Department of Engineering Science and Technology

Automated Tugboat Assisted Docking of Large Vessels

Modelling and Simulation of System Dynamics

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Master’s Thesis in Electrical Engineering ELE-3900 Spring 2022

Project Description

Automation of port operations is currently receiving a considerable amount of attention, due to the combination of new technological breakthroughs making such operations possible, and the projected gains in port throughput, safety and reliability, and operating costs. Of particular interest in this respect is the use of tugboat-assisted docking of large vessels, which has significant potential for improvement. Vessels in need of tugboat assistance are usually massive and controlled with a configuration of aft propellers and rudders. Vessel maneuvering requires forward velocity, and acceleration require long distances and time. When reaching the port, vessels reduce velocity to a dead slow, severely reducing maneuverability. The final maneuvering into the dock is assisted by tugboats, strategically positioned around the hull to provide push/pull forces. Successful vessel maneuvering with high performance requires reliable tugboat coordination, typically ensured with highly qualified helmsmen performing manual tugboat control, as well as robust communication links between the tugboats and vessel pilot.

This project focuses on developing advanced automatic control solutions to support automated tugboat-assisted docking operations. The challenging problems related to automatic docking lend themselves to solution through advanced nonlinear automatic control theory, thereby enabling fully automated vessel docking with improved efficiency and reliability. The requirement of highly skilled helmsmen will be relaxed, as the control algorithms will optimally control the tugboats to provide necessary forces for vessel maneuvering and optimize time and power consumption as well as safety in the docking operation.

In particular, the project includes the following subtasks:

1. Perform a literature review on automated ship docking and berthing operations.
2. Develop the mathematical model for a specific case of a porting vessel and supporting tugboats.
3. Develop guidance and control algorithms for the porting vessel under ideal conditions, without considering tugboat constraints.
4. If time allows for it, based on the outcome of task 2, develop guidance and control strategies for the tugboats under relaxing assumptions of continuous contact and no-slip conditions

All results must be supported by mathematical derivations as well as performance simulations in MATLAB/Simulink.

Preface

The foremost person behind this thesis work is my esteemed supervisor Raymond Kristiansen, with his technical guidance and consistent trust made it possible for me to successfully complete my work. With his help the tricky situations turn into favorable circumstances. I would like to thank him from the core of my heart for his guidance and encouraging me to work hard and smart. I have found him immensely helpful while discussing the optimization issues in this dissertation work. His critical comments on my work have certainly made me think of innovative ideas and techniques in the fields of optimization and control systems simulation.

The people with whose support this project is successful includes my friends and colleagues, especially Adeel Yusuf who has helped me a lot in understanding the control related problems and think of possible solutions. Because of his help, I was able to achieve all the objects and overcome the obstacle encountered.

Finally, I would like to thank my teachers and research fellows like Hussain Mahdi who provided useful guidance whenever I needed it.

Abstract

The main research aspect behind this project was the problem in docking the ship to the port with limited space and resources available, causing number of onsite accidents and loss of resources. The main objective is to increase safety on ports, reduce pollution and increase fuel efficiency, also reduce the docking time for the vessels, which can be achieved by developing an autonomous docking system involving automated operations of tugboats, the port, and the vessel itself using control systems with limited involvement from human. This requires the development of a predictive control path for each component involved in the process. This is a long-term goal and requires a lot of research work and prototyping. In this thesis work, some studies will be carried out from past research work related to the problems focused on this project and the solutions provided to tackle these problems. Further data will be extracted along with all the essential equations and based on it; mathematical model will be developed as well as the development of path trajectory algorithm will be carried out. Also, its feasibility will be tested using simulation-based prototyping.

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1 Introduction

1.1 Background and Motivation

Ships have been an important means of transportation for so long. They have been playing a significant role in transporting passengers and goods across the waters. Nowadays, with the introduction of airplanes, the usage of ships to transport passengers has reduced, but they still play a key role in transportation of goods between different countries. By time, with advancement in technologies, the shipping industry is also progressing in ship development technologies, making them safer, quicker, and convenient in operation. Now there is a big hype towards electrification of ships to make them environmentally friendly, by using renewable energy sources. Figure 1 shows world's first electric ship that is massive in size and is being operated to transport cargo across waters.

Figure 1: World's first autonomous electric cargo ship – Yara Birkeland [1]

Along with electrification of the ships, there is a need to introduce the perfect docking procedures for the ships. It is easier to dock smaller ships as they have smaller surface area and can make easier turn. The problem arises with the larger ship with bulky mass and large surface area. These can dock in a larger port with some effort but on narrower ports like Narvik port, it is almost impossible to dock the ship by itself. For that purpose, tugboats are utilized which push the large vessels sideways towards the port and help them dock in a narrower spot. They push the large vessels from a side and maneuver the direction in which the vessel needs to move, to be docked with the port.

The problem exists in the procedure used for docking by tugboats. As the tugboats must push the vessel sideways by exerting the force on one of its sides, the massive structure of the vessel creates a blind spot for the tugboats. To provide the required sideways motion to the vessel and to provide required turns, each tugboat needs to be guided by the captain of the ship. This is quite a time taking procedure and not even efficient. As a lot of people engage in a single process, so there are a lot of chances of misinterpretation, and it requires a lot of effort to complete the whole procedure. Hence the process needs to be optimized, so there is less consumption of resources, less time is spent in completing the procedure and less labor is required.

1.1.1 Base Project Objectives

The major goal of the base project is to create improved solutions for instrumentation and autonomous port operations involving tugboats, as well as to test these solutions in a controlled environment at Narvik’s port. These objectives can be categorized into these subgoals:

- Develop a framework of sensors and instrumentation infrastructure to support tugboat operations.
- Visualize the data and operational procedures conducted during docking using deployed instrumentation infrastructure.
- Develop advanced guidance and control algorithms for automated tugboat-assisted docking using the acquired data.
- Prototyping, simulating the developed solution, and making enhancements.
- Perform full-scale testing of developed solutions in the port of Narvik.

1.1.2 Scope of Base Project

1.1.2.1 Relevance and Benefit to Society

Automation and logistics, as enabler technologies for social progress, have a tremendous impact on the future of industry and society. In global views, cheaper and more reliable trade and transportation are in increased demand. Norway is establishing itself as a maritime nation with a significant portion of the global marine economy. Northern Norway has a high demand for qualified workers due to its sparse population. As a result, the development of technologically superior solutions is critical. Huge advances in port operations through technical solutions for instrumentation and automation will have a significant impact on society.

The emerging activities in the region will attract more industries building up a prominent level of competence, enabling possibilities for employments, and increasing effectiveness in currently established industry. New innovations and solutions for instrumentation and automation infrastructure on ports will result in increased efficiency and time-optimal operations, also making a great contribute to increasing the technical efficiency as a key factor for overall port efficiency worldwide. This will enhance the technological ladder of infrastructure and equipment resulting in significant improvement in ports efficiency frontier. Hence providing comparative gains for industry and increasing their competence in international market.

Human errors will drastically decrease due to reduced involvement from pilots, operators, and helmsman which attributes to over 60% of marine accidents due to control loss, collisions, etc. Thus, these reliable control solutions will contribute significantly to personnel safety and reduced number of accidents. Figure 2 shows such an incident, which happened due to human error during the docking procedure of the vessel. The vessel collided with the gantry crane on the port and there was a massive damage to the equipment and the vessel itself. Fortunately, there were no causalities, but the intensity of damage was much.

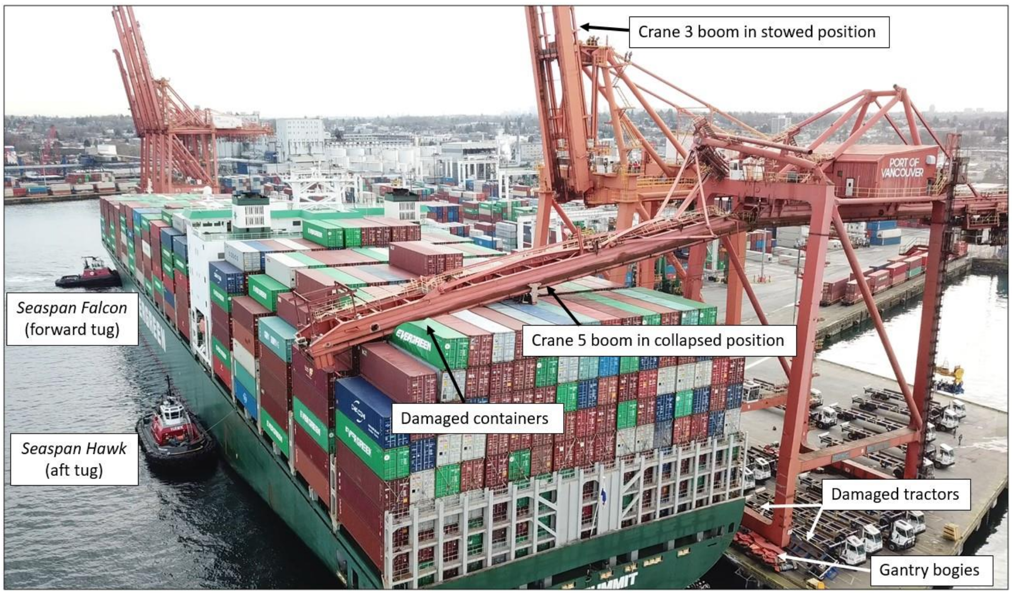

Figure 2: Vessel container ‘Ever Summit’ collided while docking on shore [2]

1.1.2.2 Environmental Impact

Increased port efficiency and throughput, because of the introduction of modern automated docking technology, will result in significant environmental benefits. To begin with, the running duration of the vessels' auxiliary diesel engines will be decreased, which is a major source of air pollution in the port. Second, by lowering docking time and relying more on environmentally friendly tugboats, docking operations will be performed in a time-efficient and fuel-efficient manner. This all adds up to a huge reduction in port emissions. During set-up and testing, full-scale trials at the Port of Narvik will use ordinary commercial operations with just minor increased tug movement and accompanying exhaust emissions.

1.1.3 Different Phases

The base project itself is so vast that it needs to be divided in a few phases which will be achieved along time. These phases are further divided into sub phases to make the whole project be easier to understand and to categorize the goals that need to be achieved. These phases can change later according to the needs of that time to make the procedure efficient. Figure 3 shows the different stages of the base project in a flow chart diagram.

