel would be used during the experiment. Having the students do manoeuvre tests with the vessel prior to experiments gave them an introduction to the vessel. The thinking behind this was to increase their time spent manoeuvring very large crude carriers in particular and directionally unstable ships in general. This was something with which most of these students had little experience. The familiarisation of Vessel 2 was divided up into eight parts. The parts were as follows:

Part one was a short exercise to find ship specific information in the Wheelhouse Poster, Pilot Card and Manoeuvring Booklet. This is information provided by the company that created the commercial simulator and is available for all vessels. It contains information such as Length OverAll (LOA), beam, draft, displacement, max rudder angle, max rudder rate, and propeller specifics. For example, information given to a navigator about draft and displacement will give an idea about a vessel's manoeuvrability as well as to what extent it will be affected by current. Information in the Manoeuvring Booklet in particular will give a good indication as to the manoeuvrability of a vessel. It is of importance to know the f-distance when using the rate of turn method described in Section 1.2.2 – Traditional Manoeuvring Practices. Figure 3b on page 14 gives a graphical depiction of the f-distance and other terms used in this exercise. This is usually learned from experience but can be found from documents such as the three mentioned at the start of this paragraph (Kjerstad 2017). A rule of thumb is that the f-distance in nm is the ship's LOA divided by $1852m$. For a vessel $185.2m$ in length, this formula would give a f-distance of $0.1nm$. Current has a great effect on this distance and will alter it proportionally to its speed and direction.

A northbound vessel travelling in a southbound current will be "pushed" backwards. This will make the f-distance shorter. If the current is travelling *with* the vessel it will "push" it forward, making the f-distance longer, and the vessel needs to start the turn earlier.

Another thing that has an impact on the manoeuvrability is the propeller's direction of rotation (see Figure 2). For all vessels used in this thesis, the propeller has a clockwise rotation. On a ship that travels in a straight line without any rudder command, a propeller rotating clockwise will cause the stern of the vessel to move toward starboard. This makes the bow move in the opposite direction. Because of forward momentum, this will cause the ship to turn toward port. This knowledge lets the student know that the vessel will turn easier to port, reducing advance and transfer compared to a starboard turn.

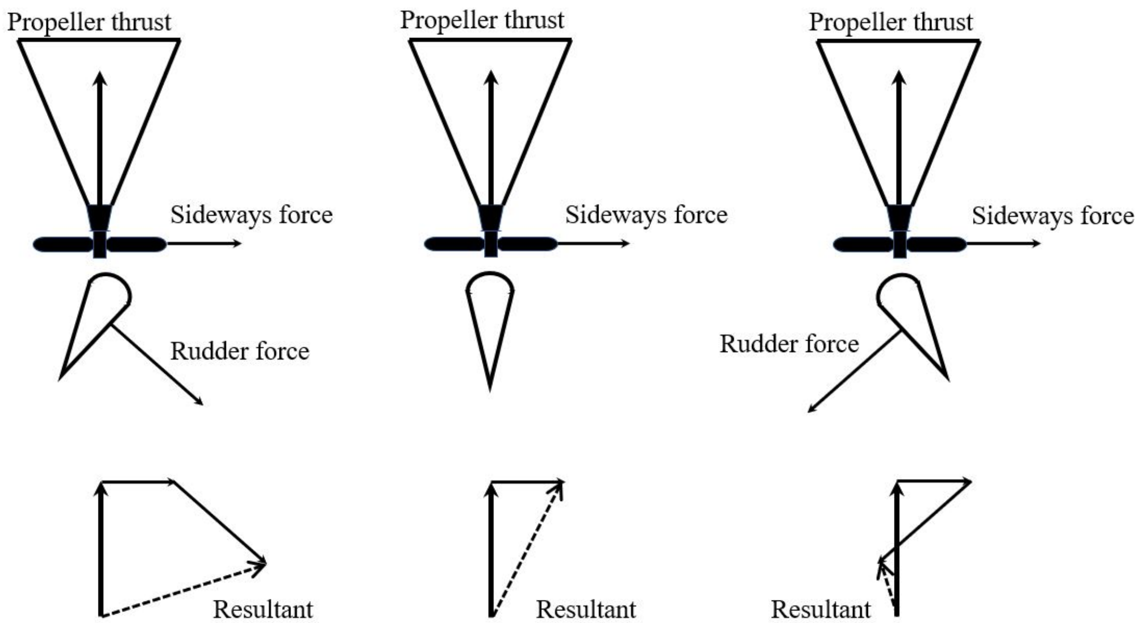


Figure 2. Description of propeller and rudder forces for a clockwise propeller. Original picture by (Kjerstad 2017, p.1-31).

Parts two and three of the manoeuvring tests were intended to test the vessel's turn characteristics with manual rudder angles in deep and shallow water. This was done with no current, waves or other elements that could interfere with the results. This was also the case for the rest of the test conducted. The tests were carried out in a collaboration between all the students.

With ten desktop simulators running in tandem; half of the ships turned to starboard and the other half to port. Rudder angles ranged from $5°$ to $25°$ with $5°$ intervals. When the vessels achieved equilibrium with the water, meaning surge, sway and rate of turn became static, the test was stopped. Data gathered from all vessels was shared between the students. Relevant data from this test is advance, transfer, tactical diameter, turning radius and the f-distance.

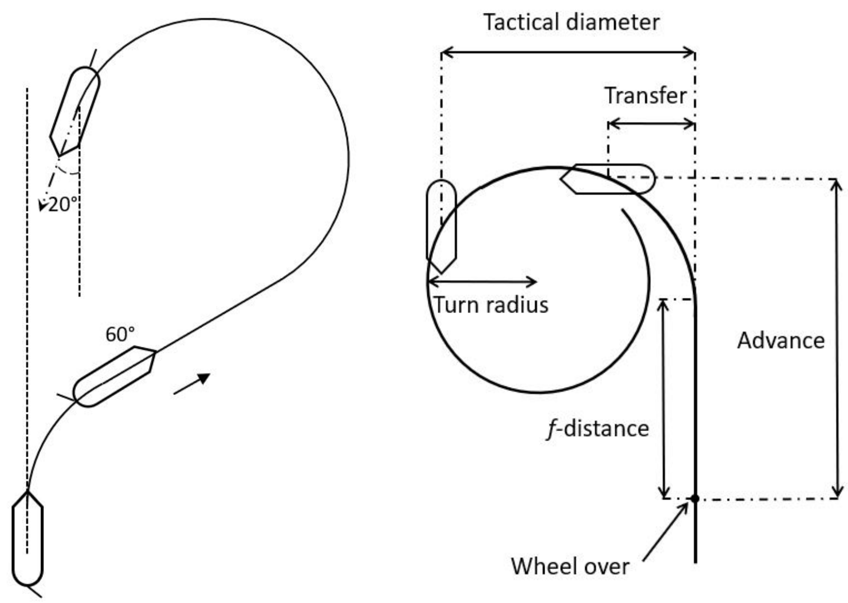
Advance is the distance the midships point travels in the original direction, from the position where the rudder order is given until the course change is $90°$. Transfer is the distance the midships point travels perpendicular to the original direction until the vessel's course has been changed by $90°$. Tactical diameter is the distance the midships point travels perpendicular to the original direction, from the position where the rudder command is given until the course has changed $180°$. Turning radius is the radius of the circle described when the ship has entered an equilibrium with the water. The f-distance is the measured distance the vessel travels from when a new rudder order is given until the vessel starts turning. This data is valuable information when it comes to planning a turn with manual rudder. It also gives an indication of what the expected turn radius is with changing rudder angles and how shallow water will affect the turning capabilities of the vessel.

Part four of the tests measured the capabilities of the autopilot in deep water. Course changes of between $15°$ and $90°$ degrees were tested in $15°$ intervals. Again, several tests were run in tandem. When the vessel had achieved a straight and stable course, the tests were stopped. Data gathered were max rudder angle, advance and transfer to the new course. Knowing the max rudder angle that the autopilot will give is valuable information about the limits of course changes when using the autopilot. Measurements of advance and transfer follow the same principles as in tests two and three. The difference is that the distances were measured when the vessel obtained the new set course, and not at $90°$ off the original course. This is essential information in planning a manoeuvre using autopilot as well as the limitations of doing so.

Part five was similar to part four. A manoeuvre diagram was created using the fixed radius function on the autopilot. Students used the autopilot to turn $90°$ off the original heading with a fixed radius ranging from 0,1nm to 0,7nm. The purpose of this test was to observe how much rudder angle was used and how narrow a turn the autopilot can make with its inbuilt limitations.

Part six built on the same general principles as the previous two. The students set a course $90°$ off the original course to both port and starboard. They programmed the autopilot to turn with a fixed rate of turn ranging from $10°/min$ to $50°/min$ in $10°/min$ intervals. Again students monitored the max rudder angle and what radius the different settings resulted in. The idea with tests four, five and six was to give the students a general idea about how sharply one can turn using the autopilot.

After tests four to six, the results were analysed. Students engaged in discussions with



(a) (b)

Figure 3. Williamson turn (Kjerstad 2017, p.2-112) (a) and description of advance, transfer, tactical diameter, f-distance and turn radius (b).

the teacher about what propeller rotation the vessel had, the limitations of the autopilot and comparisons between the turning radius expected and the one achieved. Theoretical turning radii were approximated using Equation 1.

$$\text{Radius} = \frac{\text{Vessel speed}}{\text{Rate of turn}} \tag{1}$$

Part seven had the students perform a Williamson turn (see Figure 3a). In a man overboard situation, it is of the utmost importance to perform a fast and effective manoeuvre to turn the vessel around and return to where the person fell overboard. For a smaller, more manoeuvrable vessel, a regular turning circle is sufficient, but this is ineffective for larger vessels. A Williamson turn is one way of turning the vessel around and returning to the same position where the manoeuvre was started. This is done in three steps:

- Give hard rudder to the same side as the person fell overboard. This pushes the propeller(s) away from the person in the water.
- At a heading of 60° off the initial course, give hard rudder in the opposite direction.
- When the vessel is 20° off the reciprocal course, the rudder is put midships.

The efficiency of following the standard instructions was evaluated and students were asked to make their own ship specific instructions for a second attempt. A limit of three rudder commands were set on these instructions.

The optimal solution for Vessel 2 turned out to be the following:

- Give hard rudder toward the side of the man overboard

- Once the vessel is 20° off the original course give hard rudder in the opposite direction
- When the vessel is 120° off the reciprocal course, put the rudder midships.

Vessel 2 reacts slow to changes in rudder angle and has a huge momentum. Once a decent rate of turn is achieved, it takes a long time for counter rudder to have any effect. This is more or less what is expected from a heavy, directionally unstable vessel.

Part eight in the familiarisation of Vessel 2 was a zigzag 20°/20° manoeuvre. The purpose of this test is to study the vessel's response to changing rudder angles. Essential parameters are the time between subsequent rudder movements and the first and second overshoot angle (Kjerstad 2017). The test was conducted by having the vessel hold a steady course without any rate of turn. A rudder command of 20° to either side was given. When the vessel was 20° off the original heading, 20° rudder to the opposite side was given. The overshoot angle is the number of degrees the vessel turns from the moment the new rudder command is given until the rate of turn is stopped and the ship starts changing its heading in the opposite direction. The time from first command to second is also of importance. This procedure was done two to three times, and the data are sufficient to conclude how the vessel responds to changing rudder commands. Tests showed that the vessel responds slowly to rudder commands and will most definitely overshoot by a minimum of 20° with a rudder angle of 20°. To reduce overshooting during manoeuvres, it is advised that smaller rudder angles be used during course changes.

2.1.3 Bridge Simulators

There are six bridge simulators located at NTNU in Ålesund. For the sake of simplicity, they will be numbered 1-6 in this thesis. The bridges are similar in equipment and structure with slight variations. Ideally, identical bridges would have been used to reduce outside factors from having an impact on results. However, ensuring the bridge used was the same for each test would have meant that just one pair at a time could perform the experiment; this was therefore ruled out.

Bridge 1, 2 and 3 are all very similar. Two projectors show the field of view from the perspective of the command bridge on a curved wall approximately two metres in front of the helmsman. The command module is equipped with a centrepiece containing dials and levers for the autopilot, radar screens—one on either side—and conning display. The bridges are also equipped with a lookout post and an ECDIS. The positions of these vary slightly in between the separate bridges. A steering wheel for manual steering is located in the middle of the command module. A TV screen is located at the opposite side of the curved wall, showing a stern view.

Bridge 4 has the same general setup as Bridge 1, 2 and 3. Bridge 4 does however lack a steering wheel, which means you must use a rotary lever to steer the vessel manually.

Bridge 5 is designed to work as a ferry simulator. Instead of projectors, two TV screens at either end of the bridge show a clear view in both directions. With the push of a button, you are able to change the defined forward direction of travel and the bridge is equipped with levers and dials at both ends for steering.

Bridge 6 is a bridge simulator designed as a Dynamic Positioning (DP) simulator. It is built with five TV screens placed to provide a 90 degrees field of view forward, and one screen behind to show a stern view. The conning display and binoculars are placed above the TV screens. The radar and ECDIS have a separate section on the starboard side. The DP operating station is on the port side. The main command module with steering wheel, dials and levers sits in the centre.

2.1.4 Students' Assignment

Five days prior to the experiment, the assignment was given to the participants. Maritime regulations put size and cargo restrictions on passage through Vatlestraumen (Sjøtrafikkforskriften 2015, § 128). Students were asked to disregard this in their planning. While this makes the assignment somewhat unrealistic, it increases the level of concentration and skill required to perform it successfully. Additionally, using the test vessel in confined waters it has no business going near was deemed a suitable stress test of the DSS.

The content of the assignment included information about two of the three vessels, learning objectives, learning goals and a small map of Vatlestraumen, where the exercise was to take place (see Figure 4). This is an area that the students were familiar with from previous simulator exercises. Also included in the assignment were the time and date so they would have the possibility of finding tide and current information. Initial data, coordinates for their starting position and an approximate last waypoint were also included.

Their initial position was $1.31 nm$ due south of Hilleren lighthouse, and the vessel started with a speed of 16 knots at a heading of 000°. In Vatlestraumen, the current reverses with the tidal flow at high tide and low tide: north with rising and south with falling water. The time of the exercise was set to daytime with a southbound current of 1.5 knots. Since the exercise took place in full daylight, the navigational lights were set to light up brighter so the students could see them clearly and use them as navigational aids. Visibility was good. The scenario ran without wind; the details around that decision is discussed in Section 2.2.7 – Wind.

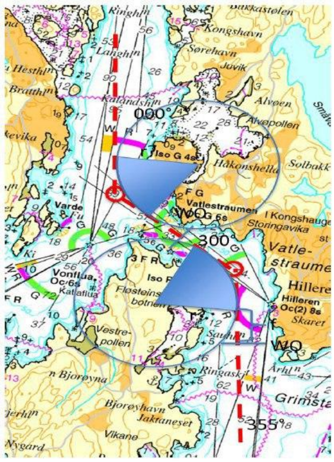


Figure 4. Map of Vatlestraumen and example track. Chart by (Kartverket 2003).

Prior to the day of the exercise, students were tasked with creating a description of Vatlestraumen using The Norwegian Pilot Guide. Using this source in conjunction with information gained from manoeuvring booklets and wheelhouse posters they were to:

- Plan how to secure the voyage using variable PI, Electronic Bearing Line (EBL) and Variable Range Marker (VRM) to find their wheel-over points.
- Create a passage plan with necessary information, including a simple-to-follow detailed list of instructions.

The goal for the students was to learn to navigate a large vessel in narrow water at high speed. Using a constant rate of turn technique, VRM, EBL and PI were to be used together with paper charts. Maintaining and controlling the position of the vessel and deciding the wheel-over point with a high level of accuracy was of utmost importance. Furthermore, they were to practice creating a pilot guide, learn to read and understand published pilot guides and put their manoeuvre test results into practice.

2.1.5 Experiment

Table 2. Vessel sequence for experiment.

Group A	Vessel 1	Vessel 2	Vessel 3	Vessel 2 DSS
Group B	Vessel 2 DSS	Vessel 1	Vessel 2	Vessel 3

Four runs through Vatlestraumen were planned, using two different sequences (see Table 2). Group A started by showing their passage plan and pilot guide to their instructor. If students had questions relating to the exercise, they could ask them at this point. They were then sent to their randomly assigned bridge simulator. After completion of their first run a debrief was held with the instructor. The debrief consisted of the students giving a brief summary of high and low points from their own performance. This process was repeated for run 2 and 3. After the debrief of run 3 the students were given a short presentation of the DSS. This included how the DSS was constructed, how it calculates the trajectory and the limitations of the system. It was emphasised that this was an offline system and that the calculated rudder commands were not to be treated as instructions cast in stone. It was also explained that if students were to initiate the manoeuvre at any point other than the decided wheel-over point, the rudder commands would be progressively less valid with increasing distance to the intended wheel-over point. They were further told that in calculating the trajectory, the assumption was made that the ship had travelled in a straight path from the starting position to the wheel-over point. Students were asked to follow the calculated commands from the DSS unless they deemed it unsafe to do so.

Finally, a paper sheet was handed out with the calculated rudder commands shown in Table 3. Prior to being sent to the bridges students had the possibility to ask questions about the presentation, the experiment or the calculated rudder commands.

Table 3. Calculated rudder commands given prior to experiment.

5° Port	Until you reach a heading of 327°
9° Starboard	Until you reach a heading of 330°
7° Port	Until the ROT is zero

Group B was given the same setup and procedure to complete their tasks as group A, apart from the change of order described in Table 2. They started the experiment by getting the presentation described above.

To preserve the integrity of the experiment, they were also asked not to speak about their experience with the DSS with classmates before the end of the day.