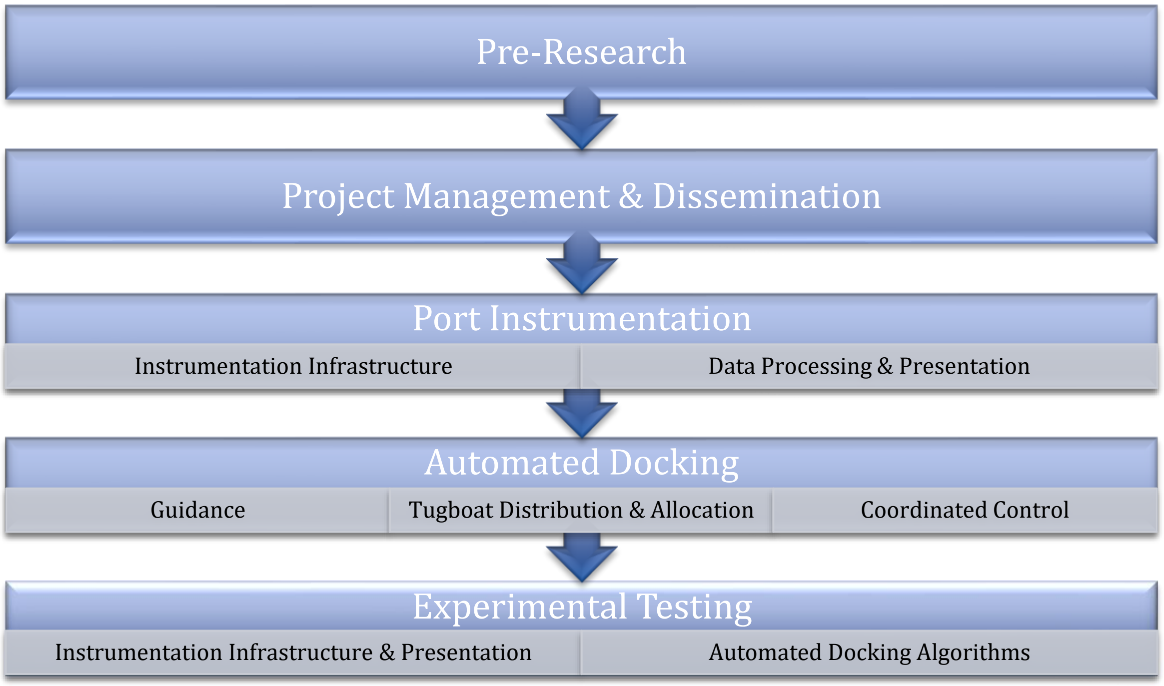

Figure 3: Different phases of base project

1.1.3.1 Pre-Research

During this initial phase of the project, all the possible outcomes will be analyzed. Initial mathematical modelling will be conducted in accordance with the required systems and their control methods, and the simulations will be made along with the development of path development techniques. Once this is done, further research work will be done to optimize the current mathematical model and the strategies used to build the reference trajectory for the ship.

1.1.3.2 Project Management and Dissemination

This phase mostly includes administrative work and non-scientific disseminations. All the related firms and organizations will be contacted and will be briefed about the whole project. After gaining their confidence, agreements and contracts will be made and handled with partners. Regular reporting of work progress will be done to keep all partners informed and confident. Furthermore, workshops and seminars will be organized, and coordination of other phases will also be done during this phase.

1.1.3.3 Port Instrumentation

This phase concerns analysis and development of necessary instrumentation infrastructure to support automated port operations. It also further addresses the first and second subgoals of the objectives. Weather conditions have high impact on port operations, so real-time information is a prerequisite. Based on port geography and subsea profiles, a distributed network of sensors must be developed, which is specifically tailored for the application. Collected data must be integrated, processed, and visualized to assist the docking procedures being held manually, also to provide short-time forecasts. This analyzed data together with different environmental and geographical knowledge, such as tidal information, etc. can become useful in long-term operation plannings by developing essential trends. In addition to researchers, industrial partners will also be involved in this phase. This phase is further divided into two sub-phases, which will describe the tasks in more details.

1.1.3.3.1 Instrumentation Infrastructure

Instrumentation infrastructure will be developed based on the type of information required, this can be based on location, environmental conditions, positioning, etc. Hence it can be divided into two categories, one dependent on requirement of general information, and the other dependent on local conditions. This can help in predicting which instrumentation is required, so they are divided as must-have, should-have and nice-to-have instrumentation infrastructures. Port of Narvik is considered as a scenario initially so suggestions for sensor network distribution for this port will also be considered. Moreover, location-specific sensor setups will also be studied as well as sensor setups that are common in docking operations assisted by tugboats. Practitioners operating in the Port of Narvik will contribute their local experience of the impact of met ocean conditions on operations.

1.1.3.3.2 Data Processing and Presentation

After gaining raw data from the instrumentation infrastructure there will be a need to process this data into a viable tool, and all the useful information must be shared with pilots, tugboat operators and other personnel, to facilitate them for their needs. Short-term predictions and forecasting are needed to be performed, so it is necessary to process, integrate and visualize data. This can lead to prototype the data processing and presentation pipeline. Investigations will be conducted to integrate different sensors and process their data accordingly to get relevant information for end-users, and to predict future changes in external environmental conditions using trends and variations. A user-friendly interface will also be made to present data to port personnel by involving practitioners in design process.

1.1.3.4 Automated Docking

This phase focuses on development of advanced automatic control solutions to support automated tugboat-assisted docking operations. The solution to the challenging problems of automatic docking can be through advanced non-linear automatic control theory, which also enables fully automated vessel docking with improved efficiency and reliability. The control algorithms will optimally control the tugboats to provide necessary forces for maneuvering and optimize time and power consumption as well as increase safety in docking operations. Furthermore, the requirement of highly skilled helmsmen will also be reduced. This phase is divided into three sub phases.

1.1.3.4.1 Guidance

Optimal trajectories for movement of vessel and tugboats are the key requirements of swift and power-optimal docking operations of large vessels. This sub-phase will provide the guidance algorithms for both vessel as well as the tugboats and will further improve the instrumentation network for port and ships to provide sufficient input data that will be required for the algorithms. Further enhancement will be made in already derived mathematical derivations from pre-research phase to develop an optimized guidance algorithm. The first step will be to develop algorithms for docking vessels to ensure that it safely and efficiently approaches towards the dock. Second step will be the development of algorithms for tugboats to ensure that required push/pull forces are provided. The third step will be to investigate for possibilities to enhance real-time guidance using integration of instrumentation and sensor solutions mounted on or in port. Guidance algorithm will work according to vessel size and shape, tugboat characteristics and power budgets, as well as weather, current and wind. In addition, they will include state feedback solutions, and thereby provide real-time trajectories for the docking vessel and tugboats which orchestrates time-optimal, safe, and efficient movement. Algorithm validity and performance will be verified theoretically using mathematical ship models and stability analysis.

1.1.3.4.2 Tugboat Distribution and Allocation

The vessels that need the assistance by tugboats for their docking operations have designated strengthened positions around the hull for tugboat push, and tethers can be attached at various positions as well. The number of tugboats required may vary according to the vessel characteristics and its payload and pushing forces may also be applied at different angle of inclination depending on the desired movement of the vessel. The focus during this phase will be to build-up strategies for tugboat allocation along the hull, and guidelines for optimal operations of tugboat fleet. A benchmark will be established for power requirements in docking operations by doing case studies on using different number of tugboats. Hence this will help in finding the most effective tugboats allocation for docking based on analyzed power consumption for tugboat fleet and the vessel being docked. Further analyzations will be done to identify potential for emission reduction throughout the docking operation by including and excluding the participation of the docking vessel. Finally, the operations will be conducted under different operational conditions (i.e., weather, wind, waves, current) to evaluate the safety, efficiency, and power consumptions.

1.1.3.4.3 Coordinated Control

Autonomous tugboat operation not only requires a control algorithm for each tugboat but also requires a coordination algorithm coming from a common source. Overall system includes a fleet of tugboats with high maneuverability providing control forces to a large vessel with reduced maneuverability. This phase will provide a co-ordinational control system that will be robust and dependable and will be able to oversee temporary delays in tugboat control forces, even in harsh weather conditions. The complex and challenging control problems can be solved in the framework of hybrid and cascaded systems theory. Mathematical model for the complete system with tugboats and docking vessel, along with mathematical description of tugboat/vessel interaction will be developed. These models will further be used to develop algorithms for coordinated control of the tugboats. The robustness and performance of the control algorithms will be verified using mathematical stability analysis, in addition to simulation studies.

1.1.3.5 Experimental Testing

The outcomes of previous phases will be evaluated appropriately using both simulations and small-scale prototyping where applicable, as well as large scale test on a real port. Suitable port to carry out these testing will be the port of Narvik. As the port is already in operations with constructed supplementary systems, a low-impact testing approach is visualized.

1.1.3.5.1 Testing of Instrumentation Infrastructure and Presentation

To ensure accessibility and practicality of the information being provided, testing of instrumentation setups, data processing and visualization will be performed in close collaboration with industrial partners. Initially deployment and development of basic infrastructure together with visualization tool prototype will be planned. Implementation and several iterations of enhancements in this prototype will contribute significant understanding of docking operations. Close cooperation with practitioners will enable to identify the most suitable instrumentation for docking operations, and what impact different setups has for pilots, tugboat operators and helmsmen.

1.1.3.5.2 Testing of Automated Docking Algorithms

Automation of docking procedure will note be done at once but will go through step wise procedures. Initially, the optimal guidance system will be deployed in operation but the whole procedure will be controls manually, and the real-time vessel guidance system will only provide the information along with the set of instructions to the main pilot that is directing the tugboat operations. This will be helpful in observing whether the system is providing the desired instructions as needed during the manual operation. Also, vital information may be obtained for further refinement of models and algorithms.

In the second step, the guidance system will assist the operation of tugboats, but still rely on manual tugboat control. Tugboat operators will be directed by the control solutions on how to move the tugboats to provide the required control forces. This reduces load of communication, allowing pilots to focus on supervising the maneuvering and receive early notification of switch between push/pull operations.

An ultimate step will be the testing of the fully automated system where the tugboats are controlled automatically, and the helmsmen on the tugboats will supervise the operation and perform manual corrections. Large scale testing of fully automated tugboats will not be performed as part of this project as this would require significant interference with the tugboat control systems, and implementation of such new innovations and technologies must maintain necessary standards. Instead, the simulation tests will be performed based on the developed mathematical system models incorporating derived guidance and control algorithms.

1.1.3.6 Current Phase

All the phases mentioned above are the part of the primary research project which will be initialized soon based on this thesis work. This work will contribute to the pre-research phase and will develop a base for further research work to be carried out by PhD research fellows.

1.2 Literature Review

1.2.1 Background Information and Current Knowledge

Because of the combination of new technical developments that make such operations feasible, as well as the predicted advantages in port throughput, safety and dependability, and operating costs, port automation is now garnering a lot of attention. With its focus on port operations in general and tugboat operations in particular, the initiative is quite timely.

According to the analysis, based on fatalities recorded by EU national accident investigation organizations, the total number of fatalities in 2020 were 18% lower than in 2019. As previously stated, such a favorable outcome was seen due to COVID-19 epidemic, which had a significant impact on worldwide shipping. As the epidemic ends, the graph will sharply rise due to increased maritime activities and increased demand for marine transportation. As a result, it is now a duty to seek solutions to such issues. Figure 4 shows the severity of maritime casualties and events as given in the report by EMSA [3]. It clearly depicts various incidence intensities as well as their cumulative aggregate. Although the number of serious occurrences is lower, it is worthwhile. However, the rate of somewhat less serious incidents is at an all-time high. These factors will result in significant financial and death consequences. These casualties and incidents are also depicted in Figure 5.

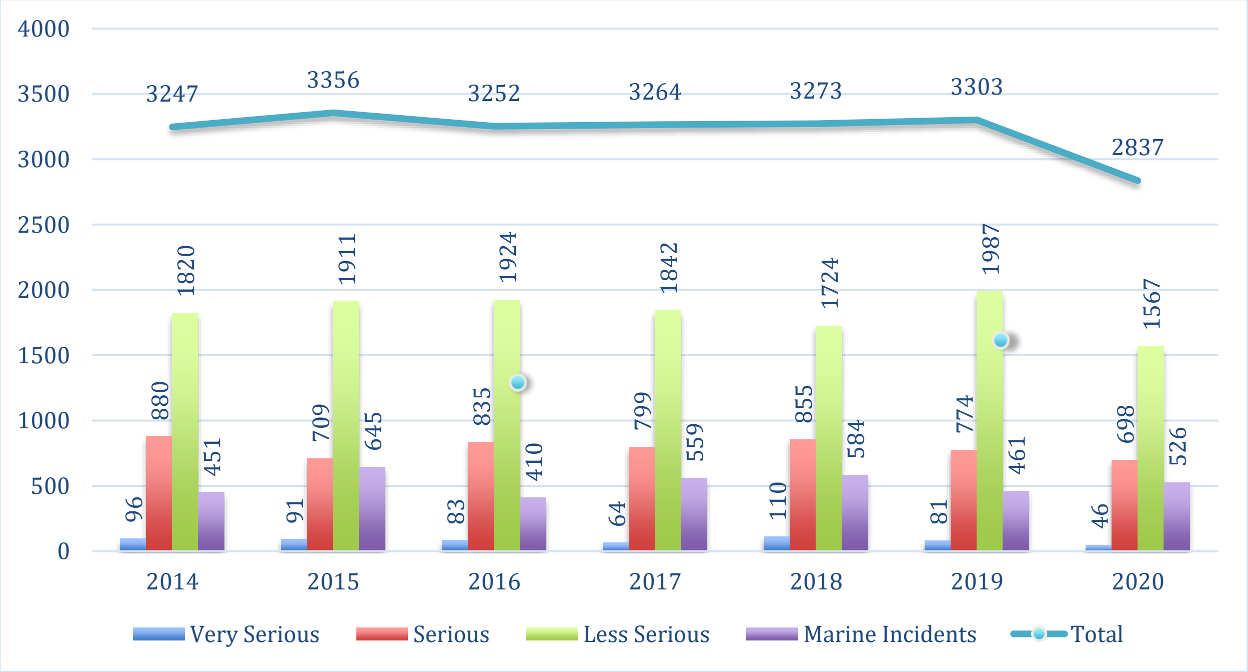

Figure 4: Severity of marine casualties and incidents

Navigational occurrences (collisions, groundings, and contacts) accounted for 43 percent of all ship-related fatalities. Simultaneously, a 15% decrease in ship-related casualties was recorded.

Accidents involving people accounted for 37% of all maritime fatalities. In compared to 2019, there was a 28 percent decrease. In addition, seven vessels were lost in 2020, five of which were fishing vessels.

In 2020, the number of pollutions caused by marine casualties continued to decline. In fact, since 2014, there has been a 68 percent decrease.

In the last six years, European Union accident investigation committees have opened 923 investigations, with 757 of them being completed. In the year 2020, 74 investigations were launched.

Finally, the aggregate number of investigations resulted in 2011 safety recommendations and actions, with most of them focusing on Ship Related Procedures / Operations and Human Factors / Training, skills, and experience [3].

Figure 5: Annual summary of marine casualties and incidents from 2014 to 2020 [4]

1.2.2 Methodologies and Approaches for Solutions

In 2022, EMSA continues to expand its knowledge in the field of marine data analytics, finding areas where artificial intelligence and machine-based learning may assist with specific operating scenarios. The following are the areas where EMSA will concentrate its efforts [5]:

- Autonomous shipping
- Passenger ship safety
- Fire safety
- Container ship safety
- EU fishing ship safety
- Life-saving appliances
- Steering and maneuverability standards
- Safety standards for the use of alternative sources of energy

Through use of instrumentation and advanced automatic control solutions, such solutions can be approached which will not only increase safety and efficiency but also reduce port emissions. Tugboat-assisted docking of large vessels having a significant potential for improvement is focused. Massive vessels need assistance from tugboats and are controlled by configuration of aft propellers and rudders. Vessel maneuvering requires forward velocity, and acceleration requires long distance and time. Maneuverability is severely reduced after reaching the port by reducing the velocity to a dead slow. Tugboats assist in final maneuvering of the vessel to the dock by strategically positioning themselves around the hull of the vessel to provide required push/pull force. For a high-performance and effective vessel maneuvering operation, a dependable tugboat coordination is essential, as well as highly skilled helmsmen conducting manual tugboat controls. This also necessitates a strong communication link between the commander of the ship and the tugboats.

Studies on tugboat operations have not included an automatic coordination and control approach. It is more of an issue with ship docking, which involves using tugboats to guide vessels in shallow waters through canals and into docks, additionally the vessel's rudders and propellers, or bow and stern thrusters. The problem is also related to the following topics studied during literature review of related problems, swarm and coordination control in general [6, 7], and cooperative manipulation of robots [8, 9], coordination, synchronization and swarm control of marine vessels [10, 11], control allocation [12, 13], marine vessels [14, 15] and dynamic positioning [16, 17].

After the turn of millennium, the problem was determined in publications on the development of the support system for tugs operation [18] and swarms of autonomous maritime vehicles manipulate huge things [19], increasing the focus on automatic tugboat coordination and control systems. Later, efforts were made on translational and rotational control [20, 21], adaptive and observer-based control [22, 23], and tugboat distribution and control allocation [24, 25].

Automated vessel docking through coordinated control of tugboats constitutes several control problems with unsolved complications. The first problem will be a non-linear underactuated tracking control problem where tracking of optimal trajectory towards the dock must be done by the vessel by using only the available forces. Secondly, vessel translation and rotation must be provided by several tugboat distribution and positioning algorithms. Third is the implementation of the whole system that includes tugboats as one system, that are providing input to another system (i.e., the vessel). Fourth one is an additional challenge of securing the tugboats with the hull of the vessel as they need to be fully stretched tether and avoid slipping, which is not possible always. Therefore, availability of desirable control forces to the vessel is not always possible, this causes a problem of hybrid, or switched systems framework. Finally, addition of actuator saturation and optimization for maximum control input, as well as incomplete knowledge of the hydrodynamics of the vessel and drag effects in low speeds, especially in sideways motion can be considered a problem.

Verification of published results have been done both theoretically and using scaled model experiments, to tackle the unsolved problems, some common basic assumptions are considered. The first assumption is that the tugboat remains firmly linked to the hull of the vessel and can provide thrust in both forward and reverse directions without any switching-time delay. This assumption seems impractical since tugboat only has direct contact with vessel while pushing and to pull it need to tether with the vessel. A second assumption is that the tugboats have no slip with fixed positions and pushing directions relative to the vessel or otherwise assuming small and slowly moving tugboat incident angles. Thus, this seems to be more technical and can minimize the trajectory tracking problem with full actuation and unknown thrust configuration. A third assumption is to divide the tugboats into pairs making it realistically dependent on tugboat fleet and vessel characteristics. Finally, the linear ship models with no constraints on available push/pull tugboat forces become the basis of derivation of results. The aim is to rely less on assumptions and come up with a proper solution involving necessary instrumentation infrastructure to gain necessary information.

1.3 Objectives and Scope

The main objectives of this thesis work are mentioned as following:

- Getting a sense of the existing systems that are used to carry out port activities.
- Find issues with the port's existing working framework systems and operations.
- Get to know about emerging technologies and their applications related to the problems.
- Consider all conceivable outcomes to determine the most effective and efficient implementation strategies.
- Putting together all the necessary materials and information for future use.
- Using several approaches to configure the capabilities of the navigational control algorithm.
- Making a preliminary simulation prototype to assess the system's viability.

These goals serve as the foundation for the thesis work's scope in relation to the primary project. The following are a few of them:

- Preliminary information for the pre-research stage will be provided, which was discussed previously in the project's phases.
- Basic modeling knowledge will be obtained, and the required model for implementation will be selected.
- The desired equations, operation control parameters, and physical values will be derived.
- A system controller that is stable and efficient for the operation will be designed.
- The fundamentals of spline theory will be discussed, as well as its application in navigation and implementation in a prototype simulation model.

1.4 Contributions and Limitations

This thesis work has shown to add to the basic project in a variety of ways, and these contributions may prove to be valuable in future projects. Some of these contributions are mentioned below:

- During the review of previous research, a lot of relevant material was retrieved that may be used as a foundation for building new tactics in the future.
- All the important mathematical equations for developing future models for overall operations have been derived based on their requirements.
- The fundamentals of spline theory were learned and applied to the ship model's route trajectory guiding system.
- A basic level simulation-based prototype of a functional ship is created, which follows the spline trajectory guiding system's track.
- The simulation-based prototyping results have been briefly explored and described to offer a basic comprehension.
- Some of the issues that may arise throughout the project's execution have been identified, and a few of them have been given some potential answers.

In addition to the contribution to the basic project, various constraints were discovered during the thesis research, some of which are listed below:

- Due to a lack of access to an actual ship, it was impossible to get practical values for the ship's original characteristics. As a result, most of the computations are based on assumed values.
- The controller was set up using assumed constant gain values, therefore it will need to be fine-tuned to be more efficient.
- The results are slightly different from the expected outcomes since the controller is not properly tuned and the characteristic values are not realistic.
- Currently, the model only includes a ship model that works independently, but in the future, a tugboat model should be added to the system.
- The present model is a simple 3DOF model that only tests for horizontal motions, but a comprehensive 6DOF model should be created in the future to cover all forms of motions and disturbances.

1.5 Dissertation Outline

- **Chapter 1**

  This chapter includes the introduction of the whole project and explains the current criteria of the thesis work covering apart from the base project. The scopes and objectives are also covered in this chapter. Moreover, information regarding previous literatures related to the project are also discussed.

- **Chapter 2**

  This chapter covers all the preliminary parameters and equations that are going to be utilized throughout the thesis work as well as the primary project.

- **Chapter 3**

  In this chapter, the derivation of mathematical model is carried out along with its simplification for current scenario of initial research and prototyping.

- **Chapter 4**

  This chapter completely focuses on the implementation of the mathematical model into simulation-based prototyping and the general discussion on the attained results.

- **Chapter 5**

  In this chapter, the whole thesis work done is discussed along with the future improvements and further enhancements that are achievable in the future.

2 Preliminaries

In this chapter, all the necessities for modeling vessels and tugboats, including definitions of coordinate reference frame and their transformations. All this material and information is extracted from the studies done in the book related to Marine Cybernetics [26] and its associated handbook [27].