2.2 Decision Support System

The following section will focus on the creation and use of the DSS in its current form. Because this is a system created within a limited time span and by people with little prior knowledge of hydrodynamics, both limitations and assumptions have been made to reduce the workload. These will be examined in Section 2.2.1 – Limitations and Assumptions. Ship handling is hard and external forces add complexity. The DSS is motivated by this statement and is a suggested solution to this problem. It is important to note that this is a system built for the sole purpose of being able to test the hypothesis of this thesis and not made for real life applications. It is therefore not to be considered a finished product and was at no point during its creation intended to become one. The DSS in its current form is an expansion of an idea to test the limitations, possibilities and feasibility of this idea. The challenges posed by building a system for decision support of rudder angles made for real life application are far greater than what can be addressed within the scope of a bachelor thesis; this is therefore merely a dip to test the waters.

The DSS is built using the Marine systems simulator toolbox (Fossen and Perez 2004) in Simulink. The main working principle behind the DSS is to take the navigator's best estimation as to how a manoeuvre should be executed and plot the resulting ship trajectory taking weather and current into account. This can then be compared to a chart overlay and modifications can be made prior to execution of the actual manoeuvre. A simplified description of the DSS is shown in Figure 5.

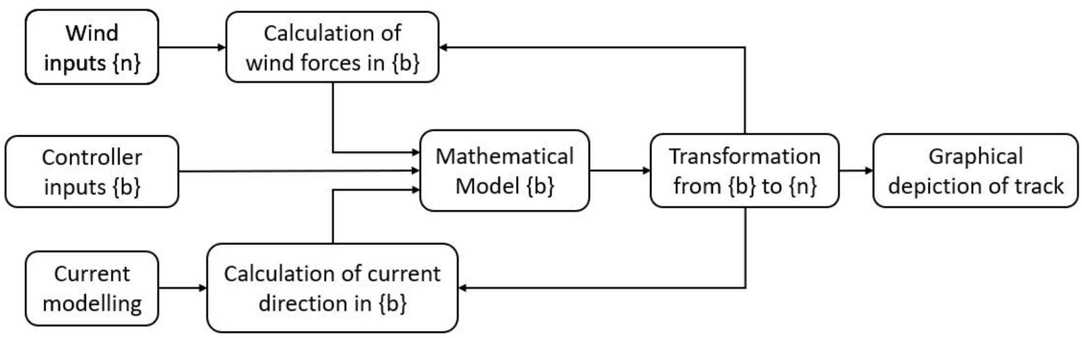


Figure 5. An overview of the Decision support system.

2.2.1 Limitations and Assumptions

The DSS was created, optimised and operated in tangent with the commercial simulator available at NTNU in Ålesund. Assuming that a simulator, however well built, is equal in realism to the real world is a hard sell to even the most ardent simulator enthusiast. It was however a necessity to make this assumption due to the practical impossibility of testing the DSS on actual ships. It would require both access to large tankers and would add a large amount of complexity to building the DSS as mentioned in Section 2.2 – Decision Support System.

The participants never used the decision support system by themselves but were given system output by the authors. The main reason for this was that in its current form, the DSS does not have a user interface. Neither creating a user interface nor teaching all the participants about the inner workings of the system was deemed feasible. It was therefore decided that one operator would use the DSS and present the knowledge gained by the system in an easy to understand and intuitive way. Rudder orders in the mathematical model are given at specific times counted from the wheel-over point. It is not considered normal procedure on a ship to count the seconds between events; this is therefore far from ideal because it would add another aspect to manoeuvring in restricted waters. However, the heading is kept track of continuously. On the basis of this, rudder orders were calculated as a rudder angle to be held until a certain heading was reached, upon which a new rudder order was to be given. The navigators participating in the test were provided with these rudder orders. This system was tested by both the authors and their peers in advance of the experiment and showed great success because it was both easy to follow and provided enough accuracy for the DSS to be effective in use.

Use of the system by the participants was made more difficult by the fact that the system was not permitted to interact with the commercial simulator in any way. The reasons for this are several and integration to some extent could have been possible. However, an application for such integration was deemed unlikely to be successful, and in any case the processing of an application would have taken time away from the testing that needed to be carried out. It was therefore decided to keep the two systems separated. This means that the DSS and the commercial simulator are two completely separate systems and that no real time updates can be shared between the two. Because of this, a few assumptions were made when it came to weather inputs.

Due to the separation of the two systems, wind and current being fed into the DSS did not originate from sensors on the ship. In a real life application, wind and current would be a combination of current table data, weather forecasts, sensor data and best estimations. During the experiments this was reduced to the authors trying to mimic real life currents and giving the same information to both commercial simulator and DSS. Wind was excluded from the experiment because of several issues with the calculation of wind forces and moments; these are discussed in Section 2.2.7 – Wind.

Another limitation of the DSS is that it uses Maneuvering Theory. This is ill suited for real life applications because it assumes zero wave excitation, something that is more of an exception than the norm in ship day-to-day operations. Maneuvering Theory will be described in detail in Section 2.2.4 – Mathematical Model and Seakeeping Theory is mentioned in Section 2.2.2 – The Classical Models of Naval Architecture.

Wind and current data is loaded into the DSS scenario by the navigator. For this experiment, this has been loaded in to the program by the same person creating the simulator scenario, meaning that actual weather conditions are the same as those loaded into the DSS.

2.2.2 The Classical Models of Naval Architecture

The classical models of naval architecture can be divided into two theories. These are Maneuvering Theory and Seakeeping Theory. Maneuvering Theory assumes that the hydrodynamic coefficients are *frequency independent* (no wave excitation) (Fossen 2011). Seakeeping theory can be used at zero or constant speed in waves where the hydrodynamic coefficients and wave forces are computed as a function of the wave excitation frequency using the hull geometry and mass distribution (Fossen 2011, p. 8). Simplified this means that:

Seakeeping Theory: Only calculates the forces and moments induced by waves but not other forces and moments.

Maneuvering Theory: Does *not* calculate forces and moments induced by waves. It considers control input forces and moments of a moving ship in calm water.

To create a system for path prediction using the classical models of naval architecture, one is compelled to use Maneuvering Theory. Seakeeping could only calculate the path of drifting objects. For simultaneous calculation of both wave and control input forces there are some newer methods such as Unified Theory (Fossen and Sagatun 1991) and Two-time Scale Method (Skejic and Faltinsen 2008).

2.2.3 Reference Frames

Motion is meaningless without a reference frame. Defining forces, speeds, accelerations and angles is absolutely crucial when calculating the movement of a ship. A car could not care less whether the wind force felt by the windshield was from the car moving through the air or gale force winds. When calculating the motion of a vessel it is often more convenient to express forces acting on the vessel in reference to a coordinate system with its origin moving with the vessel itself. For the purpose of this thesis, one Earth-centred coordinate frame and two geographic reference frames have been used. These are explained in greater detail by Fossen (2011), but a brief summary of his explanations will be given below.

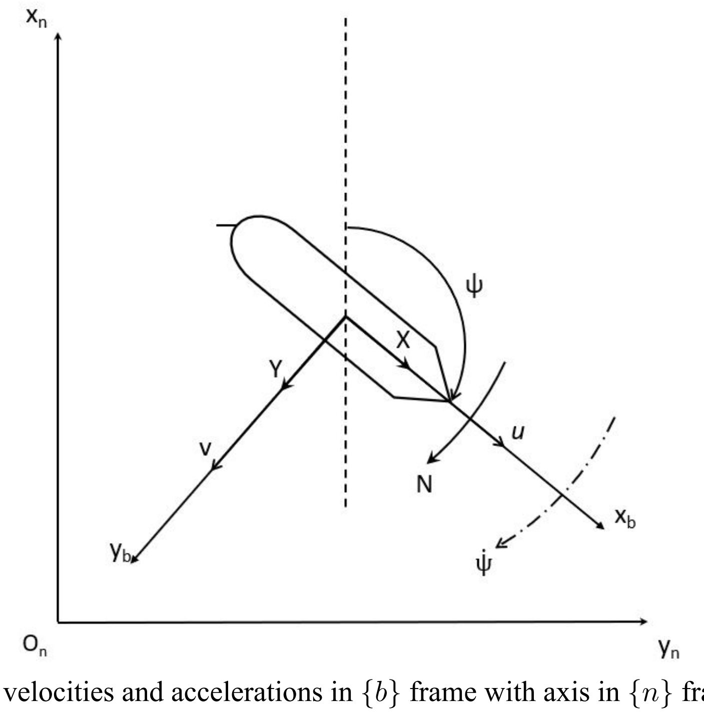


Figure 6. Forces, velocities and accelerations in $\{b\}$ frame with axis in $\{n\}$ frame shown in the bottom left.

ECEF: The Earth-centred Earth-fixed reference frame is rotating with the rotation of the earth. Its origin, as the name implies, lies at the centre of the Earth. For vessels moving at low speed this reference frame can be considered inertial, but for drifting vessels the rotation of the Earth must be considered. Coordinates in this reference frame are usually given as latitude and longitude; it is most commonly used in long distance navigation. Its sole use during the experiments was because data extracted from the commercial simulator needed transformation from the ECEF frame to a North-East-Down reference frame.

NED: The North-East-Down reference frame $\{n\}$ = (x_n,y_n,z_n), henceforth referred to as the $\{n\}$ frame, is the most intuitive reference frame and the most commonly used. The x-axis points toward north, y-axis toward east and the z-axis points toward the centre of the Earth. This is the same reference frame as one would use while looking at a common paper chart. For vessels operating within a local area the $\{n\}$ frame is sufficient for navigation. The origin usually travels with the vessel with z_n = 0 defined by a reference ellipsoid. For the purpose of this thesis the origin was chosen to coincide with the position of the wheel-over point used for the DSS trials.

BODY: The body-fixed reference frame $\{b\}$ = (x_b,y_b,z_b) has its origin at the vessel's centre of gravity and moves with the vessel. The $\{b\}$ frame is shown in Figure 6. Control forces are most commonly described in terms of the $\{b\}$ frame.

2.2.4 Mathematical Model

Nomenclature Section 2.2.4

X_b = Forces along the x-axis in $\{b\}$ frame $\left[\text{kgm/s}^2\right]$	δ = Rudder angle [rad]
Y_n = Forces along the y-axis in $\{n\}$ frame $\left[\text{kgm/s}^2\right]$	n = Shaft velocity [Rpm]
N = Moments around the z-axis $\left[\text{kgm}^2/\text{s}^2\right]$	v = Sway speed [m/s]
I_z = Moment of inertia around the z-axis $\left[\text{kgm}^2\right]$	u = Surge speed [m/s]
$\ddot{\psi}$ = Angular acceleration around the z-axis [rad/s^2]	$\dot{\psi}$ = r = Rate of turn [rad/s]
$\ddot{x}$ = The second time derivative of x = [m/s^2]	ψ = Heading [rad]
u_G = surge speed at vessels centre of gravity [m/s]	Δ = Diplacement of vessel [Kg]
V_t = Tangential velocity of circle [m/s]	$\otimes$ = Midship point
ω = Angular velocity of circle [rad/s]	β_w = True wind direction [rad]
γ_w = True wind direction with respect to true north [rad]	V_w = True wind speed [m/s]
γ_{rw} = Relative wind direction with respect to the bow [rad]	V_{rw} = Relative wind speed [m/s]

In this context, "mathematical model" is a set of equations describing the motion of a particular vessel. The aim of the mathematical model is to predict what motions external forces create on the vessel it describes. Several approaches to building a mathematical model exist. Because of the authors' limited knowledge of hydrodynamics prior to starting this bachelor thesis, it was decided to use an existing mathematical model and alter it in ways so as to describe the movement of a vessel available in the commercial simulator. This process is described in greater detail in Section 2.2.5 – Parameter Optimisation. The following part of this section will describe how Newtons second law can be applied to calculate the accelerations of a vessel and therefore its position. This will be explained in 11 steps following the explanation of Lewis (1989, p.193)

Step 1: Newton's Second Law (forces in the $\{n\}$ frame).

Because the $\{n\}$ frame is considered inertial, Newton's second law of motion $F = ma$ can be applied. The motions of a ship in three degrees of freedom (3 DOF) in the $\{n\}$ frame can therefore be described by the following equations:

$$\begin{aligned} X_n &= \Delta \ddot{x}_n \\ Y_n &= \Delta \ddot{y}_n \\ N &= I_z \ddot{\psi} \end{aligned} \tag{2}$$

Where: X_n and Y_n = Total forces in the x and y direction in $\{n\}$ frame
N = Total moment around the z-axis
Δ = displacement of the vessel
I_z = Moment of inertia around the z-axis
$\ddot{\psi}$ = The second time derivative of vessel heading.
The two dots over x,y and ψ indicate that it is the second time derivative of the symbol with respect to time. If the unit of x is metres then $\dot{x} = m/s$ and $\ddot{x} = m/s^2$.

Step 2: Transformation between $\{b\}$ and $\{n\}$ frame.

Equation 2 looks simple, but once one starts calculating it soon becomes apparent that it is of great inconvenience to describe the motions of a vessel in terms of the $\{n\}$ frame. Conversion between $\{n\}$ frame and $\{b\}$ frame is done using rotation matrices. Equation 3 uses the heading of the vessel ψ to transform back and forth between $\{n\}$ and $\{b\}$ frame in the following manner:

$$\begin{bmatrix} X_n \\ Y_n \end{bmatrix} = \begin{bmatrix} \cos\psi & -\sin\psi \\ \sin\psi & \cos\psi \end{bmatrix} \begin{bmatrix} X_b \\ Y_b \end{bmatrix} \tag{3a}$$

$$\begin{bmatrix} X_b \\ Y_b \end{bmatrix} = \begin{bmatrix} \cos\psi & \sin\psi \\ -\sin\psi & \cos\psi \end{bmatrix} \begin{bmatrix} X_n \\ Y_n \end{bmatrix} \tag{3b}$$

Step 3: Velocity in $\{n\}$ frame as a function of motion in $\{b\}$ frame.

Transformation between frames for position, velocity and acceleration work the same way. In Equation 4, velocity in the $\{n\}$ frame is described as a function of velocity in the $\{b\}$ frame.

$$\begin{aligned} \dot{x}_n &= u\cos\psi - v\sin\psi \\ \dot{y}_n &= u\sin\psi + v\cos\psi \end{aligned} \tag{4}$$

Where $\dot{x}$ and $\dot{y}$ are the first time derivatives of position in $\{n\}$ frame and u and v are surge and sway speeds in $\{b\}$ frame.

Step 4: Acceleration in $\{n\}$ frame as a function of motion in $\{b\}$ frame.

By differentiating Equation 4 with respect to time, $\ddot{x}$ and $\ddot{y}$ become:

$$\begin{aligned} \ddot{x}_n &= \dot{u}\cos\psi - \dot{v}\sin\psi - (u\sin\psi + v\cos\psi)\dot{\psi} \\ \ddot{y}_n &= \dot{u}\sin\psi + \dot{v}\cos\psi + (u\cos\psi - v\sin\psi)\dot{\psi} \end{aligned} \tag{5}$$

Step 5: Forces in $\{n\}$ frame as a function of motion in $\{b\}$ frame.

By inserting Equation 5 into Equation 2, a new expression for X_n and Y_n emerges:

$$\begin{aligned} X_n &= \Delta\dot{u}\cos\psi - \Delta\dot{v}\sin\psi + \Delta(-u\sin\psi - v\cos\psi)\dot{\psi} \\ Y_n &= \Delta\dot{u}\sin\psi + \Delta\dot{v}\cos\psi + \Delta(u\cos\psi - v\sin\psi)\dot{\psi} \end{aligned} \tag{6}$$

Step 6: Transformation of forces from $\{n\}$ to $\{b\}$ frame.

Equation 6 can now be put into the rotation matrix described in Equation 3b and simplified in the following steps for forces in the X direction:

$$\begin{aligned} X_b &= [\Delta\dot{u}\cos\psi - \Delta\dot{v}\sin\psi + \Delta(-u\sin\psi - v\cos\psi)\dot{\psi}]\cos\psi + [\Delta\dot{u}\sin\psi + \Delta\dot{v}\cos\psi + \Delta(u\cos\psi - v\sin\psi)\dot{\psi}]\sin\psi \\ X_b &= \Delta\left[\dot{u}\cos^2\psi - \dot{v}\sin\psi\cos\psi + \left(-u\sin\psi\cos\psi - v\cos^2\psi\right)\dot{\psi} + \dot{u}\sin^2\psi + \dot{v}\cos\psi\sin\psi + \left(u\cos\psi\sin\psi - v\sin^2\psi\right)\dot{\psi}\right] \\ X_b &= \Delta\left\{\dot{u}\left(\cos^2\psi + \sin^2\psi\right) - \dot{v}\sin\psi\cos\psi + \dot{v}\cos\psi\sin\psi + \left[-u\sin\psi\cos\psi + u\cos\psi\sin\psi - v\left(\cos^2\psi + \sin^2\psi\right)\right]\dot{\psi}\right\} \\ X_b &= \Delta(\dot{u} - v\dot{\psi}) \end{aligned} \tag{7}$$

Step 7: Forces as function of motions, all in $\{b\}$ frame.

The same can be done for Y Forces. Moments around the z-axis go unchanged. This results in the following rewriting of $F = ma$ for forces in the $\{b\}$ frame:

$$\begin{aligned} X &= \Delta(\dot{u} - v\dot{\psi}) \\ Y &= \Delta(\dot{v} + u\dot{\psi}) \\ N &= I_z\ddot{\psi} \end{aligned} \tag{8}$$

Step 8: Transformation of speeds from centre of gravity to midships.

It is often more convenient when calculating forces to have the origin of the $\{b\}$ frame midships ($\otimes$) than in the centre of gravity (G). This has little to say for surge speed; vectors can be moved along their path with no effect. This is not the case for sway speed and angular velocity. The formula for tangential velocity, $V_t = r\omega$, can be applied. The distance between $\otimes$ and G, x_G, represents r. The angular velocity on a vessel is the first time derivative of the ships heading ψ. ω is therefore replaced with $\dot{\psi}$. Any sway speed the ship experiences needs to be accounted for as well. The full equations for surge and sway transformation look like this:

$$u_\otimes = u_G, \quad v_\otimes = v_G + x_G\dot{\psi} \tag{9}$$

For simplicity, $u_\otimes = u$ and $v_\otimes = v$ from this point onward.

Step 9: The right hand side of the force equations in $\{b\}$ frame at midships.