2.1 General Ship Models

To get the preliminary models, along with that, the dynamical behavior of marine vehicles is also described in the literature thoroughly. The mathematical models on general form as nonlinear differential equations that were derived from previous literature are as following:

$$\dot{x} = f(x, t) \tag{2.1}$$

with initial condition $(\mathrm{x}_0, \mathrm{t}_0)$ and solution $\mathrm{x}(\mathrm{t}, \mathrm{t}_0, \mathrm{x}_0)$. Where the variable t denotes time, while x denotes system states, and in particular

$$x = [\eta\ \nu]^{\mathsf{T}} \tag{2.2}$$

in general, with $\eta = [x\ y\ z\ \phi\ \theta\ \psi]^{\mathsf{T}}$ as position and orientation, and $\nu = [u\ v\ w\ p\ q\ r]^{\mathsf{T}}$ as velocities and angular velocities.

Figure 6 taken from the handbook depicts the various sorts of motions that may be made in a vessel, and these maneuvering components will be discussed in greater depth later.

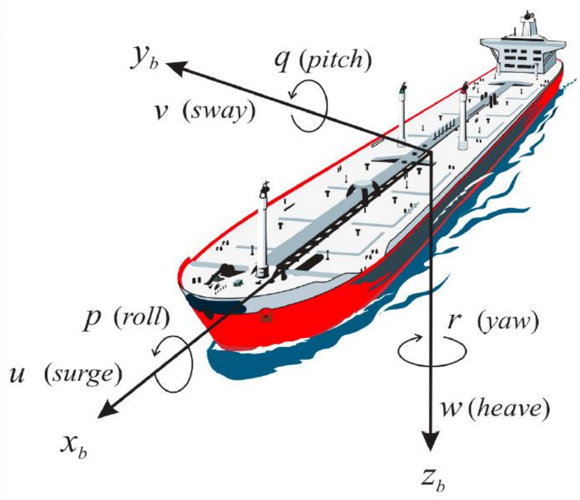

Figure 6: 6-DOFs in a marine craft [28]

2.2 Degree of Freedom (DOFs)

In naval studies, the set of distinct displacements and rotations that characterize the displaced location and orientation of a maritime ship is known as the Degree of Freedom (DOF). In three-dimensional space, a craft has a maximum of 6 DOFs in which it can move freely. Three of them are translational components (i.e., surge, sway, heave), and three are rotational components (i.e., roll, pitch, yaw).

Table 1 represents all these possible degree of freedoms in marine structures along with their notations with respect to linear forces/rotational moments, linear velocities/rotational velocities, and linear positions/rotational angles.

Table 1: The notation of SNAME (1950) for marine vessels [29]

DOF	TYPE	FORCES	VELOCITIES	POSITION/ANGLES
1	Surge	X	u	x
2	Sway	Y	v	y
3	Heave	Z	w	z
4	Roll	K	p	ϕ
5	Pitch	M	q	θ
6	Yaw	N	r	ψ

Thus, to implement all the possible outcome, actuators for creating independent forces and moments in all directions should be present in a fully functional maritime boat working in six degrees of freedom.

Since most of the marine crafts do not have actuation in all DOFs, so reduced-order models are often utilized while designing feedback control systems. Based on different utilizations, motions of the vessel are usually decoupled according to the following classifications:

2.2.1 1-DOF Models

In designing single control systems such as speed controllers (surge), heading autopilots (yaw), and roll dampers (roll), these models can be used. These models are frequently utilized in simple control system designing of small-scale fishing boats and other similar types of maritime vessels when precision and accuracy are not critical. These ships typically feature a single propeller motor with speed control that may turn at an angle to steer it in a new direction.

2.2.2 3-DOF Models

3-DOF models, which include surge, sway, and yaw, are utilized as horizontal-plane models for ships, semi-submersibles, and underwater vehicles. They are employed in path-following systems, trajectory-tracking control systems, and DP systems. In the case of slender bodies like torpedo shaped AUVs and submarines, the movements can also be separated into vertical and transverse motions.

- **Longitudinal models** (surge, heave, and pitch) for forward propulsion, plunging, and pitch regulation.
- **Lateral models** (sway, roll and yaw) for steering and progressing control.

2.2.3 4-DOF Models

This model is almost like 3-DOF model with an addition of roll factor into the already present model. This is implemented in maneuvering circumstances where the goal is to limit roll by active control of fins, rudders, or liquid tanks stabilization.

2.2.4 6-DOF Models

This is a fully coupled model involving all possible DOFs in a marine vessel, used for simulation and forecasting of coupled vessel motions. These models can also be used in sophisticated control systems for underwater vehicles, that have several degrees of freedoms.

2.3 Coordinate Frames

2.3.1 Cartesian Coordinate Frames

Figure 7 depicts the coordinate reference frames that will be discussed in depth afterwards.

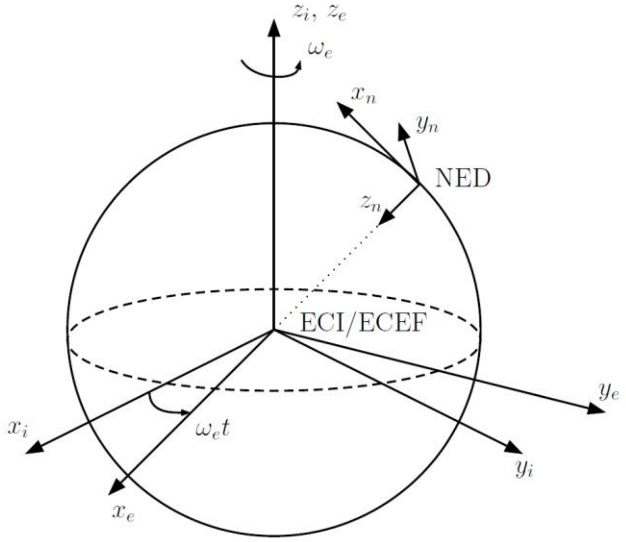

Figure 7: Reference coordinate frames ECI, ECEF & NED

2.3.1.1 Earth Centered Inertial (ECI) frame

This frame is identified by $\mathcal{F}_i$, and has its genesis at the center of the Earth. Its z_i axis is directed towards the vernal equinox, and finally the direction of the y_i axis completes a right-handed orthogonal frame.

2.3.1.2 Earth Centered Earth Fixed (ECEF) frame

This frame has its origin fixed to the center of the Earth, like $\mathcal{F}_i$, and is denoted by $\mathcal{F}_e$. But this frame rotates relative to $\mathcal{F}_i$ with an angular rotation rate $\omega = 7.2921 \times 10^{-5}$ rad/s about the axis z_e, and hence axes z_i and z_e always coincide. The rotation completes one revolution per day, so $\mathcal{F}_i$ and $\mathcal{F}_e$ coincide once per day.

2.3.1.3 North-East Down (NED) frame

This frame is denoted by $\mathcal{F}_n$ and is defined with an origin fixed relative to Earth´s ellipsoid, with x_n pointing towards true North, y_n pointing towards East, and z_n directed downwards, normal to the Earth´s surface. The plane spanned by x_n, y_n is then tangential to the Earth´s surface. For local operations, the frame $\mathcal{F}_n$ may be considered sufficiently fixed to constitute an inertial frame. The origin of the NED frame $\mathcal{F}_n$ relative to $\mathcal{F}_e$ may further be described using classical latitude and longitude parameters.

2.3.1.4 Body frame

The body frame, as illustrated in Figure 8, is attached to the vessel with its origin at a location mid-ship, allowing for a more precise description of the vessel's center of gravity and center of buoyancy. The principal axes for $\mathcal{F}_{b}$ coincides with the vessel’s principal axes of inertia, with x_b in the longitudinal direction (forward positive), y_b in the transversal direction (starboard positive), and finally z_b normal to the vessel (downward positive), completing a right-handed orthogonal frame. Note that the frame $\mathcal{F}_{b}$ refers to the body frame of a general vessel. Throughout the document, the docking vessel and the tugboats will respectively be distinguished with their own respective body frames $\mathcal{F}_{v}$ and $\mathcal{F}_{ti}$, where $i = 1,2,3, \dots, n$, for n tugboats, defined with axes similar as $\mathcal{F}_{b}$.

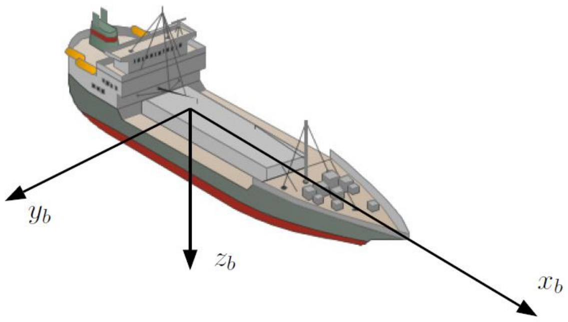

Figure 8: Vessel body reference

2.3.1.5 Port frame

Finally, the port frame $\mathcal{F}_{p}$ is defined, which acts as a reference frame for the docking operation. It is defined with origin at the exact point where the mid-ship point shall be located after completed docking. The axis x_p is directed parallel with the port edge, z_p is directed downwards, and the y_p axis points inward to finish-off a right-handed frame. Hence, when the docking operation is properly completed, the body frame $\mathcal{F}_{b}$ coincides with the port frame $\mathcal{F}_{p}$.

Figure 9 is a representation of all three frames coinciding with each other. To support the mathematical framework, some auxiliary coordinate reference frames are also defined through the text when this is necessary.

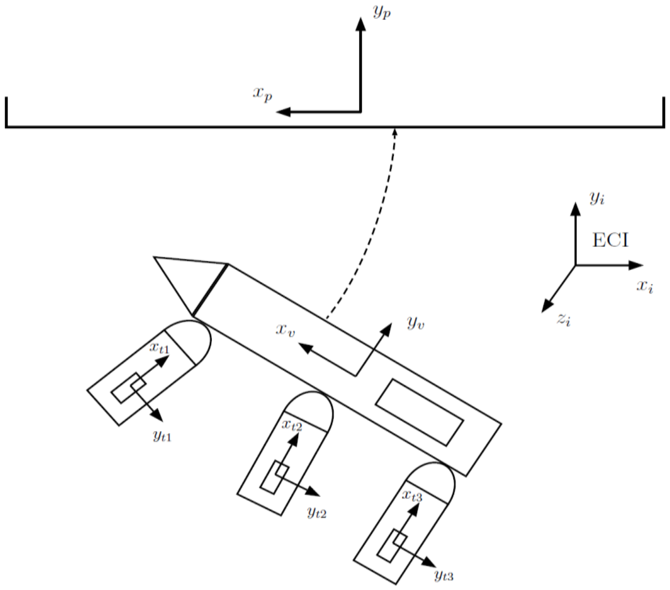

Figure 9: Reference coordinate frames for the vessel and operating tugboats

2.3.2 Coordinate Frame Transformation

The concept of rotation matrices is to employ to perform coordinate transformations and rotations between defined reference frames. The group of rotation matrices consists of 3×3 orthogonal matrices with determinant equal to 1 and is known as the special orthogonal group of third order; $SO(3)$. Since such matrices have the determinant 1, the resulting coordinate transformation or rotation will change the direction of the translated vector without impacting it length. More precisely, coordinate transformations from $\mathcal{F}_{from}$ to $\mathcal{F}_{to}$ are performed with a rotation matrix

$$R^{to}_{from} \in SO(3) = \{R \in R^{3} : R^{\top R} = I, \det \boldsymbol{R} = 1\} \tag{2.3}$$

It is also noted that the inverse rotation is given by the inverse of the rotation matrix, and further simplified to the transpose since the determinant is equal to 1, hence

$$R^{to}_{from} = \left(R^{from}_{to}\right)^{-1} = \left(R^{from}_{to}\right)^{\top} \tag{2.4}$$

2.3.2.1 Transformation between ECI and ECEF

Since $\mathcal{F}_i$ and $\mathcal{F}_e$ have coinciding z-axes, a rotation from the latter to the former is performed as a trivial rotation about this joint axis, based on Earth rotation rate, such that

$$R_i^e = \begin{bmatrix} \cos \omega_e t & -\sin \omega_e t & 0 \\ \sin \omega_e t & \cos \omega_e t & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2.5}$$

where t donates the time since last co-location of frame axes. The reverse rotation is given by the transpose of the matrix, i.e., $R_e^i = (R_i^e)^\intercal$.

2.3.2.2 Transformation between ECEF and NED

The NED frame is a geological frame, and its origin is specified by given latitude μ and longitude ι. The rotation from the $\mathcal{F}_n$ to $\mathcal{F}_e$ is formed by a combination of two principal rotations, and the final matrix is given by

$$R_e^n = \begin{bmatrix} -\cos(\iota)\sin(\mu) & -\sin(\iota) & -\cos(\iota)\cos(\mu) \\ -\sin(\iota)\sin(\mu) & \cos(\iota) & -\sin(\iota)\cos(\mu) \\ -\cos(\mu) & 0 & -\sin(\mu) \end{bmatrix} \tag{2.6}$$

2.3.2.3 Port Frame Transformation

The port frame may also be regarded as a geographical frame, and assuming relative proximity of the port frame origin to the NED frame origin, the axes z_p and z_n will be parallel. Hence, the rotation from $\mathcal{F}_p$ to $\mathcal{F}_n$ is also performed as a trivial rotation of an angle α_p describing the direction of the port edge relative to direction due north, such that

$$R_n^p = \begin{bmatrix} \cos \alpha_p & -\sin \alpha_p & 0 \\ \sin \alpha_p & \cos \alpha_p & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2.7}$$

2.3.2.4 Body Frame Transformation

The rotation of body frame relative to NED frame is described using Euler angles, and to represent $roll, pitch$ and yaw orientations of vessels in $\mathcal{F}_b$, we denote $\boldsymbol{\Theta^b} = [\phi\ \theta\ \psi]^\intercal \in S^3$. Also, we denote angular velocity of $\mathcal{F}_b$ relative to $\mathcal{F}_n$ with $\omega_{\boldsymbol{nb}}^{\boldsymbol{b}} = [p\ q\ r]^\intercal$, and is represented in $\mathcal{F}_n$. We can construct a rotation matrix based on the common zyx-convention from the defined Euler angles, as given below. Note that we will be using $c \cdot$ to represent $\cos(\cdot)$, $s \cdot$ to represent $\sin(\cdot)$, and $t \cdot$ to represent $\tan(\cdot)$.

$$R_n^b = R_{z,\psi} R_{y,\theta} R_{x,\phi} \tag{2.8}$$

$$R_n^b = \begin{bmatrix} c\psi\, c\theta & -s\psi\, c\phi + c\psi\, s\theta\, s\phi & s\psi\, s\phi + c\psi\, c\phi\, s\theta \\ s\psi\, c\theta & c\psi\, c\phi + s\phi\, s\theta\, s\psi & -c\psi\, s\phi + s\theta\, s\psi\, c\phi \\ -s\theta & c\theta\, s\phi & c\theta\, c\phi \end{bmatrix} \tag{2.9}$$

Accordingly, Euler angle rates with angular velocities related by the attitude kinematics are described as

$$\dot{\Theta} = T_{\Theta}\,(\Theta^b)\,\omega_{nb}^b \tag{2.10}$$

$$T_{\Theta}\,(\Theta^b) = \begin{bmatrix} 1 & s\psi\, t\theta & c\phi\, t\theta \\ 0 & c\phi & -s\phi \\ 0 & s\phi/c\theta & c\phi/c\theta \end{bmatrix} \tag{2.11}$$

The inverse relation can be described as following

$$\omega_{nb}^b = T_{\Theta}^{-1}\,(\Theta^b)\,\dot{\Theta} \tag{2.12}$$

$$T_{\Theta}^{-1}\,(\Theta^b) = \begin{bmatrix} 1 & 0 & -s\theta \\ 0 & c\phi & c\theta\, s\phi \\ 0 & -s\phi & c\theta\, c\phi \end{bmatrix} \tag{2.13}$$

Similarly, the position of body frame $\mathcal{F}_{b}$ relative to NED frame $\mathcal{F}_n$, which is representing $surge,\ sway\ and\ heave$ motion, is denoted by $p^n = [x_n\ y_n\ z_n]^{\top}$, similarly, $p^b = [x_b\ y_b\ z_b]^{\top}$ denotes body frame $\mathcal{F}_{b}$ relative to $\mathcal{F}_{b}$. The corresponding velocity will be $v^b = [u_b\ v_b\ w_b]^{\top}$, hence

$$\dot{p}^n = R_b^n\, v^b \tag{2.14}$$

$$v^b = (R_b^n)^{-1}\,\dot{p}^n = R_n^b\,\dot{p}^n \tag{2.15}$$

Thus, we can derive the total 6DOF kinematics and can write it with $\nu = \left[(v^b)^{\top}\ \left(\omega_{nb}^b\right)^{\top}\right]^{\top}$ and $\eta = [(p^n)^{\top}\ (\Theta^b)^{\top}]^{\top}$, such that

$$\dot{\eta} = J_{\Theta}\,\nu \tag{2.16}$$

$$J_{\Theta} = \begin{bmatrix} \boldsymbol{R_b^n} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{T_{\Theta}} \end{bmatrix} \tag{2.17}$$

where J_{Θ} is the transformation matrix, used for describing the two forms and simplifying the procedures of transformations in eq. (2.12, 2.13) and eq. (2.14, 2.15).

2.4 Basic Spline Theory

A navigational guidance system that can define a reference path for the ship is necessary for docking on the port. This will aid the ship controller in guiding the ship to the port in a smooth and efficient manner. Such a system necessitates an autonomous trajectory-building phenomena capable of predicting the whole course in real time based on the ship's present location and final distance. These devices are already in use in flights, assisting pilots in predicting their route to their destination. As a result, an air-highway was built for the plane. Navel boats are also being fitted with similar technology. There are several techniques available to provide such systems that can predict the path trajectory in real-time.

In mathematics, a spline is a particular function defined piecewise using polynomials. Even when low degree polynomials are used, this method is preferred over polynomial interpolation because it yields piecewise continuous functions with many polynomials, as seen in Figure 10. As a result, Runge's phenomenon for higher degree polynomials is avoided, and the dataset is less likely to include mistakes [30].

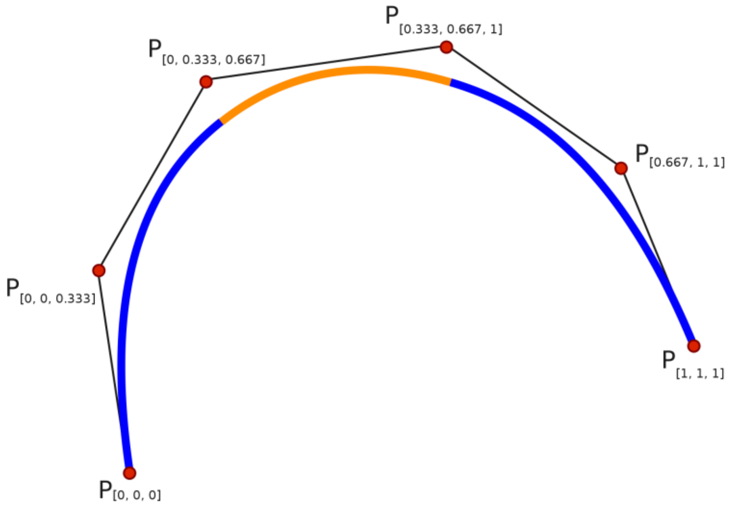

Figure 10: Parametric cubic spline [30]

In the modern era of computer technologies, the term spline is more frequently used to define computer graphics and designing. Designers use splines to make piece-wise parametric curves, hence they are creating simplicity for the construction works due to their ease and accuracy of evaluation, and capacity to approximate complicated shapes utilizing curve fitting and engaging curve designing. They have a key-role for designing being done in constructions and buildings.

Splines also comes in handy for shipbuilders and draftsmen as they use a flexible spline device to draw smooth shapes. Now, the splines can be used to make algorithms for ship's navigational systems, that can not only assist the captains of the ship but can also optimize the overall route of the ship. This system can become vital in docking operations as it can be implemented on the tugboats as well. Thus, the whole port operation and the complete journey of the ships can be predicted and planned accordingly. Figure 11 depicts an autonomous ship that employs a network of sensors to forecast its path and give an effective navigating algorithm.

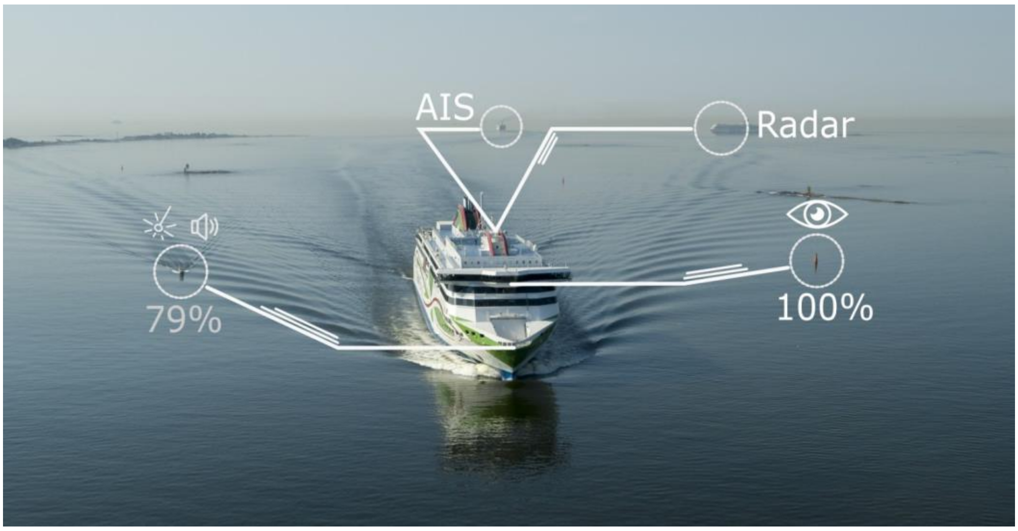

Figure 11: Autonomous ship with sensor-based navigational system [31]

Splines are of different forms, and they are categorized according to their characteristics. They are also named associated with different facts, like:

- Spline Representation
    - **B-Splines**, uses basis functions for entire spline.
    - **Bezier Splines**, uses Bernstein Polynomials (by Pierre Bezier) to each polynomial piece.
- Extended Knot Vector Formation
    - **Uniform Splines**, uses single knots for C^{n-1} continuity and spacing these knots evenly on $[a, b]$.
    - **Non-Uniform Splines**, uses knots on spacing with no restrictions.
- Imposition of Special Conditions
    - **Natural Splines**, enforces zero second derivatives at $a \text{ and } b$.
    - **Interpolating Splines**, given data values are required in the spline.