Substituting these new values for surge and sway into Equation 8 we get our final equations of motion:

$$\begin{aligned} X &= m\left(\dot{u} - vr - x_G r^2\right) \\ Y &= m\left(\dot{v} + ur + x_G\dot{r}\right) \\ N &= I_z\dot{r} + mx_G(\dot{v} + ur) \end{aligned} \tag{10}$$

Keep in mind that $\dot{\psi} = r$. A similar process is done for moments and is described in greater detail by Zaojian (2006)

From Equation 10, van Berlekom, Goddard, and The Society of Naval Architects and Marine Engineers (1972) describe how the mathematical model is created. It is incorporated into Matlab by Trygve Laudal (see Appendix C.3 – Mathematical Model). A short description will however be given here as well. The initial state vector is a list of values that the simulation is given as starting conditions. The output from the mathematical model is a time derivative of the initial state vector and therefore needs to be integrated before it is fed into the model as simulation step two. The initial state vector for this mathematical model is given in Equation 11

$$x = [u\ v\ \dot{\psi}\ x_n\ y_n\ \psi\ \delta\ n] \tag{11}$$

where:
u = surge
v = sway
$\dot{\psi}$ = first time derivative of ψ
x_n = position along the x axis in $\{n\}$ frame
y_n = position along the y axis in $\{n\}$ frame
ψ = heading
δ = rudder angle
n = propeller shaft rotation in revolutions per minute.

Step 10: Giving the forces a mathematical expression.

The hydrodynamic and control surface forces in the model can be described by Equation 12:

$$\begin{aligned} X &= F_x(\dot{u}, \dot{v}, \dot{\psi}, \delta, n) \\ Y &= F_y(\dot{u}, \dot{v}, \dot{\psi}, \delta, n) \\ N &= F_N(\dot{u}, \dot{v}, \dot{\psi}, \delta, n) \end{aligned} \tag{12}$$

To give the left hand side of Equation 10 a mathematical expression a method developed by Abkowitz (1964) is used. Abkowitz suggested using Taylor Series to model the forces and moments acting on a ship. The resulting hydrodynamic derivatives are then added in the following fashion to calculate the overall forces in X, Y and N. Below, there is an example of forces in the X direction in $\{b\}$ frame with respect to surge speed:

$$F_x(u) = X_0 + X_u \Delta u + \frac{1}{2} X_{uu} \Delta u^2 + \frac{1}{6} X_{uuu} \Delta u^3 \tag{13}$$

Where: X_0 = The initial forces in the X direction, $\Delta u = u_1 - u_0$, $Xu = \frac{\partial X}{\partial u}$, $Xuu = \frac{\partial^2 X}{\partial u^2}$, $Xuuu = \frac{\partial^3 X}{\partial u^3}$.

Step 11: The model.

Added mass is a force felt by the hull of a vessel moving through a liquid. This force comes from the fact that the vessel is not moving through a vacuum and therefore needs to clear a path through the medium in order to progress forward. In everyday language, words like aerodynamic and hydrodynamic often refer to the magnitude of the added mass. If an object is streamlined, less matter needs to be moved away from the path to be replaced by the object. By making the object streamlined, m in Newton's second law is reduced and therefore less force is needed to accelerate the object. In the case of naval architecture, this is often denoted $X\dot{u}$, $Y\dot{v}$ and $N\dot{r}$ for surge, sway and yaw respectively. A square box of volume V would have more added mass in the surge direction than a torpedo shaped object of the same volume. With this extra component of mass in the equations, the second time derivative of u (acceleration) in the surge direction is calculated using Equation 14:

$$\frac{F_x(u, v, \psi, \delta, n)}{(\Delta - X\dot{u})} = \dot{u} \tag{14}$$

2.2.5 Parameter Optimisation

The mathematical model used in the DSS was built for a vessel similar in shape to the one chosen for experiments but not equal in manoeuvring characteristics. The need for optimisation becomes apparent when comparing tracks from the unmodified model and the commercial simulator for a 35° turning circle to port (see Figure 8 on page 28). Optimisation was carried out in three steps. These will be explained in greater detail below. One of the great problems with not calculating the forces but using data science to optimise against a cost function arises when wind forces are added into the mathematical model. In the model prior to optimisation, hydrodynamic derivatives are calculated after model tests (van Berlekom, Goddard, and The Society of Naval Architects and Marine Engineers 1972). These forces are then plotted as a function of acceleration in its respective degree of freedom in a process better described in 2.2.4 – Mathematical Models. In optimisation, the process is somewhat reversed. Data of accelerations in three degrees of freedom were gathered from the commercial simulator and these were then matched to accelerations calculated by the DSS. When changing the hydrodynamic derivatives described in Equation 13, careful consideration needs to be taken to make sure that both mass and added mass are given their correct values with respect to the Bis System described by Norrbin (1970). A lack of data about the vessel meant that added masses could not be calculated. This means that in theory, and with high probability in this case, the model is able to describe the movements of the vessel because the product of the equations for acceleration still yield the correct result. It is however difficult to know if m in the equation $a = \frac{F}{m}$ is given a correct value, or has just been scaled in such a way that it accurately predicts the motion of the commercial simulator.

Step 1: Gathering data from the commercial simulator.

Gathering data on the manoeuvrability of Vessel 2 was done in sea trials in a simulator. Because the simulator is constructed in such a way as to give the user full control of weather, the sea trials could be done under somewhat unrealistic conditions to the authors' benefit. Trials were conducted in an open environment with a water depth of 200 m and with no current, wind or waves. The vessel started at equilibrium with all values of the initial state vector being equal to zero, apart from surge being equal to speed over ground and shaft velocity being equal to 74 rpm. In the list of trials (Table 4), this is true unless otherwise stated. The following manoeuvre trials were carried out:

Table 4. Manoeuvre test performed for parameter estimation.

Coasting stop 1	Shaft speed set to zero
Coasting stop 2	Standard setup
Crash stop	Standard setup
Turning circles	Rudder angles ranging from 5°–35° in 5° intervals.
Zigzag test	Both 10°/10° and 20°/20° tests

Position, accelerations and both linear and angular velocities were logged. Manoeuvre trials are described in more detail in Section 2.1.2 – Manoeuvre Tests Using Desktop Simulators.

While it would not have been possible to perform the coasting stop with zero shaft velocity in reality, it did help in estimating the parameters, since for this particular test propeller forces could be excluded. Optimisation was therefore started with the estimation against coasting stop 1, and once trajectories and velocities matched those of the simulator trials proceeded to coasting stop 2. In the second round of estimation only forces concerning propeller forces were altered. The third step in the process estimated rudder forces using data gathered from turning circle trials. In these tests hydrodynamic derivatives modelling rudder forces were estimated. The final fit between the DSS and the simulator was done on the zigzag tests. Here all parameters were estimated again, but harsh limits on the deviation from previous estimations were used.

Step 2: Using Monte Carlo Simulation to narrow down the search.

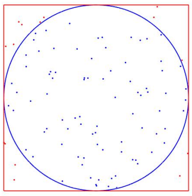
Before step two can be explained, Monte Carlo Simulations need a proper introduction. A useful experiment is to estimate the value of π using a dartboard. The first step is to put a frame around the dartboard so that the square created is tangent to the circle on all four sides. The area of the dartboard is $\pi \times r^2$ and the area of the square is $(2r)^2$, making the ratio of circle to square $\frac{\pi}{4}$. Throwing darts at random, the ratio between darts inside the circle to darts outside it would be equal to the ratio of area within the circle to area outside it, giving us the equation $\frac{\pi}{4} = \frac{Number\ of hits\ inside\ the\ circle}{Total\ number\ of\ throws}$. Any darts hitting outside both circle and square are disregarded and not counted as thrown. Solving this equation with respect to pi gives: $\pi = 4 \times \frac{N_{inside}}{N_{total}}$. The first throw will be either a hit or a miss. This would make the estimated value of π either 0 or 4. With increasing number of throws, or iterations, the estimated value would slowly get closer to the actual value of π. This process is illustrated for an increasing number of iterations in Figure 7. Figure 7e shows that the error in calculating π using this method is close to zero after 400,000 iterations.

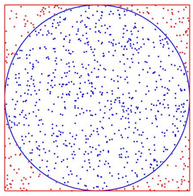
In the example above, the darts have an equal chance of hitting any point within the square and thus follow a uniform distribution. For this thesis, values for the hydrodynamic derivatives followed a normal distribution. Values for 1 σ were set by taking values from two other vessels. Both were supertankers with one being slightly smaller and one slightly larger than the vessel for which the model was being optimised. If for example the derivative Yvv were to be optimised, the values for Yvv for ship 1 and ship 2 would be set as -1σ and 1σ respectively. For any randomly generated numeric value for Yvv there would be a 68% chance of it being within this range. One hundred and fifty randomly generated numbers were created and the simulation was run with each value. The resulting sway speeds of these simulations were compared to the logged sway speed from the commercial simulator trials described in Table 4. To evaluate the size of the error a cost function needs to be used. In the example above the cost function would be π - estimated value of π, but for optimisation of the mathematical model Mean Square Error (MSE) was used (see Equation 15).

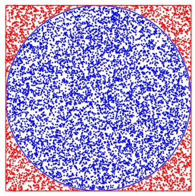
$$\frac{1}{n}\sum_{i=1}^{n}\left(Y_i - \hat{Y}_i\right)^2 \tag{15}$$

Where n is the number of iterations, Y_i is the speed or acceleration values gathered from the commercial simulator and $\hat{Y}_i$ is the values of the same parameter calculated by the DSS.

Whenever more than one derivative is optimised at the same time, the list of random numeric values is put together in random order. This process was repeated for all hydrodynamic derivatives in the model with careful consideration taken to keep values within a reasonable limit. In the mathematical modelling done in Simulink, $(\Delta - X\dot{u})$ (see Equation 14 on page 25) is referred to as "$m11$". In the Bis System, displacements for semi submerged vessels are always converted to



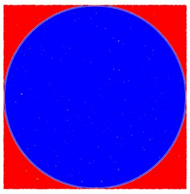




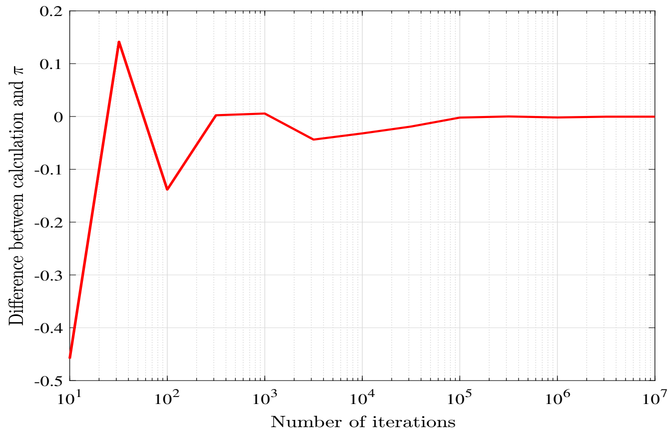
(a) N = 100. π = 3.4000.

(b) N = 1000. π = 3.1760.

(c) N = 10,000. π = 3.1516.



(d) N = 100,000. π = 3.1476.



(e) Error in value of π with increasing number of iterations.

Figure 7. Values of π with increasing number of iterations N.

1 (Fossen 2011, p.149). The value of $m11$ is calculated by subtracting the added mass component of surge, $X\dot{u}$, from the nondimentionalized displacement, Δ. Because $X\dot{u}$ is a negative, small number, $m11$ will have a value close to 1 but not smaller than 1. Consideration was therefore taken to keep $m11$ within reasonable limits.

Step 2 also gives information about how sensitive speeds in their respective degree of freedom are to changes in hydrodynamic derivatives. Yvv is a negative number and it is reasonable that the vessel would encounter a large amount of resistance from being pushed sideways through the water. This means that Yvv is a large number and sway speeds would be very sensitive to changes in this particular derivative. Unfortunately, it is not always obvious what derivatives reduce the radius of a turning circle without reducing surge speed.

Step 3: Fine-tuning of hydrodynamic derivatives.

The last step of optimisation was done in a somewhat crude manner. Part of the optimisation was to match the trajectory from a turning circle between the DSS and a commercial simulator. Optimisation for trials with no use of the rudder had been done before and gave satisfactory results, thus it could be assumed that most of the derivatives that did not account for rudder forces were somewhat accurate. The focus then became changing the derivatives that did account for rudder forces.

$Nccd$ calculates Yaw moment with respect to water flow over the rudder c^2 and rudder angle δ_r. The numeric value of $Nccd$ would start at the best estimate from step 2; then be changed in tandem with changes in other derivatives that control rudder forces. Again mean square error is used to track the difference between logged values and values from the DSS. It is important to note that it is not the position X_n and Y_n that are compared, but $\dot{\psi}$, u and v. This process continues for as many iterations as are needed to give a satisfactory result. Whenever fine-tuning needs to be done within a limited amount of time, the greatest enemy of progress can often be perfection. For this

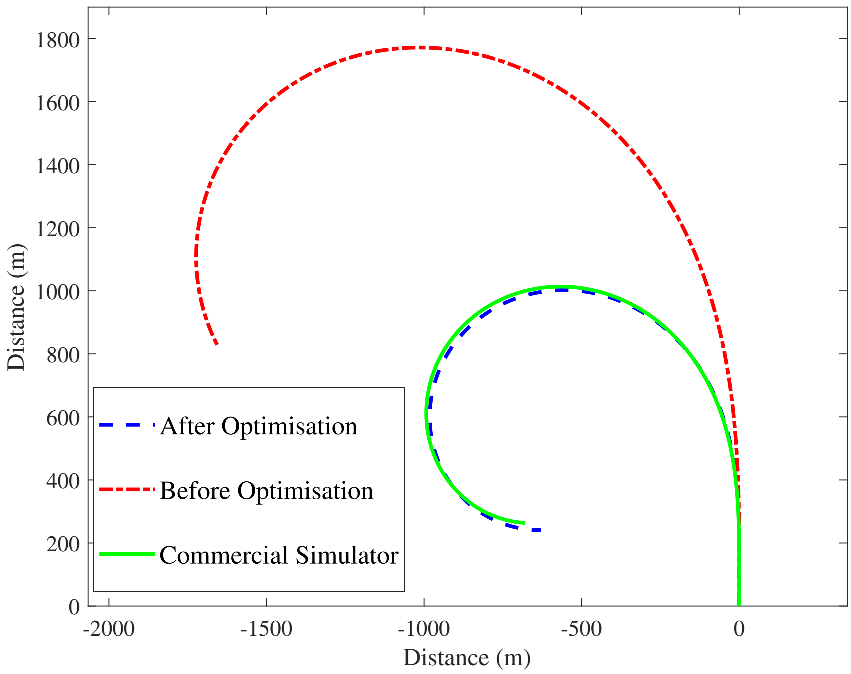


Figure 8. Comparison of turning circles to port post and prior of optimisation.

thesis, a deviation in position by 15 metres and heading by 5° is equal to a position error at the bow by 28 metres. It would be exceptionally poor seamanship to plan a voyage in coastal waters such that a position of the ship being off by 28 metres could spell disaster; this was therefore accepted as a negligible error for inland waters.

2.2.6 Current

Tidal currents change in direction and intensity with the topography of the seabed. In straits and fjords, the current is confined to travel parallel to land and changes with high and low tide (Kjerstad 2017). Because of this, the DSS needed to be able to accept different current inputs with changing positions. This was solved by adding a program that took in coordinates for rectangular boxes and created a specific current direction and velocity. This differs from the method of input in the simulator where a polygon is created and specific weather is added into this polygon. For the case of current, this is done by adding vectors of specific lengths and directions. If several vectors are added into the polygon, the program interpolates between them and current therefore seamlessly changes between vectors. In the DSS, the current is divided into its north and east components with southerly and westerly current given as negatives. Lastly, the current is converted into body frame and given as input to the mathematical model as components of surge and sway speed. This is subtracted from the surge and sway speed of the vessel and converted into relative surge and sway speed. This is described graphically in Figure 9.

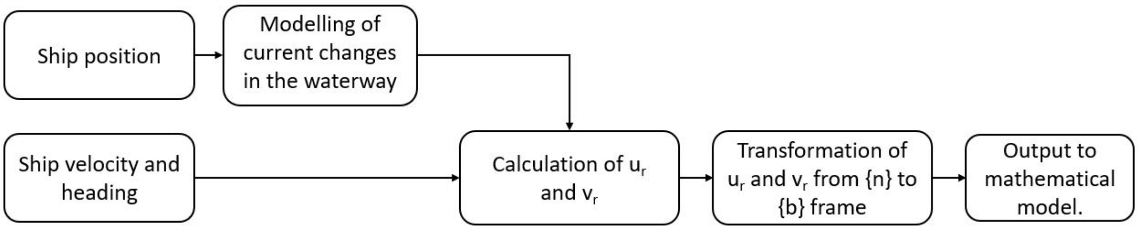


Figure 9. Expansion of current calculations in the DSS.

2.2.7 Wind

A graphical description of how wind is included in the DSS is shown in Figure 11. The definition of wind is the horizontal movement of air over the surface of earth. The direction is defined as the opposite of the direction the air travels. This can be illustrated by dropping a plastic bag and letting it drift with the wind. The direction opposite to the direction the bag travels is said to be the wind direction. Kjerstad (2017) write that because wind direction is irregular, it is common to measure the mean direction over a period of 10 minutes. Input into the simulator is given as a direction between 0-360 degrees and the value then fluctuates around that value by plus or minus 10 degrees. Because of limitations in time, a function such as this has not been built into the DSS in its current form. True wind direction is instead given as a constant input.

Two things need to be known to calculate the force of wind felt on a vessel at any given time. The first is the relative wind speed and direction with respect to the bow, V_{rw} and γ_{rw} respectively. A graphical depiction of wind angles are shown in Figure 10. The second is the wind coefficients. The equation to calculate forces from wind found in most physics textbooks is $F = \frac{1}{2} \times \rho \times v^2 \times A \times C$, where F is the force, ρ is the density of wind, v is the *relative* velocity of wind, A is the projected area affected by wind and C is a dimensionless drag coefficient. The wind coefficients are calculated by tools found in the MSS Toolbox. These are programs made based on research done by Isherwood (1972) and Blendermann (1994). Both are briefly described in Section 1.2.4 – Hydrodynamic Models. The code for both Blendermann and Isherwood can be found in Appendix C.1 – Wind.