Interpolating splines is the one that is mostly used in guidance and navigation systems. Furthermore, there is a special case for Spline Interpolation, known as Cubic Spline Interpolation, which produces a smoother interpolating polynomial, that has lower error then other interpolating polynomials such as Lagrange polynomial and Newton polynomial. This method is often used to avoid the problem of Runge's phenomenon.

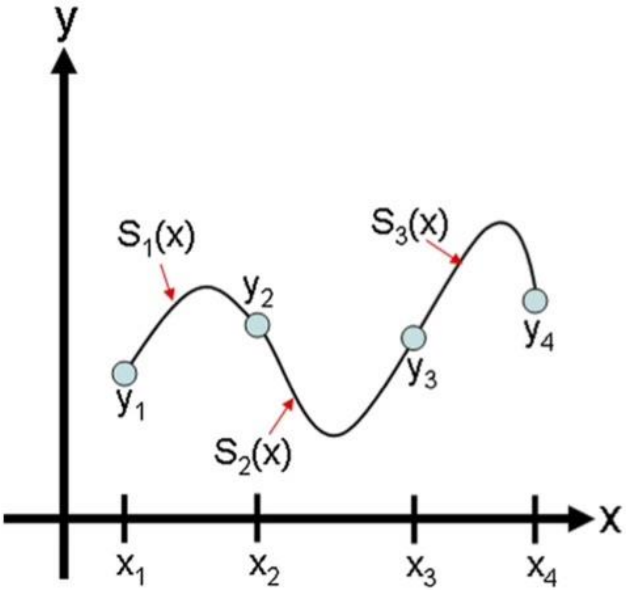

Figure 12: Cubic spline interpolation *[32]*

Assume that the points (x_i, y_i) and (x_{i+1}, y_{i+1}) similar to the points in Figure 12, are joined by a cubic polynomial $S_i(x) = a_i x^3 + b_i x^2 + c_i x + d_i$ that is valid for $x_i \leq x \leq x_{i+1}$ for $i = 1, \dots, n-1$. To find the interpolating function, the coefficients $a_i, b_i c_i, d_i$ for each cubic function must be determined first. For n points, there are $n-1$ cubic functions to find, and each cubic function requires four coefficients. Therefore, there is a total of $4(n-1)$ unknowns, and so $4(n-1)$ independent equations are needed to find all the coefficients.

First, the cubic functions must intersect the data points on the left and the right:

$$S_i(x_i) = y_i, i = 1, \dots, n-1, \tag{2.18}$$

$$S_i(x_{i+1}) = y_{i+1}, i = 1, \dots, n-1 \tag{2.19}$$

which gives us $2(n-1)$ equations.

Next, each cubic function should join smoother with its neighbors as feasible, so splines are constrained to have continuous first & second derivatives at the sample points $i = 2, \dots, n-1$.

$$S_i'(x_{i+1}) = S_{i+1}'(x_{i+1}), \qquad i = 1, \dots, n-2, \tag{2.20}$$

$$\mathrm{S_i''(x_{i+1}) = S_{i+1}''(x_{i+1}), \qquad i = 1, \dots, n-2,} \tag{2.21}$$

which gives us $2 \cdot (n-2)$ equations.

Two further equations are necessary to obtain the coefficients of $Si(x)$. These latter two constraints are flexible, and they can be chosen to suit the conditions of the interpolation being performed. A common set of final restrictions is to assume that the second derivatives are zero at the endpoints. This signifies that the curve is a “straight line” at the end points. An example is given in Figure 13. Explicitly,

$$S_1''(x_1) = 0, \tag{2.22}$$

$$S_{n-1}''(x_n) = 0. \tag{2.23}$$

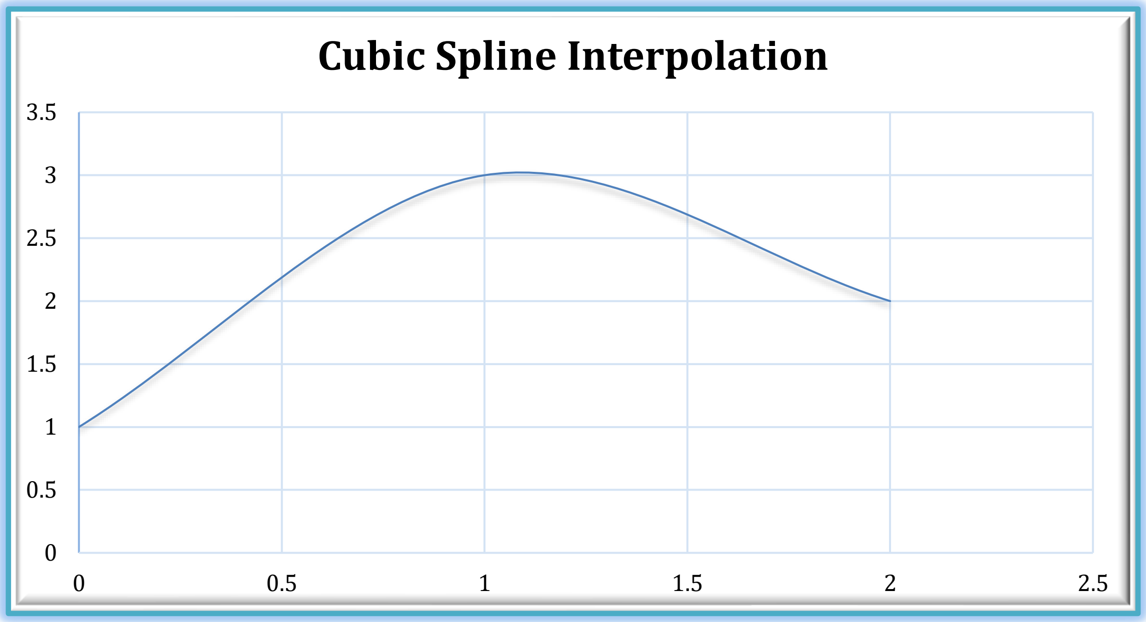

Figure 13: Representation of cubic spline interpolation

To determine the coefficients of each cubic function, the constraints are written specifically as a system of linear equations with $4(n-1)$ unknowns. For n data points, the unknowns are the coefficients a_i, b_i, C_i, d_i of the cubic spline, S_i joining the points x_i and x_{i+1}.

For the constraints $S_i(x_i) = y_i$, given:

$$a_1x_1^3 + b_1x_1^2 + c_1x_1 + d_1 = y_1, \tag{2.24}$$

$$a_2x_2^3 + b_2x_2^2 + c_2x_2 + d_2 = y_2, \tag{2.25}$$

$$\dots$$

$$a_{n-1}x_{n-1}^3 + b_{n-1}x_{n-1}^2 + c_{n-1}x_{n-1} + d_{n-1} = y_{n-1}. \tag{2.26}$$

For the constraints $S_i(x_{i+1}) = y_{i+1}$, given:

$$a_1x_2^3 + b_1x_2^2 + c_1x_2 + d_1 = y_2, \tag{2.27}$$

$$a_2x_3^3 + b_2x_3^2 + c_2x_3 + d_2 = y_3, \tag{2.28}$$

$$\dots$$

$$a_{n-1}x_n^3 + b_{n-1}x_n^2 + c_{n-1}x_n + d_{n-1} = y_n. \tag{2.29}$$

For the constraints $S_i'(x_{i+1}) = S_{i+1}'(x_{i+1})$, given:

$$3a_1x_2^2 + 2b_1x_2 + c_1 - 3a_2x_2^2 - 2b_2x_2 - c_2 = 0, \tag{2.30}$$

$$3a_2x_3^2 + 2b_2x_3 + c_2 - 3a_3x_3^2 - 2b_3x_3 - c_3 = 0,$$

$$\dots$$

$$3a_{n-2}x_{n-1}^2 + 2b_{n-2}x_{n-1} + c_{n-2} - 3a_{n-1}x_{n-1}^2 - 2b_{n-1}x_{n-1} - c_{n-1} = 0. \tag{2.31}$$

For the constraints $S_i''(x_{i+1}) = S_{i+1}''(x_{i+1})$, given:

$$6a_1x_1 + 2b_1 - 6a_2x_2 - 2b_2 = 0, \tag{2.32}$$

$$6a_2x_3 + 2b_2 - 6a_3x_3 - 2b_3 = 0, \tag{2.33}$$

$$\dots$$

$$6a_{n-2}x_{n-1} + 2b_{n-2} - 6a_{n-1}x_{n-1} - 2b_{n-1} = 0. \tag{2.34}$$

Finally for endpoint constraints $S_1''(x_1) = 0$ and $S_{n-1}''(x_n) = 0$, given:

$$6a_1x_1 + 2b_1 = 0, \tag{2.35}$$

$$6a_{n-1}x_n + 2b_{n-1} = 0. \tag{2.36}$$

These equations are linear in the unknown coefficients a_i, b_i, c_i and d_i. These can be put in matrix form and solved for the coefficients of each spline by left division. Whenever the matrix equation $Ax = b$ for x is solved, A must be a square and invertible and will always be like that until the x_i values in the data set are unique in case of finding cubic spline equations [32].

3 Mathematical Modelling

3.1 Vessel Models

3.1.1 Full 6-DOF Model

By using the handbook, maneuvering theory is studied briefly and is implemented, as a base for dynamic model of vessels, which is considered the most suitable framework for this application [27]. Therefore, the full 6-DOF vessel model is as follows

$$\dot{\eta} = J_{\Theta}\, \nu \tag{3.1}$$

$$M\, \dot{\nu} + C(\nu)\, \nu + D(\nu)\, \nu + g(n) = \tau_c + \tau_{\omega} \tag{3.2}$$

where M is the mass/ inertia matrix, $C(\nu)$ represents Coriolis and centripetal forces, $D(\nu)$ represents damping effects, and $g(\eta)$ is a vector of gravitational/buoyancy forces and moments. The parameters τ_c represents control inputs, while τ_{ω} is a vector of wind and wave-induced forces.

In particular, the mass/inertia matrix may be written as $M = M_{rb} + M_a$, separated into rigid mass/inertia and added mass. The rigid body matrix can be written as

$$M_{rb} = \begin{bmatrix} m\boldsymbol{I} & -m\boldsymbol{S}\left(\boldsymbol{r}_{\boldsymbol{g}}^{\boldsymbol{b}}\right) \\ m\boldsymbol{S}\left(\boldsymbol{r}_{\boldsymbol{g}}^{\boldsymbol{b}}\right) & \boldsymbol{J} \end{bmatrix} \tag{3.3}$$

where m is the total mass of the vessel, J is the vessel inertia matrix, $r_g^b = \left[r_{gx}\; r_{gy}\; r_{gz}\right]^{\top}$ is the location of the center of gravity with respect to origin of $\mathcal{F}_{b}$ and $S(\cdot)$ operator representing $S(x)y = x \times y$, such that

$$S\left(r_g^b\right) = \begin{bmatrix} 0 & r_{gz} & -r_{gy} \\ -r_{gz} & 0 & r_{gx} \\ r_{gy} & -r_{gx} & 0 \end{bmatrix} \tag{3.4}$$

If the origin of $\mathcal{F}_{b}$ coincides with center of gravity, $r_g^b = 0$ and rigid body matrix simplifies to

$$M_{rb} = \begin{bmatrix} m\boldsymbol{I} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{J} \end{bmatrix} \tag{3.5}$$

Added mass M_a represents the necessary force for acceleration the stationary fluid around the vessel hull, which is significant since the docking vessel is being forced to move sideways (i.e., tugboat push/pull). In general, the matrix M_a is represented as:

$$M_a = -\begin{bmatrix} X_{\dot{u}} & X_{\dot{v}} & X_{\dot{w}} & X_{\dot{p}} & X_{\dot{q}} & X_{\dot{r}} \\ Y_{\dot{u}} & Y_{\dot{v}} & Y_{\dot{w}} & Y_{\dot{p}} & Y_{\dot{q}} & Y_{\dot{r}} \\ Z_{\dot{u}} & Z_{\dot{v}} & Z_{\dot{w}} & Z_{\dot{p}} & Z_{\dot{q}} & Z_{\dot{r}} \\ K_{\dot{u}} & K_{\dot{v}} & K_{\dot{w}} & K_{\dot{p}} & K_{\dot{q}} & K_{\dot{r}} \\ M_{\dot{u}} & M_{\dot{v}} & M_{\dot{w}} & M_{\dot{p}} & M_{\dot{q}} & M_{\dot{r}} \\ N_{\dot{u}} & N_{\dot{v}} & N_{\dot{w}} & N_{\dot{p}} & N_{\dot{q}} & N_{\dot{r}} \end{bmatrix} \tag{3.6}$$

The matrix parameters denote the added mass force / moment in specific directions due to accelerations in specific directions, such that e.g.,

$$X = -X_{\dot{u}}\dot{u}, \qquad X_{\dot{u}} = \frac{\partial X}{\partial \dot{u}} \tag{3.7}$$

and likewise for other parameters.

The matrix representing Coriolis and centripetal forces/moments may be similarly separated into a rigid-body part and an added-mass part, such that $C(\mathrm{v}) = \mathrm{C}_{\mathrm{rb}}(\mathrm{v}) + C_a(\mathrm{v})$. The former may be expressed using LaGrange parametrization as

$$C_{rb}(\mathrm{v}) = \begin{bmatrix} 0_{3x3} & -mS(\mathrm{v}^b) - mS(\omega_{nb}^b)S(r_g^b) \\ -mS(\mathrm{v}^b) - mS(r_g^b)S(\omega_{nb}^b) & -S(\mathrm{J}\omega_{nb}^b) \end{bmatrix} \tag{3.8}$$

Or in a velocity-independent Newton-Euler representation as

$$C_{rb}(\mathrm{v}) = \begin{bmatrix} 0_{3x3} & -mS(\omega_{nb}^b)S(r_g^b) \\ mS(r_g^b)S(\omega_{nb}^b) & -S(\mathrm{J}\omega_{nb}^b) \end{bmatrix} \tag{3.9}$$

Coriolis and centripetal forces/moments resulting from added mass may be expressed based on the added-mass matrix, such that if $M_a = \{a_{ij}\}, i = 1{,}2$ with $a_{ij} \in \mathrm{R}^{3x3}$, then

$$C_a(\mathrm{v}) = \begin{bmatrix} 0 & -S(a_{11}\mathrm{v}^b + a_{12}\omega_{nb}^b) \\ -S(a_{11}v^b + a_{12}\omega_{nb}^b) & -S(a_{21}v^b + a_{22}\omega_{nb}^b) \end{bmatrix} \tag{3.10}$$

Hydrodynamic damping effects on surface ships in fluids is complex, and are caused by potential damping, skin friction, wave drift damping, vortex shedding and lifting forces. Total hydrodynamic can, in the absence of ocean currents be conveniently written as $D(\mathrm{v}) = D +$

$D_n(\nu)$; that is a sum of a linear damping matrix D formed by potential damping and skin friction, and a nonlinear damping matrix $D_n(\nu)$ caused by quadratic damping and higher order terms. Linear viscous damping with decoupled surge dynamics and an assumption of port/starboard symmetry can be written as

$$D = -\begin{bmatrix} X_u & 0 & 0 & 0 & 0 & 0 \\ 0 & Y_v & 0 & Y_p & 0 & Y_r \\ 0 & 0 & Z_w & 0 & Z_q & 0 \\ 0 & K_v & 0 & K_p & 0 & K_r \\ 0 & 0 & M_w & 0 & M_q & 0 \\ 0 & N - v & 0 & N_p & 0 & N_r \end{bmatrix} \tag{3.11}$$

where the parameters relate damping effects to specific (angular) velocities, like added mass, such that

$$X = -X_u u, \qquad X_u = \frac{\partial X}{\partial u} \tag{3.12}$$

and likewise for the other parameters. The diagonal damping terms may be estimated using fixed time constants $T\ \cdot$, relative damping ratios $\zeta\ \cdot$, additional damping $\Delta\zeta\ \cdot$, natural frequencies $\omega\ \cdot$ and the natural periods $T_{n,}\cdot$, such that

$$-X_u = \frac{m + A_{11}(0)}{T_{surge}} = \frac{8\pi\zeta_{surge}\left(m + A_{11}(0)\right)}{T_{n,surge}} \tag{3.13}$$

$$-Y_v = \frac{m + A_{22}(0)}{T_{sway}} = \frac{8\pi\zeta_{sway}\left(m + A_{22}(0)\right)}{T_{n,sway}} \tag{3.14}$$

$$-Z_w = 2\Delta\zeta_{heave}\omega_{heave}\left(m + A_{33}(\omega_{heave})\right) \tag{3.15}$$

$$-K_p = 2\Delta\zeta_{roll}\omega_{roll}\left(I_x + A_{44}(\omega_{roll})\right) \tag{3.16}$$

$$-M_q = 2\Delta\zeta_{pitch}\omega_{pitch}\left(I_y + A_{55}\left(\omega_{pitch}\right)\right) \tag{3.17}$$

$$-N_r = \frac{I_z + A_{66}(0)}{T_{yaw}} = \frac{8\pi\zeta_{yaw}\left(I_z + A_{66}(0)\right)}{T_{n,yaw}} \tag{3.18}$$

The nonlinear damping matrix may be expressed using quadratic drag formulas as

$$D_n(\nu) = -\begin{bmatrix} X_{|u|u}|u| & 0 & 0 & 0 & 0 & 0 \\ 0 & Y_{|v|v}|v| + Y_{|r|v}|r| & 0 & 0 & 0 & X_{|v|r}|v| + Y_{|r|r}|r| \\ 0 & 0 & X_{|w|w}|w| & 0 & 0 & 0 \\ 0 & 0 & 0 & K_{|p|p}|p| & 0 & 0 \\ 0 & 0 & 0 & 0 & M_{|q|q}|q| & 0 \\ 0 & N_{|v|v}|v| + N_{|r|v}|r| & 0 & 0 & 0 & X_{|v|r}|v| + X_{|r|r}|r| \end{bmatrix} \quad (3.19)$$

Finally, the vector $g(\eta)$ of gravitational/buoyancy forces and moments is composed of the restoring forces δf_r^b and the restoring moments m_r^b. The derivation is based on Archimedes fact that buoyancy and weight are in balance, such that $mg = \rho g \nabla$, with m as mass, g as gravity constant, ρ as water density and ∇ as the nominal displaced water volume. Restoring forces are given by the relation

$$\delta f_r^b = R_n^b \begin{bmatrix} 0 \\ 0 \\ -\rho g \int_0^{zd} A_{wp}(\zeta) d \end{bmatrix} \quad (3.20)$$

With z_d as heave displacement and $A_{wp}(\zeta)$ as the water plane area of the vessel as a function of the heave position. Further, the moment arms in roll and pitch are written as

$$r_r^b = \begin{bmatrix} -\overline{GM_L} sin(\theta) \\ \overline{GM_T} sin(\phi) \\ 0 \end{bmatrix} \quad (3.21)$$

where $\overline{GM_L}$ and $\overline{GM_T}$ are the longitudinal and transverse metacentric heights, respectively.

Also, the restoring force vector is written as

$$m_r^b = r_r^b \times f_r^b \quad (3.22)$$

with

$$f_r^b = R_n^b \begin{bmatrix} 0 \\ 0 \\ -\rho g \nabla \end{bmatrix} \quad (3.23)$$

Which finally enables composing the full vector of restoring forces and moments as

$$g(\eta) = -\begin{bmatrix} \delta f_r^b \\ m_r^b \end{bmatrix} \quad (3.24)$$

3.1.2 Simplified 3 DOF Model

To simplify the model and fulfil the purpose, neglect vertical motion (heave) as well as rotations out of plane (roll and pitch). This reduces state space to $\eta = [x_n \; y_n \; \psi]^{\intercal}$, so model becomes

$$\dot{\eta} = R_{z,\psi} \nu \tag{3.25}$$

$$M\dot{\nu} + C(\nu) + D(\nu)\nu + g(\nu) = \tau_c + \tau_\omega \tag{3.26}$$

The system matrices are then reduced according to subsets, which through homogeneous mass distributions and port/starboard symmetry, may be further simplified.

The 3DOF model makes the calculations easier for us as we can neglect several calculations and is feasible as in the current phase of project when we only need to predict the path of the docking vessel as well as the tugboats. Once we are done with these initial phases, we should move back to the 6DOF system as we must consider all the possibilities of movement for the vessel as well as the tugboats.

3.2 Vessel / Tugboat Interaction

The relation between tugboat and the vessel, when they interact with each other during a docking operation, is discussed in detail in reference to the information provided in the handbook [27] and relevant equations for forces and moments are derived, which will be utilized in the mathematical model of the whole system.

3.2.1 Relation between tugboats and vessel

Figure 14 describes the relative distance relation between a tugboat and the vessel. In general, d_{xti} is defined as the distance between the vessel's center of gravity and frontal hull point of i'th tugboat along x_b axis, and d_{yti} is the distance between the vessel's center of gravity and frontal hull point of $i'th$ tugboat along y_b axis. The pushing force of the i'th boat is defined by f_i, and the inclination angle by α_i. So, the pushing force f_i is normal to vessel when the inclination angle $\alpha_i = 90°$.