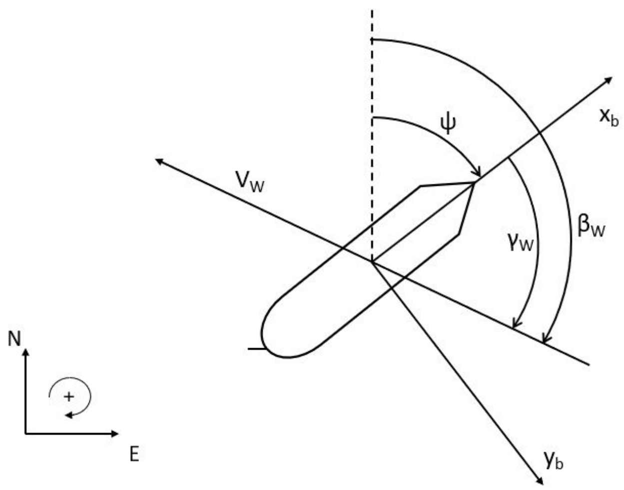


Figure 10. Graphical description of wind angle of attack, γ_W relative to the bow, wind direction β_W and wind speed V_W.

Calculation of relative wind speedV_{rw} and relative wind angle γ_{rw} is done in the three boxes to the left in Figure 11. Heading ψ, ship speed through water U, V_w and β_w are used to calculate the relative wind direction in $\{n\}$ frame using Equation 16.

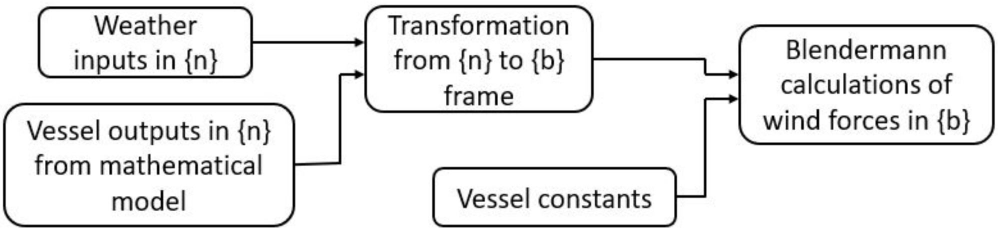


Figure 11. Expansion of wind calculations in the DSS.

$$\beta_{rw} = \text{arctan}\,2\left(\begin{bmatrix} \sin\beta_w * V_w + \sin\psi * U \\ \cos\beta_w * V_w + \cos\psi * U \end{bmatrix}\right) \tag{16}$$

Relative wind speed and angle is then calculated using Equation 17 and Equation 18

$$V_{rw} = \sqrt{(\sin\beta_w * V_w + \sin\psi * U)^2 + (\cos\beta_w * V_w + \cos\psi * U)^2} \tag{17}$$

$$\gamma_{rw} = |\psi - \beta_{rw}| \tag{18}$$

Wind was built into the DSS, but the decision to exclude it from the experiments was made for two reasons. The manoeuvring booklet provided by the commercial simulator includes wind forces and moments. When comparing the forces and moments from this document with forces calculated using the formulas of Isherwood and Blendermann, the moments from the manoeuvring booklet were an order of magnitude greater than those calculated using MSS. Great care was taken to make sure that both inputs were correct and units were equal to those stated in the manoeuvring booklet. The differences in wind moments can be seen in Figure 12.

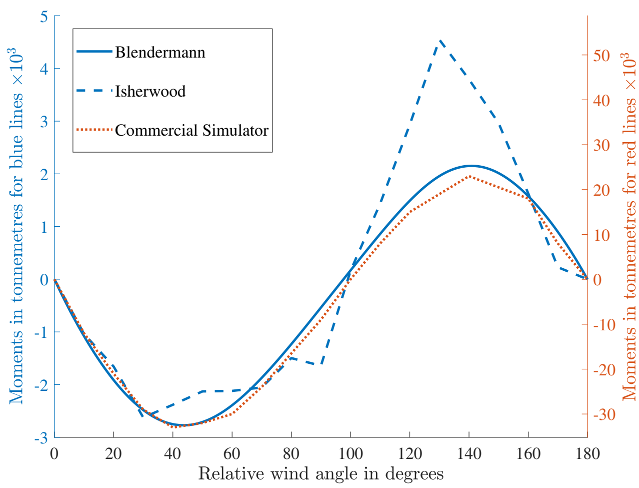


Figure 12. Wind moments calculated using Blendermann and Isherwood compared to moments taken directly from the manoeuvring booklet. Blue lines uses the left y-axis and red lines the right y-axis.

Comparing the general shape of the graphs given by the commercial simulator and by Blendermann, seen in Figure 12, it is likely that they use his method to calculate wind coefficients. It is, however, unlikely that the moments and forces given in the manoeuvring booklet are the same as those used by the simulator. Because the simulator acts as a black box for the authors of this thesis, extensive testing would need to be carried out to find out if the size of wind forces and moments are realistic. Because of this, it could not be confirmed that the effects of wind were realistic enough for them to be accurately predicted by well-established formulas.

The second reason wind was excluded from the experiment had to do with the lever arm at which forces create a moment around the centre of rotation. Blendermann (1994) defines the Yawing-moment arm lever as a distance X_F away from the centre of gravity. He shows that this distance will vary with different angles of attack and the general shape of the vessel. However, this only calculates the distance between the centre of gravity and the point of attack. This is *not* synonymous with the Yawing-moment lever arm in *any* case but for one. A ship that is dead in the water with no trim and has no forces or accelerations acting on it will pivot around its centre of gravity.

According to Rowe and Nautical Institute (2000) the lever arm should be calculated from the centre of effort of wind and the *apparent* pivot point. Recent studies into the nature of the pivot point emphasise that this is to be considered more of a cause than a consequence. The pivot point is not the lever arm of anything. Seo (2017) brings up some common misconceptions about the pivot point.

- *It moves toward the bow or toward the stern with surge motion.*
  This is not the case and disproved by both Seo (2017) and Capt. Cauvier (2008).

- *It is the centre of rotation.*
  The pivot point is an imaginary point. In a famous example two tugs are fastened to the stern and bow respectively. With stern movement of the vessel the proper explanation is that the *centre of lateral resistance* moves about 10% of the ships length toward the stern and the ship starts turning to starboard. This turning makes the pivot point appear to be 1/4 of the ships length toward the stern when in reality it is still very close to midships (Capt. Cauvier 2008).

- *The pivot point is the fulcrum of the turning moment.*
  It is not a physical entity and thus is *not* the point from which lever arms should be calculated (Seo 2017).

For wind forces to be seamlessly fed into a mathematical model, the lever arm needs to be properly calculated. No formula to calculate the position of the centre of lateral resistance was found and solutions to this problem in Dynamic Positioning systems or simulators could not be obtained.

How and whether this problem has been solved in simulators and DP systems is still uncertain. For the latter case, this would make no noticeable difference as velocities are generally low and forces not accounted for are dealt with by the Kalman filter. In the case of simulators, testing would need to be carried out. This was deemed too time consuming and together with the fact that the simulator works as a black box for the authors, it was decided to drop wind from the experiments.

2.3 Method of Analysis

Data gathered from the experiment was sorted on the basis of a pass or fail criteria. A vessel that had no contact with either land, navigational marks or the seabed was registered as pass.

For evaluating the relationship between two categorical, nominal values, Marshall and Boggis (2016) suggests a χ^2-test. Four of these were carried out with the null hypothesis that there would be no significant change in results with the DSS being introduced early in the experiment. The results of these tests are shown in Section 3.2 – Statistical analysis. Calculations of p-values and the raw data from the experiment are presented in appendix B.

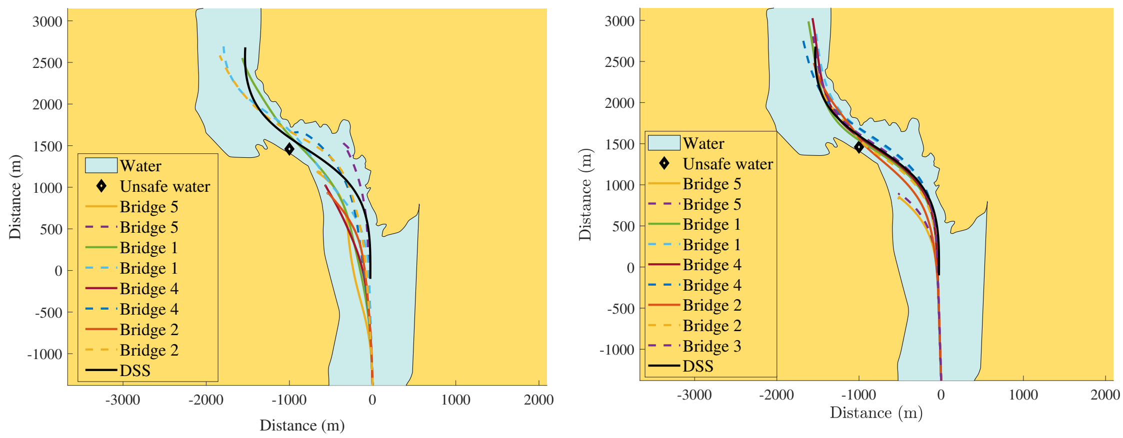
3 Results

3.1 Overview

During this study, one experiment was carried out with the purpose of proving the hypothesis that the DSS increases navigational safety. The results gathered during this experiment will be presented in the sections below.

3.1.1 Track Graphs

Figures 13 and 14 show tracks made by the participants during the experiment. It should be noted that some of the runs that appear to have passed through Vatlestraumen have made contact with the seabed. This fact comes out poorly in graphs showing just tracks but they are counted as failed attempts in the statistical analysis.



(a) Group A without DSS assistance. (b) Group A with DSS assistance.

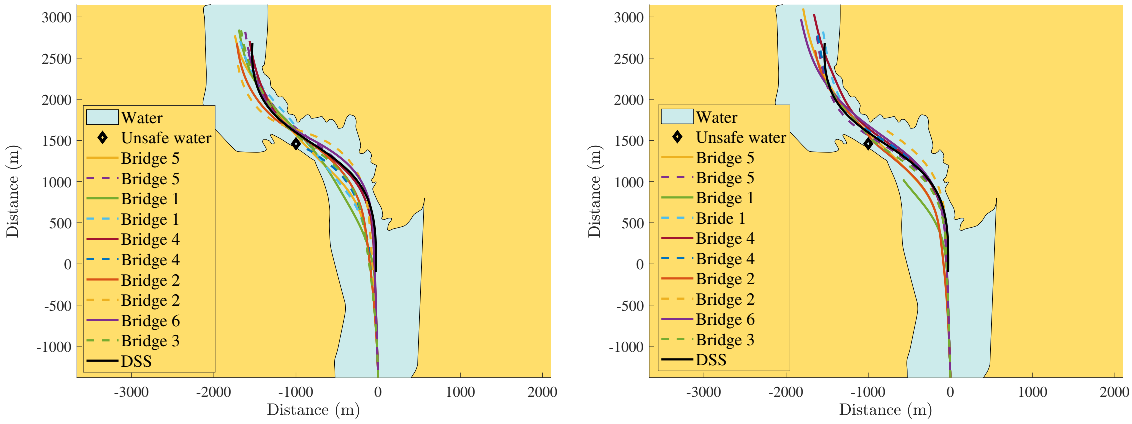
Figure 13. Tracks from Group A. The black track is the predicted track obtained using the suggested rudder commands from the DSS.

Group A:

Group A were first taken through the exercise with Vessel 1 from Table 1 on page 10 and later tried an unassisted attempt with Vessel 2, making it their second run at the Vatlestraumen passage that day. The tracks from these runs with Vessel 2 are shown in Figure 13a. They proceeded to do the exercise with Vessel 3 before their final attempt with Vessel 2, which was with the assistance of the DSS. The tracks for these runs are shown in Figure 13b.

Group B:

Group B started the experiment with a passage through Vatlestraumen assisted by the DSS using Vessel 2. This is shown in Figure 14b. They proceeded with Vessel 1 followed by an unassisted attempt with Vessel 2. Tracks from these runs are shown in Figure 14a. The last run was with Vessel 3.

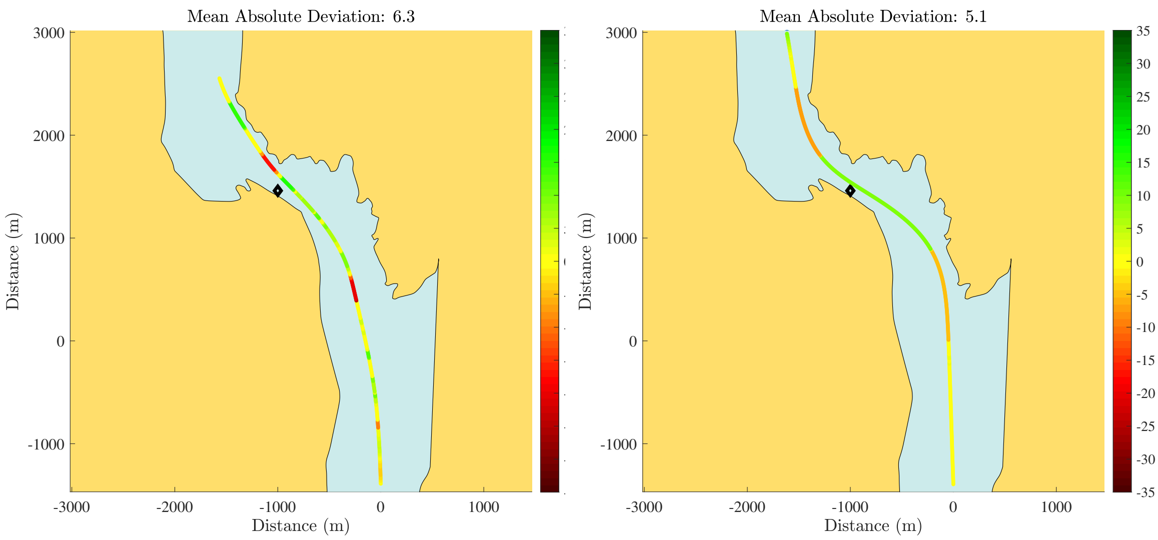


(a) Group B without DSS assistance. (b) Group B with DSS assistance.

Figure 14. Tracks from Group B. The black track is the predicted track obtained using the suggested rudder commands from the DSS.

3.1.2 Rudder Graphs

Figure 15 shows the tracks of an individual run during the experiment. The track is colour coded to indicate rudder angles used at all points throughout the run.



(a) Rudder angles without DSS assistance. (b) Rudder angles with DSS assistance.

Figure 15. Rudder angles for a single pair of participants with and without the DSS.

To add a numerical value to what is shown in colours in Figure 15, Mean Absolute Deviation (MAD) was applied. This takes the mean rudder angle for an individual run and compares it to the rudder angle given at any time during the run. Some bridges ran aground and left the rudder at a steep rudder angle. A limit to the data points counted was set to whenever the speed dropped below 8 knots. This method applied to a zigzag test would give a value close to zero. Counter rudder and rudder would be of equal size and applied for approximately equal time.

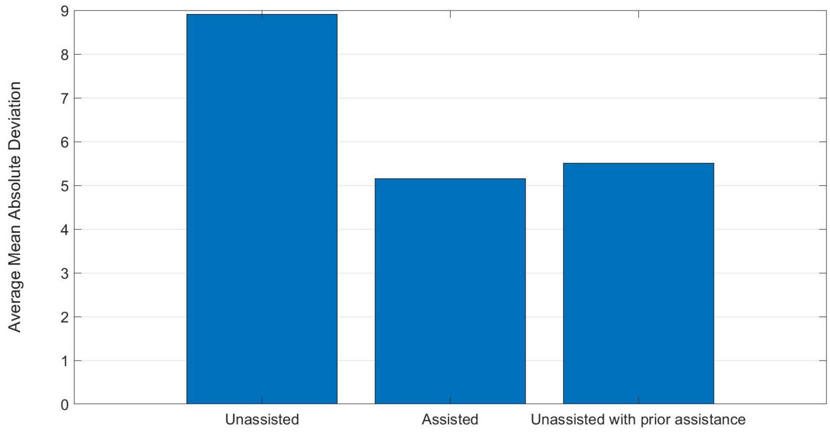


Figure 16. Comparison of Mean Absolute Deviation of different types of runs.

3.2 Statistical Analysis

Statistical analysis was carried out on the results from the experiments. Logged data from experiments show some vessels hitting sand bottom. This occurs at a position marked out by a diamond in rudder graphs from the experiment. Because of this, some of the vessels that appear to pass the exercise in the graphs in Section 3.1.1 – Track graphs are counted as failed attempts for the purpose of statistical analysis. P-values were calculated using χ^2 statistics for different data sets. The main results of the analysis are presented below, but they are shown in full in Appendix B – Statistical Analysis. The Null hypothesis is that there is no significant change in results whether the DSS was used in the first or second Vessel 2 run.

Results for all vessels: The null hypothesis is that there is no significant change in results whether the DSS was used in the first or second Vessel 2 run, at $p < .05$.

χ^2 (2, N = 74) = 0.5572, p = 0.4554

Results for Vessel 2 & DSS runs only: The null hypothesis is that there is no significant change in results whether the DSS was used in the first or second Vessel 2 run, at $p < .05$.

χ^2 (2, N = 38) = 3.7021, p = 0.0543

Results for all vessels except DSS: The null hypothesis is that there is no significant change in results whether the DSS was used in the first or second Vessel 2 run, at $p < .05$.

χ^2 (2, N = 55) = 0.5562, p = 0.4558

Results for all vessels except Vessel 2: The null hypothesis is that there is no significant change in results whether the DSS was used in the first or second Vessel 2 run, at $p < .05$.

χ^2 (2, N = 37) = 0.5787, p = 0.4468

4 Discussion

It is mentioned in the introduction that all known current systems for path prediction are largely reactive. A perfectly planned track in a chart machine gives little help to a person not familiar with the manoeuvring characteristics of the particular vessel. This problem is to a certain extent solved in Dynamic Positioning systems by removing control from the navigator. This thesis is an attempt to create a system that transforms the navigator's desired path into a set of suggested rudder commands. The idea is to leave the planning in the hands of the navigator and help him in executing manoeuvres.

The discussion section is divided up into three parts. The first part discusses the results from the experiment performed. The second part is an attempt at identifying factors that might to some extent invalidate the results obtained from said experiment. The last part is the authors' suggestions for further research and development.

4.1 Results

During this study, one experiment was carried out, with the purpose of proving the hypothesis that the DSS increases navigational safety. Results from the experiment carried out show promising results, but statistical analysis shows that further experiments are needed in order for these results to be statistically significant.

To keep this section organised and clear, a division had to be made. For the sake of simplicity, the subdivisions were organised so that it is possible to see the results for individual parts.

4.1.1 Track Graphs

Defining a good manoeuvre might seem like a straightforward task at first, but how a good manoeuvre is defined differs significantly between navigators. Instead of trying to define an optimal trajectory in the form of some number or quantifiable value, the decision was made to show the tracks and let the readers decide for themselves. In this section, the authors present their interpretation of these graphs with respect to the hypothesis.

Looking at the graphs in Figures 13 and 14, things appear very promising for the use of a DSS in navigation in restricted waters. When the participants tried the run without the help of the DSS, several failed to find an appropriate WOP. As a result of starting their turn too early or too late, they quickly left the centre of the channel. Those who did not spot the danger in time to make corrective measures ended up running aground. In contrast, when the participants tested with the help of the DSS, more of them were close to the predicted track that the DSS had proposed and fewer ran aground.

In Figure 14, the unassisted and assisted attempts at first glance show similar results. At closer analysis some of the attempts with DSS hit sand bottom. This is discussed further in Section 4.1.3 – Statistical Analysis.

4.1.2 Rudder Graphs

Estimating the best rudder angle on a vessel without directional stability is usually harder than on a ship with directional stability. Effects from changes in rudder angle happen slowly at first and once a decent rate of turn is achieved it takes longer for counter rudder to have an effect. As a rule, this problem will become greater with increasing draft. Information about the time it takes for counter rudder to have an effect is usually gathered from zigzag tests. In the case of Vessel 2, large rudder angles tend to give the ship a rate of turn too great for counter rudder to be effective. This has the effect that counter rudder needs to be applied early or at a greater angle than the initial rudder angle. Limits to safe water only increases this problem where the navigator on one side wants to make narrow turns and on the other is dependent on effective and quick responses to rudder and counter rudder. As a way of illustrating the amount of control in a manoeuvre, illustrations of rudder angles along the tracks during experiments is a good measure of how much control the navigator has.

Examining the rudder graphs in Figure 15 and Appendix D – Rudder Graphs, a clear pattern emerges. When using – or having previously used – the DSS, the rudder is used with more confidence. For both the initial turn to port and the counter-turn to starboard, the participants start with rudder angles that are close enough to optimal so that only minor adjustments are required. In contrast, the completely unassisted trials show a lot of guessing and second-guessing. Frequent and large changes in rudder angle are common.

As a supplement to the graphs, the mean absolute deviation (MAD) of the rudder angles used have been calculated. This numerical value is a means to directly compare individual trials. An individual number alone is meaningless; it is referencing one specific instance of this specific manoeuvre. However, when compared, they illustrate who found a good plan and stuck to it, and who were forced to make many and/or large corrections throughout.

A manoeuvre executed using small rudder angles is not automatically the best one. There are times when it is prudent or even necessary to use the full capabilities of the rudder. There is, however, a difference between confidently and purposefully using large rudder angles and rapidly changing rudder angles back and forth.

The beneficial side effects of using smaller rudder angles are obvious. The reduced drag means that the manoeuvre can be performed with a reduced loss of speed, which again saves on both time and fuel consumption.

Results from Figure 16 clearly show smaller values for assisted or previously assisted runs in comparison with unassisted ones. This means that navigators that were given or had been given assistance from the DSS self-corrected themselves less. When the time required to find a close to optimal rudder angle has been reduced or eliminated, the navigator has more time and attention to spare for other critical aspects of navigation.

4.1.3 Statistical Analysis

An initial look at the analysis for the different χ^2 tests the authors ran suggests the hypothesis of the thesis has been disproved. However, there are some things that need to be addressed before it can be concluded that this is the case. The hypothesis for this thesis was that a decision support system showing ship trajectories would improve navigational safety. This could not be the null hypothesis for the statistical analysis for one crucial reason:

Data gathered on all vessels indicate that no significant difference can be shown between using the

DSS first or last. This is however more or less in line with what has been mentioned in Section 1.1 – Motivation about systems giving little input about the manoeuvrability of a vessel. For Vessel 2, the DSS gives a good idea about how the passage through Vatlestraumen could be carried out. For the other vessels it might just add confusion and even harm the navigator's own idea about what rudder angle is more suitable. The fact that Vessel 2 is directionally unstable and 1 and 3 are both directionally stable would add to this effect. Results from all vessels, apart from assisted and unassisted attempts with Vessel 2 (Table 7 on page 48), show a slight trend for navigators that started with the assisted attempt performing worse on the other vessels. It should however be noted that this result could just as likely have happened by chance. Group B showed an improvement of 8.2% compared to Group A. This is only slight and therefore the null hypothesis from Section B – Statistical Analysis cannot be rejected at $p < .05$.

Results for vessels except those with the assistance of the DSS show a slight improvement with a success rate of 73% for Group B to 64% for Group A. Both the difference between the groups and the sample size is rather small so little weight can be put on these numbers. One can, however, speculate about where the difference comes from:

- Group B, learning from their experience with the DSS.
- Group A, following instructions from the DSS instead of their learnt expertise from previous attempts.
- The difference happening by pure chance.

It should be noted that because the DSS assisted attempt was either at the start or end of the exercise, attempts 1, 2 and 3 are counted for Group A while attempts 2, 3 and 4 are shown for Group B. It is therefore impossible to say if this improvement is because of more experience in Vatlestraumen, more experience with Vessel 2 or because of improvements from being assisted by the DSS.

The data gathered from the use of *only* Vessel 2 show promising results. This is a comparison between attempt 2 and 4 for Group A versus 1 and 3 for Group B. Group B had a success rate of 75% compared to Group A with 44%. The fact that Group B shows better results despite the fact that they achieved them on earlier attempts goes against the interpretation that people learned the task, improving with later attempts. An interesting side point is the fact that both groups had relatively equal success rate using the DSS: 55% for Group A compared to 60% for Group B. The unassisted attempt show Group B getting 90% and Group A 38%, a significant difference. This would seem to indicate that given prior input from the DSS, Group B showed great improvements when they took the information gathered and created their own instructions more suited to their previous plan. While not statistically significant at $p < .05$ the p-value is 0.0543. This result is harder to explain away as pure chance.

4.2 Experimental Limitations

The authors formed their research group in the spring of 2019 and decided which topic they wanted to pursue in-depth. The work started and went on during the autumn of 2019. The development process was left open; no precautions were taken to keep things secret. Among other things, information about the concepts behind the system and the progress made was freely available. It is conceivable that some of the participants in the experiment had advance knowledge of what to expect, and that preconceived notions had an impact on how they approached the experiment.

The information provided in the briefing before the participants were to use the DSS was not entirely consistent. The thesis authors intended that the instructions were to be followed unless the participants deemed it unsafe to do so. This was not conveyed in a clear and unambiguous manner. Because of this, the degree to which participants trusted the instructions may have varied and potentially influenced experimental results. The authors should instead have created a script or a pre-made video of the presentation, taking careful consideration to use neutral language. A frequently asked questions list with pre-determined answers should have been used. Questions asked outside this list would be left unanswered as to not influence participants.

The experiment was carried out as part of a navigational course. This imposed certain limitations on how it could be set up. It was required that participants perform the same tasks; the only aspect open for adjustment was the order. Thus a proper control group could not be set up. Two more rounds of experiments were planned, one in mid-March, and one in late March or early April. These were intended to include a group doing repeated runs without DSS assistance. This would have made it possible to better isolate the learning effect from multiple runs. Unfortunately, three days before the first additional experiment was set to take place the campus closed down, and remained closed for the duration of the semester.

During the experiment, participants were debriefed between each vessel change. This allowed participants to ask questions that had occurred to them while they were in the bridge simulator. One case that stood out was a question about how to use a PI. Since the experiment was incorporated with teaching sessions, the instructor answered and demonstrated its use. The instructor then drew the area, showing where to put out two offset VRMs and EBLs, as well as explaining how a PI across the bow could be used to determine the WOP for the vessel. As a result, this group received far more information regarding a solution to the navigational challenge than the other groups. Although this is something that the participants should already master at this stage in their course, had the authors had a script to adhere to this would not be a source of error. It is unlikely that this became a major source of error, but it did give one group an advantage as they had this opportunity to refresh their knowledge while the other participants did not.

Another disadvantage of having the experiment as part of a navigational course was that the participants did their own planning beforehand. Adding to this, the challenge involved in defining a well executed manoeuvre precluded deviations from the planned track from being used as a measure of success. A pre-designed passage plan loaded into the ECDIS would alleviate this problem, by making it possible to measure the participants' ability to follow the planned track, with or without the aid of the DSS.

The group composition of the participants was not something the authors had control over. As mentioned earlier, students work in a set pair after doing a personality test and considering their background in the maritime industry, to plausibly obtain the optimal composition. The decisions behind the creation of pairs may result in some people working very well together and others not; this factor should not be ignored. To avoid this, random pairs could have been used, or single participants. As a best available option, the selection of who would do their first run with Vessel 2 unaided and who would use the DSS first was randomised.

On the day of the experiment, participants also had training on the desktop simulators detailed in Section 2.1.2 – Manoeuvre Tests Using Desktop Simulators. This work was unrelated to the experiment, but used Vessel 2, the one the DSS was built for. Half of them did this before the experiment and half after. Consequently, half of the participants had had a very recent opportunity to refamiliarise themselves with the manoeuvring characteristics of Vessel 2, something which may have aided their performance during the experiment. However, these participants were evenly divided between groups A and B, which should limit any influence on the experimental results.

The first half of Group A (see Appendix B – Statistical analysis), had a pair who had to start on a bridge simulator originally not intended for use. The pair started on Bridge 6 and had to run all four of their trials there. This happened because there had been a double booking of bridge simulators that day. To minimise the chance of a source of error, the pair placed on this bridge were already familiar with it. This only affected one half of Group A; with the exception outlined in the next paragraph, the other half and the whole of Group B ran their trials on bridge simulators with which they were already familiar.

Bridge 5 was in use throughout the experiment. This bridge is considerably different from bridge 1-4 (see Section 2.1.3 – Bridge Simulators). This is a potential source of error, as the participants were less familiar with this bridge compared to the others. This could mean that pairs using this bridge underperformed compared to their peers using the conventional bridge designs.

4.3 Further Research and Development

This section contains suggestions from the authors for further research and development, listed in order of importance. Primarily, further experiments are needed to test the hypothesis. If results from these prove the validity of the DSS, a natural next step would be to expand into real life applications.

4.3.1 Additional Experiments

As discussed in the section on statistical analysis, the single experiment performed did not yield enough or good enough data to reach any firm conclusions. This was not at all unexpected. The sample size was small, and the constraints of the educational format meant that setting up a proper control group was not possible.

Before any serious consideration can be given to taking this research further, the weaknesses identified above should be addressed. In particular, the issue about the extent to which improvements seen in second-run performances were due to learning by trying versus having seen and used the suggestions from the DSS. To facilitate this, repeated runs without DSS input are necessary in order to isolate the different learning factors involved.

4.3.2 Real Life Applications

A natural step after conducting experiments in a simulator created to mimic the real world is to move the experiments to said real world. The first thing that comes to mind is safety. Before a system can be tested aboard real ships in any scale at all, a DSS would need to go through extensive testing to eliminate problems with the system itself. The first phase of implementing a tool made to increase safety would naturally be to make sure that the system itself is safe. Due to external factors the current DSS and the commercial simulator run as separate systems. This would obviously not be the case for a real DSS. Because navigational safety is dependent on knowledge of seabed topography, the DSS created for this thesis could greatly benefit from integration with an electronic charting system. A system made for real life applications would not be static in the same way as the DSS is in its current form. The trajectory would be updated at regular time intervals with changes in sensory data. None of these issues would presents insurmountable technological hurdles.

A system such as the DSS in this thesis does however face several challenges that all need to be addressed. Most of these problems have solutions already. The likely place to start is to change to a mathematical model using the Unified theory by Fossen and Sagatun (1991) instead of Maneuvering Theory. Among other benefits, this has the added advantage of working with wave excitation in 6 degrees of freedom.

Conducting an experiment such as the one described in the pages above on a real ship out on the ocean would require rebuilding the experiment from the ground up. It is close to impossible to say how much extra effort this would take. Integrating systems that are created to work separately is its own field of engineering. Path prediction is a subject that, while not solved in a maritime context, is far more advanced than that which has been used during the course of this thesis.

The Norwegian Forum for Autonomous Ships (Rodseth and Nordahl 2017) mention that advanced Aids to Navigation (AtoN) and Automatic Identification System (AIS) could be used to supply advanced or autonomous ships with information about waves, current, wind and other parameters. Data that are gathered close to narrow straights or harbour entrances could be an excellent source of sensor data for a system trying to predict ship trajectories for the benefit of the navigator.

The optimisation process mentioned in Section 2.2.5 – Parameter Optimisation could be used in a real life setting with data about ship accelerations and external forces gathered from sensors. Motion reference units, wind sensors and measurements of current or current modelling could be used in tandem with GPS tracks gathered during normal operations. Comparing data from sensors and GPS tracks against tracks calculated by the DSS could, in theory, be used for optimisation. To the best of the authors' knowledge, this is not something that has been attempted on real ships, but is a common approach for optimisation of mathematical models. This could prove a method for both building and continuously optimising a mathematical model while in use. The system would be installed with data from a similar vessel and work in a sleep mode until sufficient accuracy was obtained. Whether this method would be viable is left up to future tests. If it does work, it could be a possible way of implementing a DSS such as this on ships on a large scale.

The problems mentioned with the lever arm of wind is also a subject for further research before a system could be implemented in real life applications. The problem with defining a position of the actual centre of rotation for an object at motion is something for which no adequate answer was found during the work on this thesis. The reasons for this may range from the fact that it is an imaginary problem invented by the authors, to that it disappears in a vector based method such as the Unified Theory.

5 Conclusion

The intention of this thesis has been to explore the hypothesis that a path predictor suggesting ship specific rudder inputs improves navigational safety. The first goal was to build a system to test this hypothesis. This goal was achieved: the system was built, and it works.

The completed experiment indicates two things in support of the hypothesis:

- Tests performed using the DSS or having previously used the DSS have a marked tendency towards fewer groundings.
- Rudder usage appears to be under better control in tests performed using the DSS or having previously used the DSS.

When the time required to find a close to optimal rudder angle has been reduced or eliminated, the navigator has more time and attention to spare for other critical aspects of navigation. The authors contend that this increases navigational safety.

Once again, it must be stressed that while the results regarding success rates look promising, statistical significance is only achieved for $p < .10$, and not for $p < .05$. Further tests, employing a more rigorous use of control groups and with a better control over the associated variables, would go a considerable distance towards proving or disproving the hypothesis.

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Appendix

A Consent form.

Samtykkeskjema

Loggføring av data i simulator

NTNU Ålesund og vi bachelorstudenter ([redacted]), vil informere om at

det vil bli loggført data fra alle broer under simulatorøvelsen 'Stor-Større-Størst' fredag 28.Februar 2020 til bruk i Bacheloroppgave.
Loggføringen vil kun være av handlinger utført i simulator, ikke video eller bilder av deg. Dataen som blir hentet ut vil heller ikke kunne spores tilbake til deg som person.

Loggene vil ikke være tilgjengelig for noen andre enn bachelorgruppen. Videre vil loggene bli lagret og oppbevart digitalt i en trygg og designert sky med begrenset tilgang for andre en bachelorstudentene.

Samtykket kan trekkes tilbake. Tilbaketrekning av samtykket må skje skriftlig til [redacted] innen 27.februar 2020 klokken 16:00.

Samtykkeerklæring for loggføring av data

Jeg samtykker i loggføring av øvelsen 'Stor-Større-Størst', som er tatt av NTNU Ålesund og Bachelorstudentene, og informasjonen kan benyttes i forskningssammenheng.

Navn:...

Dato:...

Sted:...

Signatur:...

B Statistical analysis

The experiment was performed using four groups. In Table 5 below, these are labelled one through four chronologically. Groups one and three performed their first Vessel 2 run unassisted, while groups two and four performed their first Vessel 2 run with DSS assistance. As the table shows, the four groups were later combined into two based on run order, called A and B. This is how they are referenced throughout the text.

Table 5. Data gathered from experiments. Runs without incidents are counted as 1.

Group A				
	Vessel 1	Vessel 2	Vessel 3	DSS
Group number	One	One	One	One
Bridge 5	0	0	1	0
Bridge 1	1	1	1	1
Bridge 4	1	0	1	1
Bridge 2	1	0	1	0
Bridge 3/6				
Group number	Three	Three	Three	Three
Bridge 5		0	1	0
Bridge 1	1	1	1	1
Bridge 4	0	0	1	1
Bridge 2	0	1	1	0
Bridge 3/6	1		0	1
Score	5	3	8	5
Runs	8	8	9	9
Average	0.625	0.375	0.889	0.556
Group A Average				**0.618**

Group B				
	DSS	Vessel 1	Vessel 2	Vessel 3
Group number	Two	Two	Two	Two
Bridge 5	1	1	1	0
Bridge 1	0	0	1	1
Bridge 4	1	1	1	1
Bridge 2	0	1	1	1
Bridge 3/6	1	1	1	0
Group number	Four	Four	Four	Four
Bridge 5	1	0	1	1
Bridge 1	1	0	1	0
Bridge 4	1	1	0	0
Bridge 2	0	1	1	1
Bridge 3/6	0	1	1	1
Score	6	7	9	6
Runs	10	10	10	10
Average	0.600	0.700	0.900	0.600
Group B Average				**0.700**

Table 6. χ^2 Results for different data sets

Results for all vessels

	Fail	Pass	Row totals	
DSS last	13	21	34	
DSS first	12	28	40	
Column totals	25	49	74	Grand total

Expected values all vessels

	Fail	Pass	Row totals	
DSS last	11.49	22.51	34	
DSS first	13.51	26.49	40	
Column totals	25	49	74	Grand total
p-value =	0.4554	N =	74	
Statistic =	0.5572			

Results for vessels except Vessel 2 & DSS

	Fail	Pass	Row totals	
DSS last	4	13	17	
DSS first	7	13	20	
Column totals	11	26	37	Grand total

Expected values for vessels except Vessel 2 & DSS

	Fail	Pass	Row totals	
DSS last	5.05	11.95	17	
DSS first	5.95	14.05	20	
Column totals	11	26	37	Grand total
p-value =	0.4468	N =	37	
Statistic =	0.5787			

Table 7. χ^2 Results for different data sets

Results for Vessel 2 & DSS only

	Fail	Pass	Row totals	
DSS last	10	8	18	
DSS first	5	15	20	
Column totals	15	23	38	Grand total

Expected value Vessel 2 & DSS only

	Fail	Pass	Row totals	
DSS last	7.11	10.89	18	
DSS first	7.89	12.11	20	
Column totals	15	23	38	Grand total
p-value =	0.0543	N =	38	
Statistic =	3.7021			

Results for vessels except DSS

	Fail	Pass	Row totals	
DSS last	9	16	25	
DSS first	8	22	30	
Column totals	17	38	55	Grand total

Expected values for vessels except DSS

	Fail	Pass	Row totals	
DSS last	7.73	17.27	25	
DSS first	9.27	20.73	30	
Column totals	17	38	55	Grand total
p-value =	0.4558	N =	55	
Statistic =	0.5562			

C Matlab Code

C.1 Wind

The following is the code version of what is being described in Figure 11 on page 30. Both Blendermann and Isherwood are included.

Calculation of relative wind speed and angle with respect to bow:

```
function [out,k]    = fcn (in)
%Created for bsc thesis - 2020
%Calculations of relative wind speed and angle.

a = in(1); % True wind angle (deg)
b = in(2); % True wind speed (m/s)
c = in(3); % Heading (deg)
u = in(4); % Surge speed (m/s)
v = in(5); % Sway speed (m/s)

d = sqrt(u^2 + v^2); % ship speed over ground (m/s)

%Decomposition of wind.
e = sind(a)*b;
f = cosd(a)*b;

%Decomposition of ship speed.
g = sind(c)*d;
h = cosd(c)*d;

%Adding ship and wind speed.
x = [e;f];
z = [g;h];

%calculation of relative vector.
y = x+z;

%Wrapping value between 0-180.
h = atan2(y(1,1),y(2,1));
j = h*(180/pi);
if j < 0
    j = 360+j;
end

%Angle and lenght of relative wind vector.
negangle = (180/pi)*atan2(sind(c-j),cosd(c-j));
gamma_r = abs(negangle);
%y bytt till uu
U_rw = (y(1,1)^2+(y(2,1)^2))^0.5;

%k is positive for port and negative for starboard.
%k is saturated so value is -1 or 1.
```

```
k = negangle;

%output to Blendermann
out = [gamma_r U_rw]';
```

Isherwood calculation of wind coefficients:

The inputs used for Vessel 2 are: LOA: 305m, B: 48m, ALw: 2697.3m^2, AFw: 1550.2m^2, A_SS: 370.74m^2, S: 145.48m, C: 127m, M: 2st

```
function tau_w  = isherwood72(in)
% [tau_w] = isherwood72(gamma_r,V_r,Loa,B,ALw,AFw,A_SS,S,C,M) returns
↪  the the wind
% force/moment vector w_wind = [tauX,tauY,tauN] and the optionally wind
↪  coefficients
% cx,cy and cn for merchant ships using the formulas of Isherwood
↪  (1972).
%
% INPUTS:
gamma_r = in(1); % relative wind angle (deg)
V_r     = in(2); % relative wind speed (m/s)
Loa     = in(4); % length overall (m)
B       = in(5); % beam (m)
ALw     = in(6); % lateral projected area (m^2)
AFw     = in(7); % frontal projected area (m^2)
A_SS    = in(8); % lateral projected area of superstructure (m^2)
S            = in(9); % length of perimeter of lateral projection of
↪  model (m)
%                      excluding waterline and slender bodies such as
↪  masts and ventilators (m)
C            =  in(10); % distance from bow of centroid of lateral
↪  projected area (m)
M       = in(11);% number of distinct groups of masts or king posts seen
↪  in lateral
k       = in(3); % k = 1 forces from port / k = -1 forces from starboard
%                      projection; king posts close against the bridge
↪  front are not included
%
% Author:    Thor I. Fossen
% Date:      10th September 2001
% Revisions: 19.04.2004, changed velocity from knots to m/s. This was a
↪  bug
%            20.11.2008, changed name from windcoef to isherwood72,
↪  updated
%                        signs and notation to comply with Blendermann
↪  (1994).
% Edited for bsc thesis December 2019
% if in~=10, error('the number of inputs must be 10');end

% constants
rho_a = 1.224;            % density of air at 20 C
```

```
% CX_data = [gamma_r
↪          A0          A1          A2          A3          A4          A5          A6          ]
CX_data= [...
0         2.152         -5.00         0.243         -0.164         0
↪   0         0
10          1.714         -3.33         0.145         -0.121         0
↪               0               0
20          1.818         -3.97         0.211         -0.143         0
↪   0              0.033
30          1.965         -4.81         0.243         -0.154         0
↪   0             0.041
40          2.333         -5.99         0.247         -0.190         0
↪         0              0.042
50          1.726         -6.54         0.189         -0.173         0.348         0
↪   0.048
60          0.913         -4.68         0
↪   -0.104         0.482         0            0.052
70          0.457         -2.88         0
↪   -0.068         0.346         0            0.043
80          0.341         -0.91         0            -0.031         0
↪   0              0.032
90          0.355         0             0            0
↪         -0.247         0            0.018
100          0.601         0             0             0
↪   -0.372         0             -0.020
110          0.651         1.29          0            0
↪   -0.582         0             -0.031
120          0.564         2.54          0            0
↪   -0.748         0             -0.024
130          -0.142         3.58          0
↪   0.047         -0.700         0            -0.028
140          -0.677         3.64          0
↪   0.069         -0.529         0            -0.032
150          -0.723         3.14          0
↪   0.064         -0.475         0            -0.032
160          -2.148         2.56          0            0.081         0
↪   1.27          -0.027
170          -2.707         3.97          -0.175         0.126         0
↪   1.81          0
180          -2.529         3.76          -0.174         0.128         0
↪            1.55          0             ];

% CY_data = [gamma_r
↪   B0          B1          B2          B3          B4          B5          B6]
CY_data = [...
0   0         0         0         0         0         0         0
10          0.096         0.22          0            0            0
↪         0         0
20          0.176         0.71          0            0            0
↪   0            0
```

```
30          0.225        1.38        0            0.023        0
↪   -0.29        0
40          0.329        1.82        0            0.023    0
↪               -0.59        0
50          1.164        1.26        0.121        0
↪   -0.242         -0.95        0
60          1.163        0.96        0.101        0
↪   -0.177         -0.88        0
70          0.916        0.53        0.069        0            0
↪               -0.65        0
80          0.844        0.55        0.082        0            0
↪               -0.54        0
90          0.889        0            0.138        0            0
↪               -0.66        0
100          0.799        0            0.155        0            0
↪               -0.55        0
110          0.797        0            0.151        0            0
↪   -0.55        0
120          0.996        0            0.184        0
↪   -0.212         -0.66        0.34
130          1.014        0            0.191        0
↪   -0.280         -0.69        0.44
140          0.784        0            0.166        0
↪   -0.209         -0.53        0.38
150          0.536        0
↪   0.176         -0.029        -0.163        0            0.27
160          0.251        0
↪   0.106         -0.022        0            0            0
170          0.125        0
↪   0.046         -0.012        0            0            0
180 0        0        0        0        0        0        0        ];

% CN_data = [gamma_r
↪   C0         C1         C2         C3         C4         C5]
CN_data = [...
0   0        0        0        0        0        0
10          0.0596        0.061        0            0            0
↪   -0.074
20          0.1106        0.204        0            0            0
↪   -0.170
30          0.2258        0.245        0            0            0
↪   -0.380
40          0.2017        0.457        0
↪   0.0067        0            -0.472
50          0.1759        0.573        0
↪   0.0118        0            -0.523
60          0.1925        0.480        0
↪   0.0115        0            -0.546
70          0.2133        0.315        0
↪   0.0081        0             -0.526
```

```
80         0.1827        0.254         0
 ↪  0.0053        0             -0.443
90         0.2627        0             0             0             0
 ↪  -0.508
100        0.2102  0             -0.0195       0
 ↪  0.0335        -0.492
110        0.1567        0             -0.0258       0
 ↪  0.0497        -0.457
120        0.0801        0             -0.0311       0
 ↪  0.0740        -0.396
130        -0.0189        0
 ↪  -0.0488       0.0101        0.1128        -0.420
140        0.0256        0
 ↪  -0.0422       0.0100        0.0889        -0.463
150        0.0552        0
 ↪  -0.0381       0.0109        0.0689        -0.476
160        0.0881        0
 ↪  -0.0306       0.0091        0.0366        -0.415
170        0.0851        0             -0.0122       0.0025        0
 ↪           -0.220
180 0       0       0       0       0       0       ];

% interpolate in the tables
A0 = interp1(CX_data(:,1),CX_data(:,2),gamma_r);
A1 = interp1(CX_data(:,1),CX_data(:,3),gamma_r);
A2 = interp1(CX_data(:,1),CX_data(:,4),gamma_r);
A3 = interp1(CX_data(:,1),CX_data(:,5),gamma_r);
A4 = interp1(CX_data(:,1),CX_data(:,6),gamma_r);
A5 = interp1(CX_data(:,1),CX_data(:,7),gamma_r);
A6 = interp1(CX_data(:,1),CX_data(:,8),gamma_r);

B0 = interp1(CY_data(:,1),CY_data(:,2),gamma_r);
B1 = interp1(CY_data(:,1),CY_data(:,3),gamma_r);
B2 = interp1(CY_data(:,1),CY_data(:,4),gamma_r);
B3 = interp1(CY_data(:,1),CY_data(:,5),gamma_r);
B4 = interp1(CY_data(:,1),CY_data(:,6),gamma_r);
B5 = interp1(CY_data(:,1),CY_data(:,7),gamma_r);
B6 = interp1(CY_data(:,1),CY_data(:,8),gamma_r);


C0 = interp1(CN_data(:,1),CN_data(:,2),gamma_r);
C1 = interp1(CN_data(:,1),CN_data(:,3),gamma_r);
C2 = interp1(CN_data(:,1),CN_data(:,4),gamma_r);
C3 = interp1(CN_data(:,1),CN_data(:,5),gamma_r);
C4 = interp1(CN_data(:,1),CN_data(:,6),gamma_r);
C5 = interp1(CN_data(:,1),CN_data(:,7),gamma_r);

% wind coeffisients
CX =  -(A0 + A1*2*ALw/Loa^2 + A2*2*AFw/B^2 + A3*(Loa/B) + A4*(S/Loa) +
 ↪  A5*(C/Loa) + A6*M);
```

```
CY =    B0 + B1*2*ALw/Loa^2 + B2*2*AFw/B^2 + B3*(Loa/B) + B4*(S/Loa) +
↪  B5*(C/Loa) + B6*A_SS/ALw;
CN =    C0 + C1*2*ALw/Loa^2 + C2*2*AFw/B^2 + C3*(Loa/B) + C4*(S/Loa) +
↪  C5*(C/Loa);

% wind forces and moment (changed value of tauX to *-1 to better match
% expected values)
tauX = (0.5*CX*rho_a*V_r^2*AFw)*-1;
tauY = 0.5*CY*rho_a*V_r^2*ALw;
tauN = 0.5*CN*rho_a*V_r^2*ALw*Loa;

if k <0
    tauY = tauY*k;
    tauN = tauN*k;
else tauY = tauY;
    tauN = tauN;
end

tau_w = [tauX,tauY,tauN]';
```

Blendermann calculation of wind coefficients:

The inputs used for Vessel 2 are: ALw: 2697.3m^2, AFw: 1606m^2, sH: -25,3m, sL: 7.3m, Loa: 305m, vessel no: 15

```
function [tau_w,CX,CY,CK,CN] =blendermann(gamma_r,V_r,AFw,ALw,sH,sL,Loa)
% [tau_w,CX,CY,CK,CN] =
↪  blendermann94(gamma_r,V_r,AFw,ALw,sH,sL,Loa,vessel_no) returns the
↪  the wind
% force/moment vector w_wind = [tauX,tauY,tauN] and the optionally wind
↪  coeffisients
% cx,cy and cn for merchant ships using the formulas of Isherwood
↪  (1972).
%
% INPUTS:
%gamma_r    = relative wind angle (rad)
%V_r        = relative wind speed (m/s)
%ALw        = lateral projected area (m^2)
%AFw        = frontal projected area (m^2)
%sH         = horizontal distance to centroid of ALw (from main section)
%sL         = vertical distance to centroid of ALw (from water line)
%Loa        = length overall (m)
%vessel_no = 15;
%   15. Tanker, loaded

%
% Author:     Thor I. Fossen
% Date:       20th November 2008
% Revisions:
% Edited for bsc thesis Feb 2020
```

```
% conversions and constants
rho_a = 1.224;              % density of air at 20 C

% BDATA = [CD_t        CD_l_AF(0)        CD_l_AF(?)         ?         ?
BDATA = [0.70        0.90        0.55        0.40        3.1];

CDt              = BDATA(1);
CDl_AF_bow       = BDATA(2);
CDl_AF_stern     = BDATA(3);
delta            = BDATA(4);
kappa            = BDATA(5);

Hm  = ALw/Loa;

% two cases for CDl

if gamma_r <= pi/2
    CDlAF = CDl_AF_bow;
else
    CDlAF = CDl_AF_stern;
end
% wind coefficients
CDl = CDlAF*AFw/ALw;
den = 1-0.5*delta*(1-CDl/CDt).*sin(2*gamma_r).^2;

CX = -CDlAF.*cos(gamma_r)./den;
CY =  CDt*sin(gamma_r)./den;
CK =  kappa*(sH/Hm)*CY;
CN =  (sL/Loa - 0.18*(gamma_r - pi/2)).*CY;

% wind forces and moment
tauX = 0.5*CX*rho_a*V_r^2*AFw;
tauY = 0.5*CY*rho_a*V_r^2*ALw;
tauN = 0.5*CN*rho_a*V_r^2*ALw*Loa;

tau_w = [tauX,tauY,tauN]';
```

C.2 Current

Code version of what is described in Figure 9 on page 29

Modeling of current in the waterway

```
function [Vangle,Vc] = fcn(x,y)

Vc = 1.5;
Vangle = 180;


if x <= 0.52*1852
```

```
    Vc = 1.5;
    Vangle = 183;
else if x > 0.52*1852 && x <= 0.63*1852
        Vc = 1.5;
        Vangle = 155;%205;

else if x > 0.63*1852 && x <= 0.86*1852
            Vc = 1.5;
            Vangle = 137;%223;

else if x > 0.86*1852 && x <= 1.03*1852
        Vc = 1.5;
        Vangle = 120;%240;

else if x > 1.03*1852 && x <= 1.32*1852
        Vc = 1.5;
        Vangle = 145;%215;

else if x > 1.32*1852 && x <= 1.67*1852
        Vc = 1.5;
        Vangle = 175;%195;

else if x > 1.67
        Vc = 1.5;
        Vangle = 180;

    end
    end
    end
    end
    end
    end
end
```

Decomposition of current

```
function nu_c = fcn(beta_c,V_c,psi)
%Decomposition of current in {n}
nu_c(1) = cos(beta_c)*V_c;
nu_c(2) = sin(beta_c)*V_c;

x = nu_c(1);
y = nu_c(2);

%transofmation from {n} to {b}
u_c = cos(psi)*x-sin(psi)*-y;
v_c = sin(psi)*-x+cos(psi)*y;

%Current speed decomposed in {b}
nu_c = [u_c;v_c];
```

C.3 Mathematical model

Mathematical model post edit

```
function [xdot] =tanker2(in)
% File edited for bsc thesis in november 8th 2019
% [xdot,U] = tanker(x,ui) returns the speed U in m/s (optionally) and
↪  the
% time derivative of the state vector: x = [ u v r x y psi delta n ]'
↪  for
% a large tanker L = 304.8 m where:
%
% u     = surge velocity, must be positive  (m/s)        - design speed
↪  u = 8.23 m/s
% v     = sway velocity                     (m/s)
% r     = yaw velocity                      (rad/s)
% x     = position in x-direction           (m)
% y     = position in y-direction           (m)
% psi   = yaw angle                         (rad)
% delta = actual rudder angle               (rad)
% n     = actual shaft velocity             (rpm)         - nominal
↪  propeller 80 rpm
%
% The input vector is :
%
% ui      = [ delta_c  n_c h ]'  where
%
% delta_c = commanded rudder angle                 (rad)
% n_c     = commanded shaft velocity               (rpm)
% h       = water depth, must be larger than draft (m)      - draft is
↪  18.46 m
%
% Reference : Van Berlekom, W.B. and Goddard, T.A. (1972). Maneuvering
↪  of Large Tankers,
%             Transaction of SNAME, 80:264-298
%rk
% Author:     Trygve Lauvdal
% Date:       1994-05-12
% Revisions: 2001-07-20, T. I. Fossen: added speed output U, changed
↪  order of x-vector
%            2005-05-02, T. I. Fossen: changed the incorrect expression
%                        c = sqrt(cun^2*u*n + cnn^2*n^2) to c =
↪  sqrt(cun*u*n + cnn*n^2)
%                        - thanks to Dr. Euan McGookin, University of
↪  Glasgow
%            2020-11-08, Edited for use in DSS for bsc thesis
% ________________________________________________________________
%
% MSS GNC is a Matlab toolbox for guidance, navigation and control.
% The toolbox is part of the Marine Systems Simulator (MSS).
%
```

```
% Copyright (C) 2008 Thor I. Fossen and Tristan Perez
%
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% (at your option) any later version.
%
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%
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% along with this program.  If not, see <http://www.gnu.org/licenses/>.
%
% E-mail: contact@marinecontrol.org
% URL:     <http://www.marinecontrol.org>

% Check of input and state dimensions
x  = in(1:8);
ui = in(9:11);
tau_w = in(12:14);
nu_c = in(15:16);

% Normalization variables
L   =  295;           % length of ship (m)
g   =  9.8;             % acceleration of gravity (m/s^2)


% Dimensional states and input
delta_c = -ui(1); %minus sign to make a positive delta_c give a positive
 ↪  r.
n_c      = ui(2)/60;
h        = ui(3);

u      = x(1)-nu_c(1);
v      = x(2)-nu_c(2);
r      = x(3);
psi    = x(6);
delta = x(7);
n      = x(8)/60;
U      = sqrt(x(1)^2 + x(2)^2);

%wind forces (values from Blendermann)
tau_X = tau_w(1);
tau_Y = tau_w(2);
tau_N = tau_w(3);

tau_X = tau_X/(1*1025*g*250);
tau_Y = tau_Y/(1*1025*g*250);
tau_N = tau_N/(1*1025*g*250*L);
```

```
% Parameters, hydrodynamic derivatives and main dimensions
delta_max  = 35;        % max rudder angle      (deg)
Ddelta_max = 1.4;      % max rudder derivative (deg/s)
n_max      = 74;        % max shaft velocity    (rpm)

t   =  0.22;
Tm  =  38;
T   =  18.66;

cun =  0.605;
cnn =  29.04188948620969;

Tuu = -0.007433509;
Tun = -0.000709782;
Tnn = 0.000304667666997686;

m11 =   1.069997082612927;          % 1 - Xudot
m22 =   1.300077829591485;          % 1 - Yvdot
m33 =   0.0500951623451746;         % kz^2 - Nrdot

d11 =  1.500000506589733;          % 1 + Xvr
d22 = -0.884020635910677;          % Yur - 1
d33 = -0.0800826820892927;          % Nur - xG

Xuu    = -0.0336857567385002;
Xvv    = 1.199999517477226;
Xvr   = 0.200000252205158;
Xccdd  = 0.093;
Xccbd  = 0.152;


YT     = 0.04;
Yvv    = -1.000236874299409;
Yuv    = -1.9522680319442 9;
Yurz   = 0.06563151370946;
Yccd   = 0.208;
Yccbbd = -2.16;

NT      = -0.02;
Nvr     = -0.572913891187877;
Nuv     = -0.401080504015567;
Nur    = -0.0182348035962499;
Nccd    = -0.098;
Nccbbd  = 0.688;


% Rudder saturation and dynamics
if abs(delta_c) >= delta_max*pi/180,
   delta_c = sign(delta_c)*delta_max*pi/180;
end
```

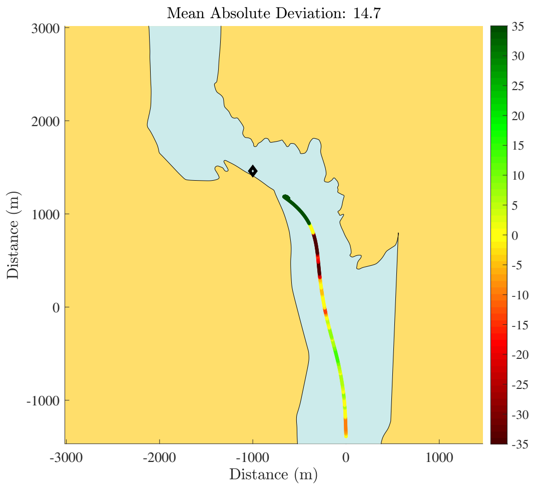
```
delta_dot = delta_c - delta;
if abs(delta_dot) >= Ddelta_max*pi/180,
   delta_dot = sign(delta_dot)*Ddelta_max*pi/180;
end

% Shaft saturation and dynamics
if abs(n_c) >= n_max/60,
   n_c = sign(n_c)*n_max/60;
end

n_dot = 1/Tm*(n_c-n)*60;

% Forces and moments
%if u<=0, error('u must be larger than zero'); end
beta = v/u;
gT   = (1/L*Tuu*u^2 + Tun*u*n + L*Tnn*abs(n)*n);
c    = sqrt(cun*u*n + cnn*n^2);

gX   = 1/L*(Xuu*u^2 + L*d11*v*r + Xvv*v^2 + Xccdd*abs(c)*c*delta^2 ...
     + Xccbd*abs(c)*c*beta*delta + L*gT*(1-t) ...
     + L*Xvr*v*r + tau_X);

gY   = 1/L*(Yuv*u*v + Yvv*abs(v)*v + Yccd*abs(c)*c*delta + L*d22*u*r ...
     + Yccbbd*abs(c)*c*abs(beta)*beta*abs(delta) + YT*gT*L ...
     + L*Yurz*u*r + tau_Y);

gLN  = Nuv*u*v + L*Nvr*abs(v)*r + Nccd*abs(c)*c*delta +L*d33*u*r ...
     + Nccbbd*abs(c)*c*abs(beta)*beta*abs(delta) + L*NT*gT ...
     + L*Nur*u*r + tau_N;

% Dimensional state derivative
xdot = [  gX/m11
          gY/m22
          gLN/(L^2*m33)
          cos(psi)*u-sin(psi)*v
          sin(psi)*u+cos(psi)*v
          r
          delta_dot
          n_dot         ];
```

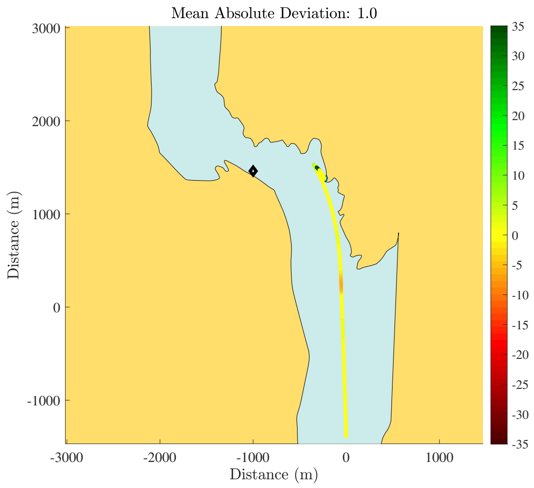
Rotation after mathematical model

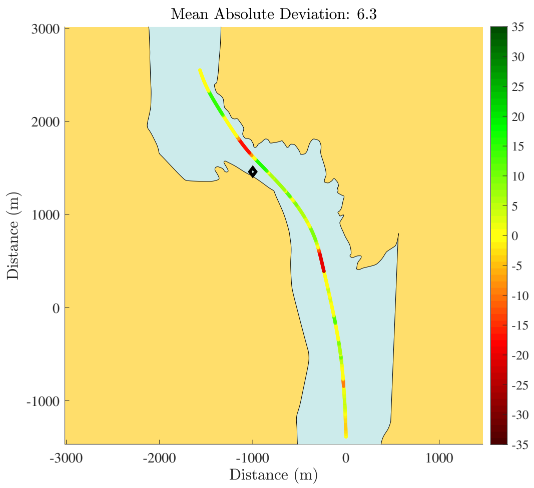
```
function [Heading,NED] = ROTATION(x,y,r)

%transformation from mathematical model output to {n}
NED = [y x];

% Wrap heading 0-360 degrees
if r < 360 & r > 0
    Heading = r;
elseif r >= 360 & r < 720
    Heading = r-360;
elseif r <= 0 & r > -360
    Heading = r+360;
elseif r <= -360
    Heading = r+720;
else Heading = r;
end

%Output to graphics, current and wind.
NED = NED;
Heading = Heading;
```

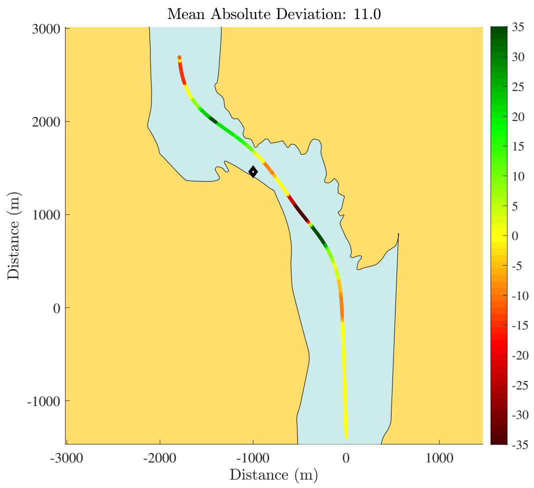
D Rudder Graphs

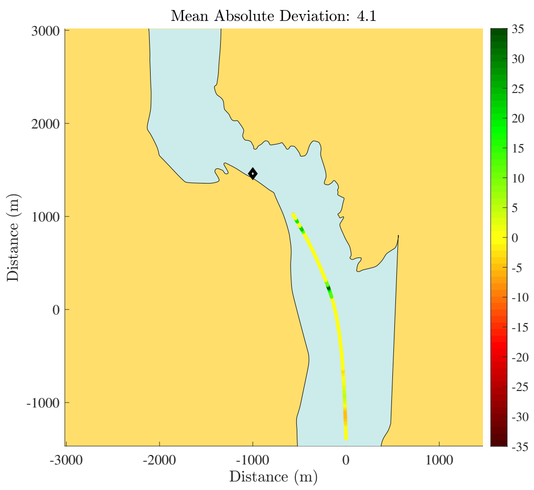
Rudder graphs for Group A without DSS

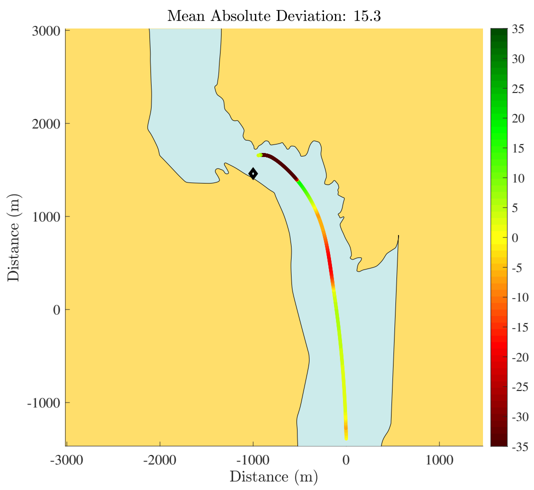




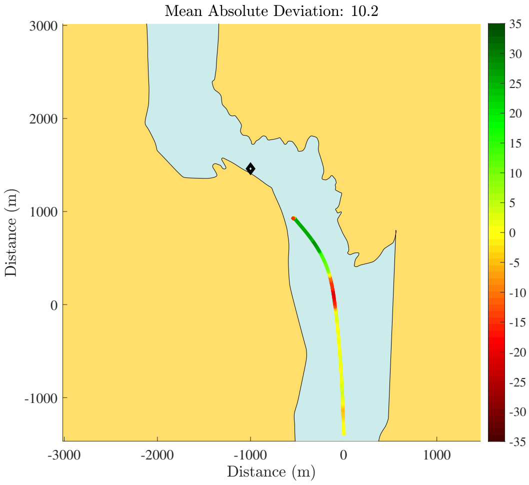


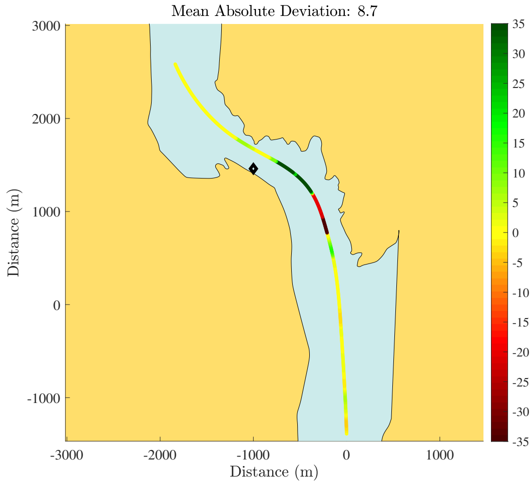




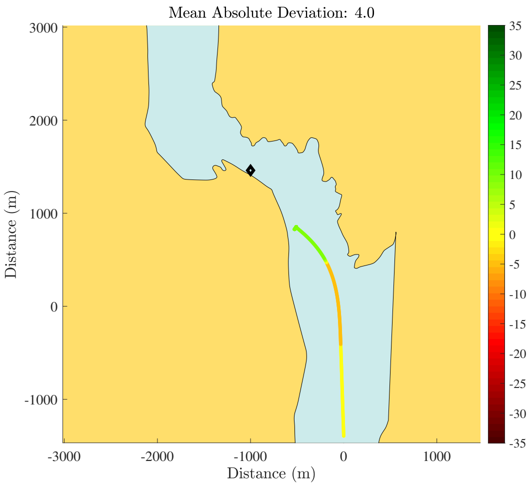


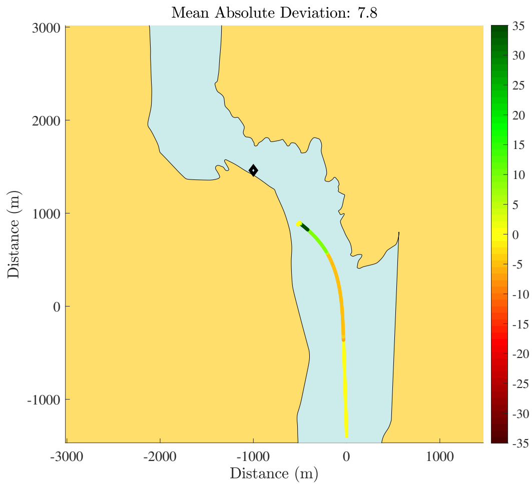
Continuation of rudder graphs for Group A without DSS

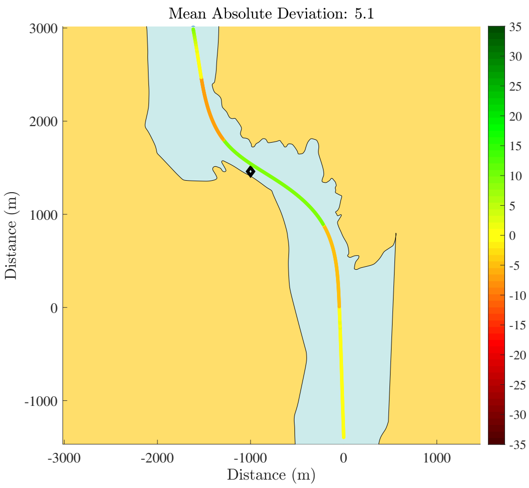


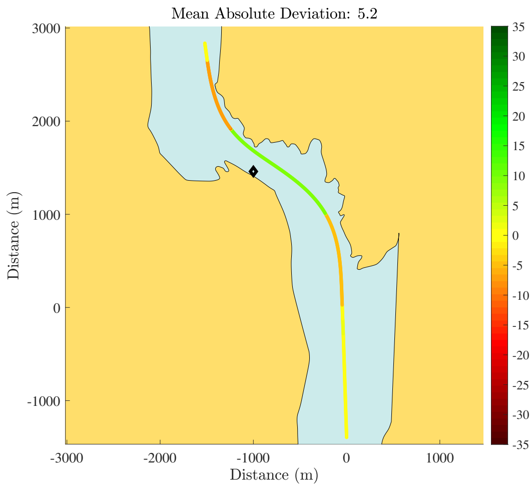


Rudder graphs for Group A with DSS

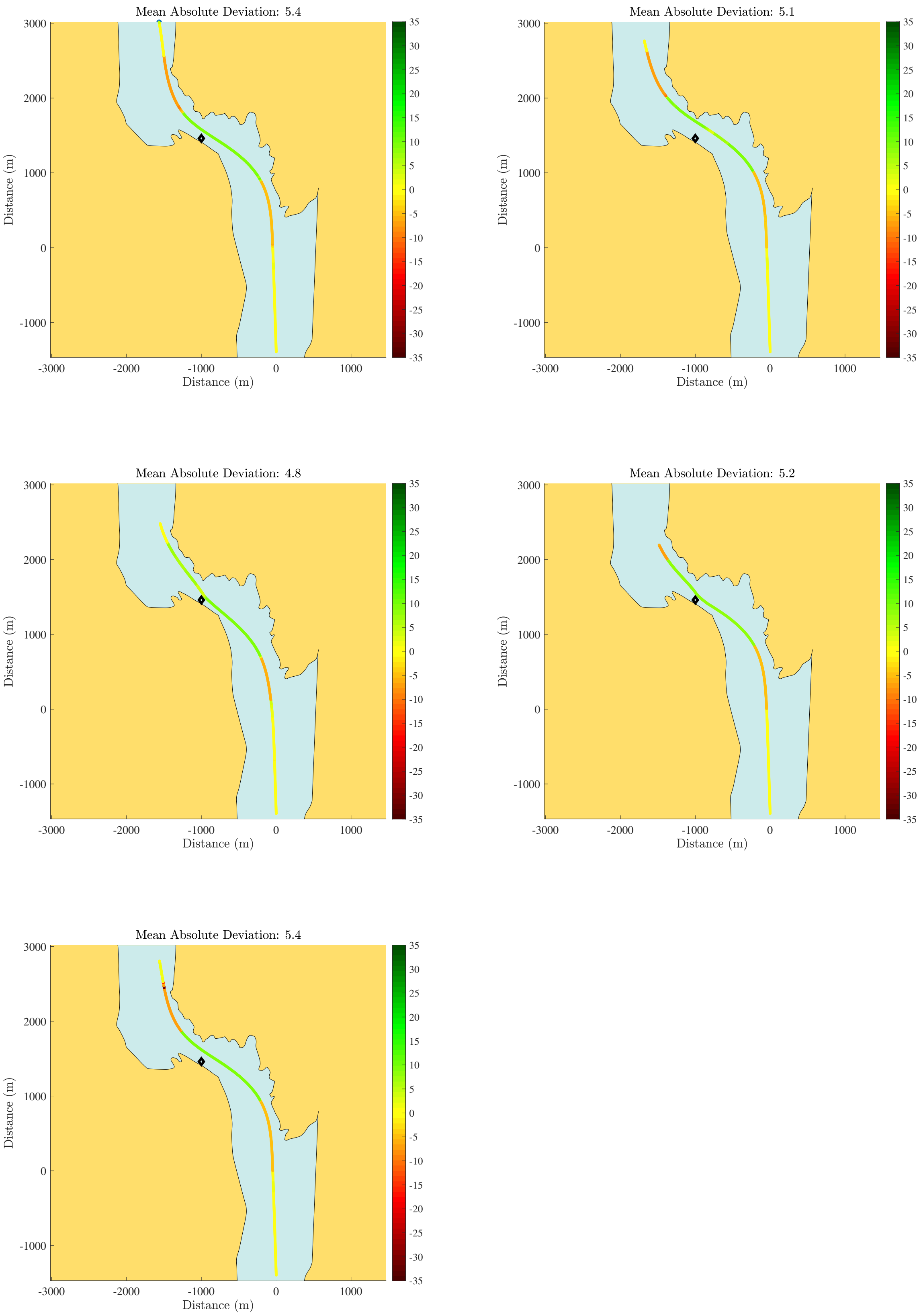




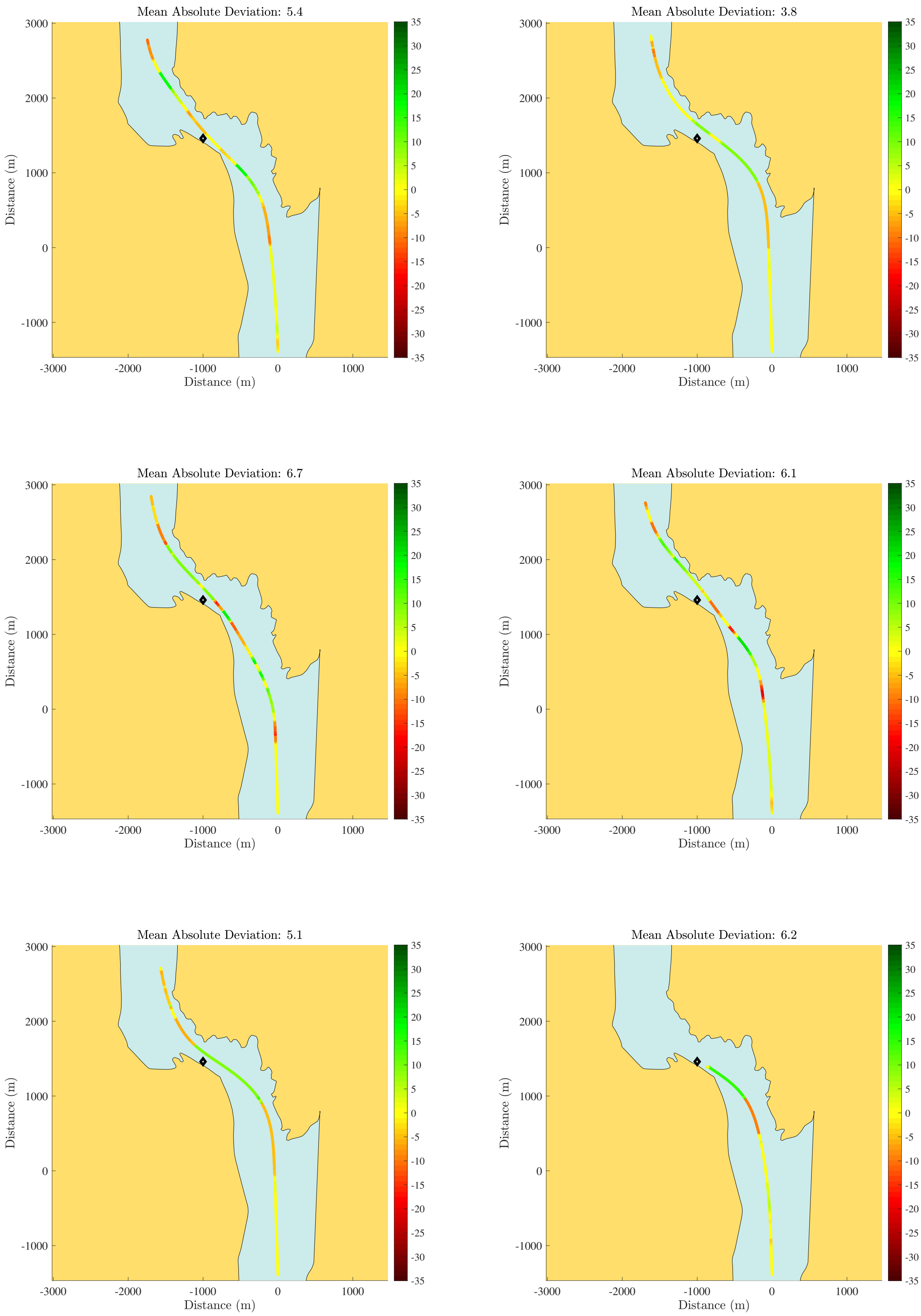




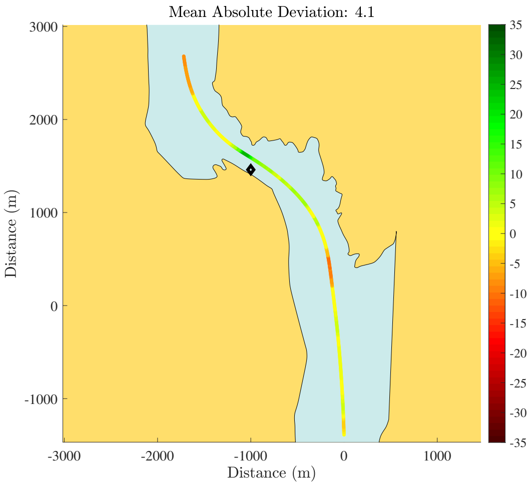
Continuation of rudder graphs for Group A with DSS

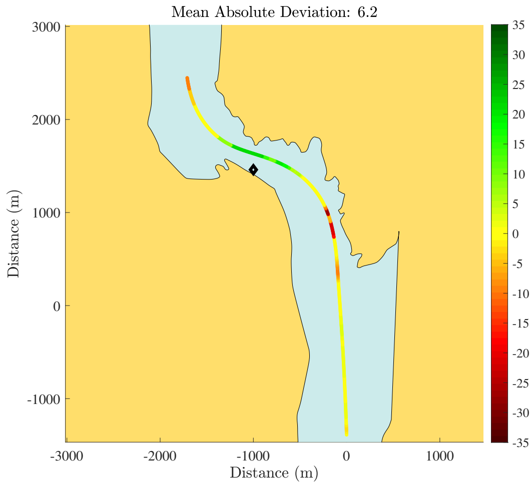


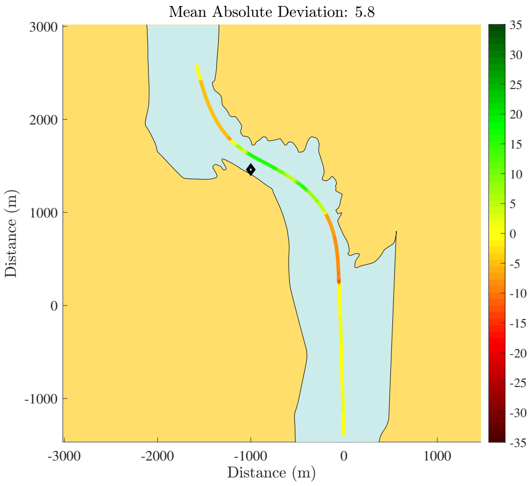
Rudder graphs for Group B without DSS

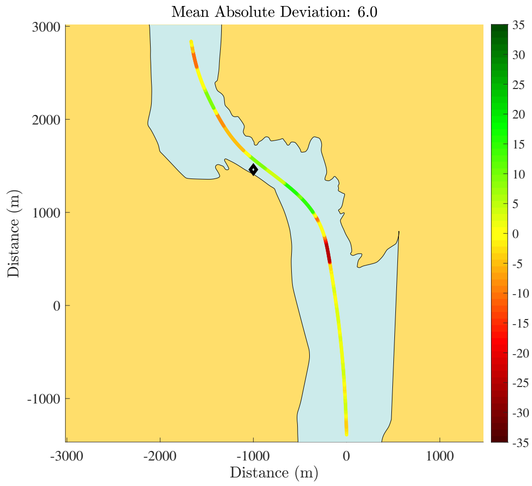


Continuation of rudder graphs for Group B without DSS

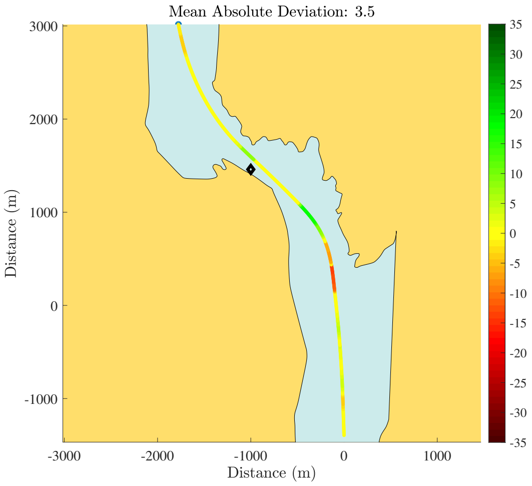


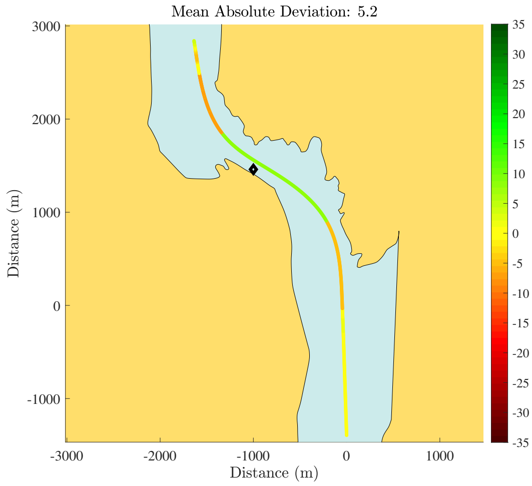




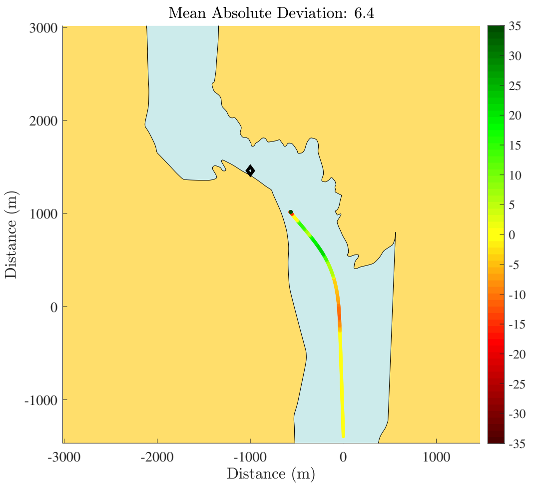


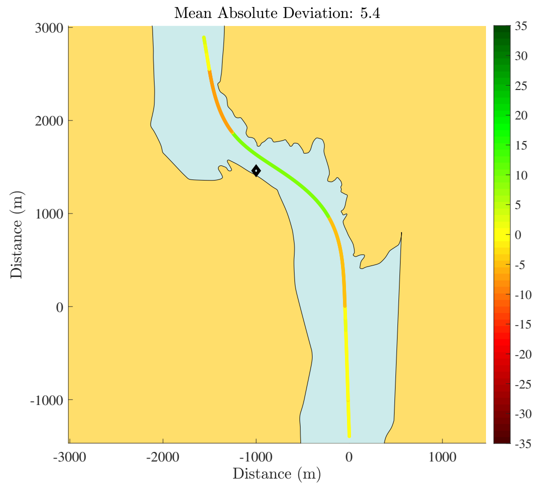
Rudder Graphs for Group B with DSS

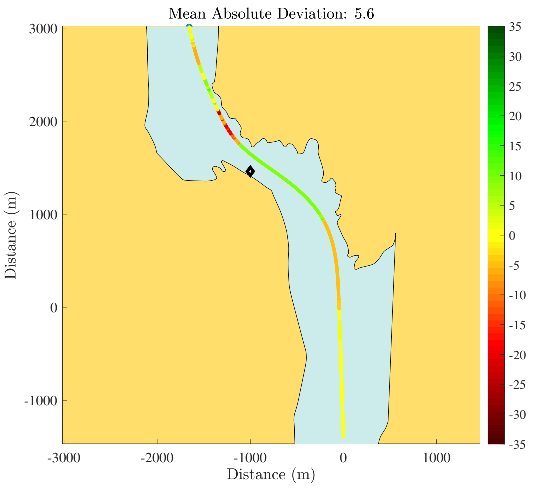


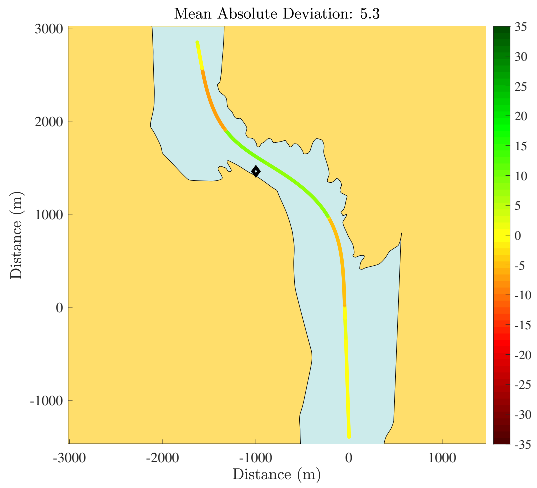


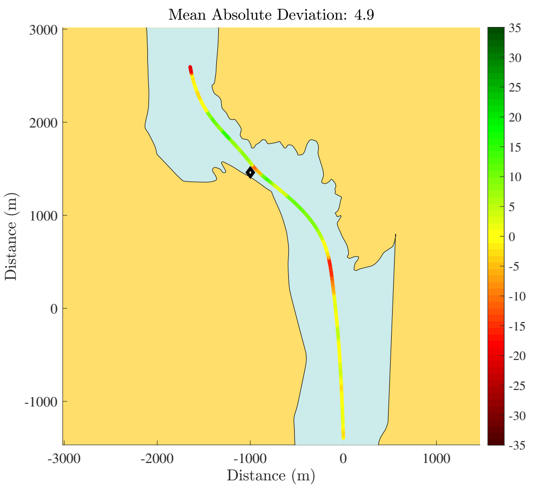
Continuation of rudder graphs for Group B with DSS

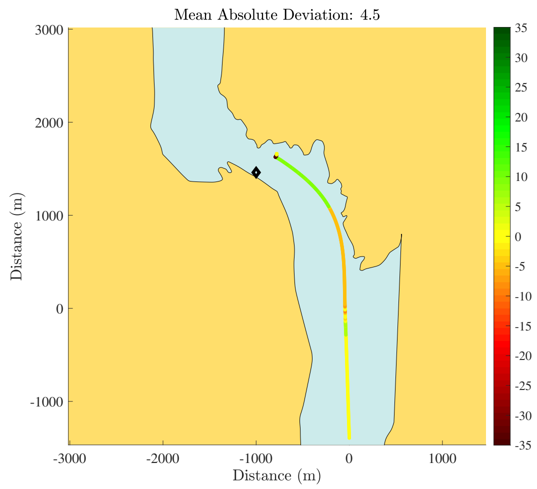




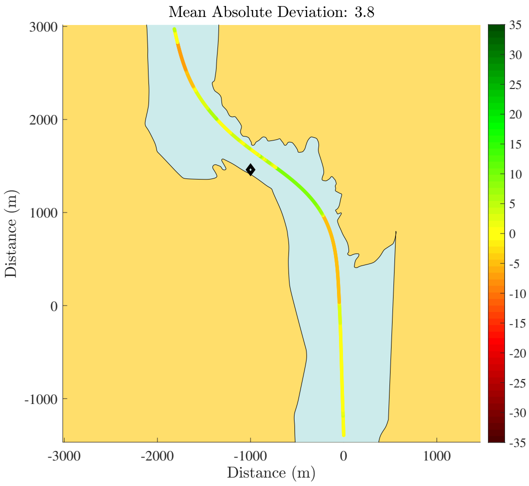


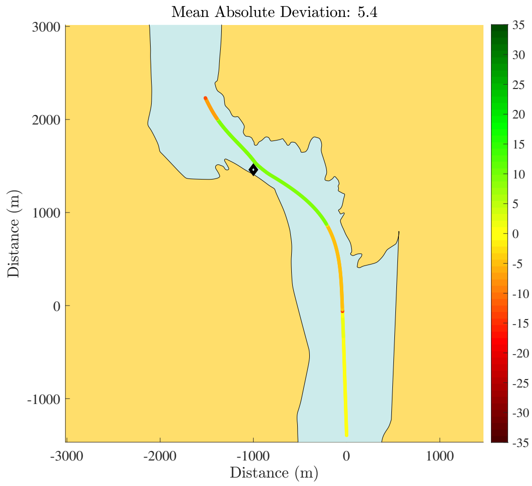






Continuation of rudder graphs for Group B with DSS





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