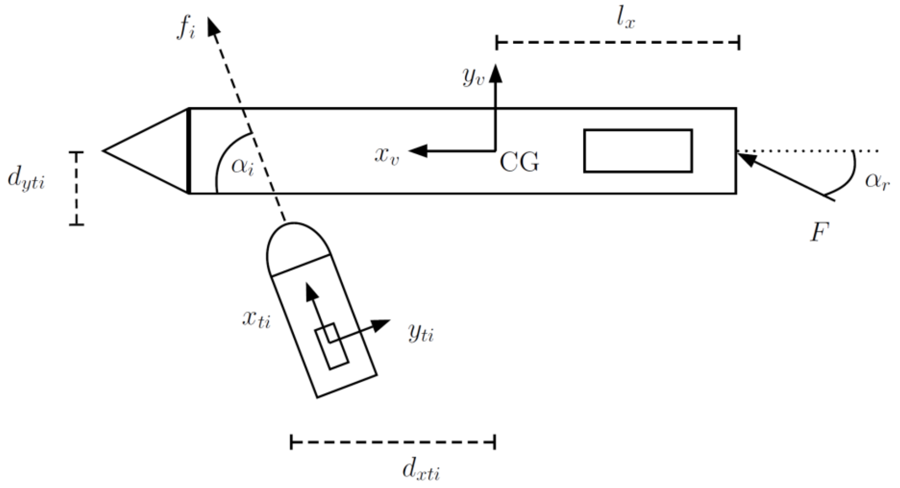

Figure 14: Vessel and tugboat relative distance description

3.2.2 Forces and moments

The control forces and moments working on the vessel, which are self-provided, as well as from push/pull given by tugboats, are described by the vector τ_c. These are split into two parts, vessel forces and moments given by its own actuator configuration and represented by τ_v, and the additional forces and moments provided by the tugboats which is represented by τ_t. The general form of the vessel control input is given by

$$\tau_v = \begin{bmatrix} \boldsymbol{f}_v \\ \boldsymbol{r}_v \times \boldsymbol{f}_v \end{bmatrix} = \begin{bmatrix} F_x \\ F_y \\ F_z \\ F_z l_y - F_y l_z F_y l_x - F_x l_y \end{bmatrix} \tag{3.27}$$

with $f_v = [F_x\ F_y\ F_z]^\intercal$ as force vector and $r_v = [l_x\ l_y\ l_z]$ as moment arms. Vessels within current scope of work is usually equipped with propellers and rudders mounted centered aft, which provides a longitudinal and lateral forces together with a yawing moment depending on the rudder angle. The force components $F_x = F\cos(\alpha_r)$, $F_y = F\sin(\alpha_r)$ and $F_z = 0$, are obtained from the rudder angle α_r and the propeller thrust force F. Similarly, the moment components $M_x = 0, M_y = 0$ and $M_z = F_y l_x$, are also obtained. Hence,

$$\tau_v = \begin{bmatrix} F\cos(\alpha_r) \\ F\sin(\alpha_r) \\ 0 \\ 0 \\ 0 \\ F l_x \sin(\alpha_r) \end{bmatrix} \tag{3.28}$$

Forces and moments enacted by the tugboats are dependent on location and inclination angle of the tugboats, for simplicity, only longitudinal and lateral forces are assumed, along with a yawing moment, are provided by tugboats with the aft propeller configuration. Particularly, a force f_i will be provided with an inclination of α_i, when the i'th tugboat is in a proper location, such that [33]:

$$\tau_{ti} = B(\alpha_i)f_i \tag{3.29}$$

$$B(\alpha_i)f_i = \begin{bmatrix} \cos \alpha_i \\ \sin \alpha_i \\ 0 \\ 0 \\ 0 \\ -d_{yti}\cos(\alpha_i) + d_{xti}\sin(\alpha_i) \end{bmatrix} \tag{3.30}$$

Moreover, the total contribution of forces and moments from n tugboats can be obtained as

$$\tau_t = \sum_{i=1}^{n} \tau_{ti} = \sum_{i=1}^{n} (\alpha_i)f_i \tag{3.31}$$

which may further be reduced to fit the simplified 3DOF model considering surge, sway, and yaw only.

4 Simulation and Results

4.1 Simulation Modelling

The whole model was simulated using MATLAB and Simulink. This model was designed using all the research work done during mathematical modelling. In the designing of this project, a special library made by Fossen, named as “Marine System Simulator (MSS)” toolbox was used [28]. This library is designed to provide different functions that relate to most of the equations mentioned in the second and third chapter.

The model consists of following components which are connected to together to give the required system providing the desired results:

4.1.1 Vessel Model

The ship model, as illustrated in Figure 15, is the most important aspect of the system since it reflects the ship's actual structure. The model will react in the same way as a real ship will do when specific inputs are given to the model. Real environmental and climatic disturbances, are fed to the model so the model can respond like the real ship vessel. In current scenario, a tanker vessel model is considered in the simulations. The control value of this model is the torque τ, which is responsible for controlling the velocity parameters ν of the ship, hence this velocity is responsible for change in position and orientation parameters η. The system outputs change in velocities ν´ and change in position and orientation η′ in response to the torque fed to it. Furthermore, it needs feedback input of ν and η, which makes the system a closed-feedback loop.

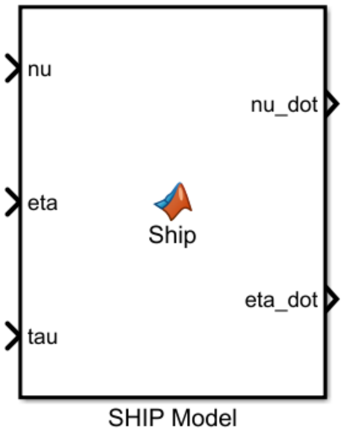

Figure 15: Vessel model block

4.1.2 Controller

A ship itself cannot operate without any control parameters, so the torque input of the ship model needs to be controlled by a controller accordingly to get the desired results. The controller is responsible for providing specific torque signal to the ship according to the desired velocities, position, and orientation. Furthermore, it is also responsible for stabilizing the output of the model. The controller looks for the difference between desired and actual output of the model and generates an error signal which it uses to stabilize the system. Controller can be of different types depending on the gain constant values, i.e., proportional gain K_p, integral gain K_i, and differential controller K_d. Based on these values, we have three different kinds of controllers, i.e., PD, PI or PID controller. To regulate and stabilize the model, we are currently employing a PD controller, as illustrated in Figure 16.

A PD controller can be represented by it transfer function:

$$K(s) = k_p + k_d s = k_d \left(s + \frac{k_p}{k_d}\right) \tag{4.1}$$

Thus, a single zero is added to the loop transfer function by a PD controller. The phase contribution of the PD controller increases from 0° at low frequencies to 90° at high frequencies.

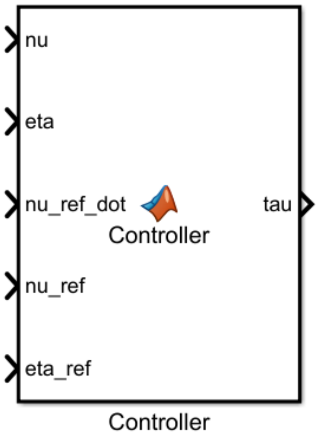

Figure 16: PD-controller block

4.1.3 Reference Tracker

The reference tracker, also known as the reference provider, is a sub-system that is responsible for delivering a reference path to the controller, as shown in Figure 17. It keeps track of the current parameters of the ship model and provides the reference parameters accordingly to the controller.

As the model approaches the desired reference parameters, it sends a signal to the trajectory source that the reference point has reached. This sub-system receives a reference η value from a source and outputs the desired η′ and ν′. These parameters are also fed back to the sub-system to minimize the error in them.

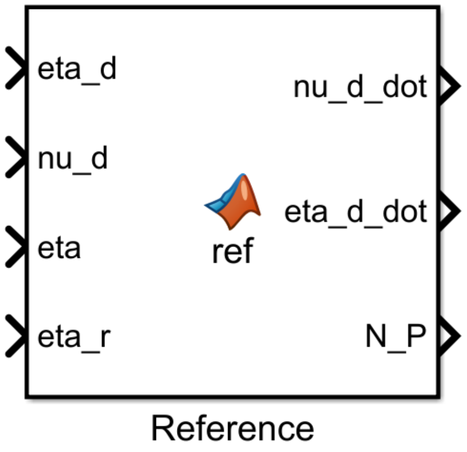

Figure 17: Reference tracker block

4.1.4 Spline Trajectory

The route direction for the entire system is provided by the Spline Trajectory sub-system, as shown in Figure 18. The algorithm in this block creates a path that needs to be followed by the ship. It has coordinated points assigned inside it, which are needed to be followed. Based on these points, the sub-system generates a path trajectory using the spline theory. This trajectory is divided into several position and orientation points η, which are fed to the system point by point, according to the count number provided into its input.

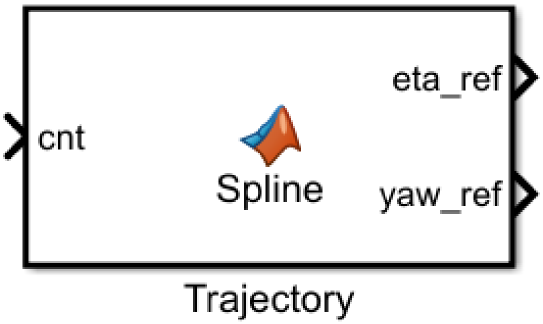

Figure 18: Spline trajectory block

4.1.5 Counter

Figure 19 shows a counter subsystem shown in figure is like a triggered step-up counter, which counts one integer up with every signal pulse received at its input. The counter is playing an important part in the guidance system as it provides the count number to the controller denoting the index number of the point on the trajectory. The input N_P denotes Next Point, which means that with every N_P pulse a new reference point is needed along the reference trajectory.

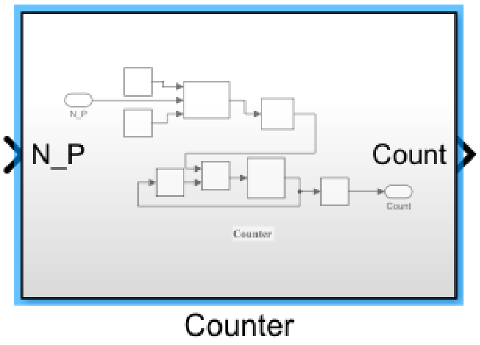

Figure 19: Pulse triggered step-up counter block

The block, as shown in Figure 20, is constructed using a basic logic that adds an integer '1' to the counting with each pulse input. This is achieved by using a triggered two way switch whose first input is ‘0’ when the control value is zero and ‘1’ when control value is one. This output from the switch is fed to the sum block, but there is a delay block in between which solves the overlap data problem. The second input of the sum block is a feedback loop from its output. This loop cannot be directly fed but also needs a memory block in between to store the last value. In addition to this, an initial condition block is also being used just after the output of sum block to provide an initial value of ‘1’ for the counter so it does not start from ‘0’. There is also a need of a saturation limiter to keep the values within the range of spline trajectory maximum points.

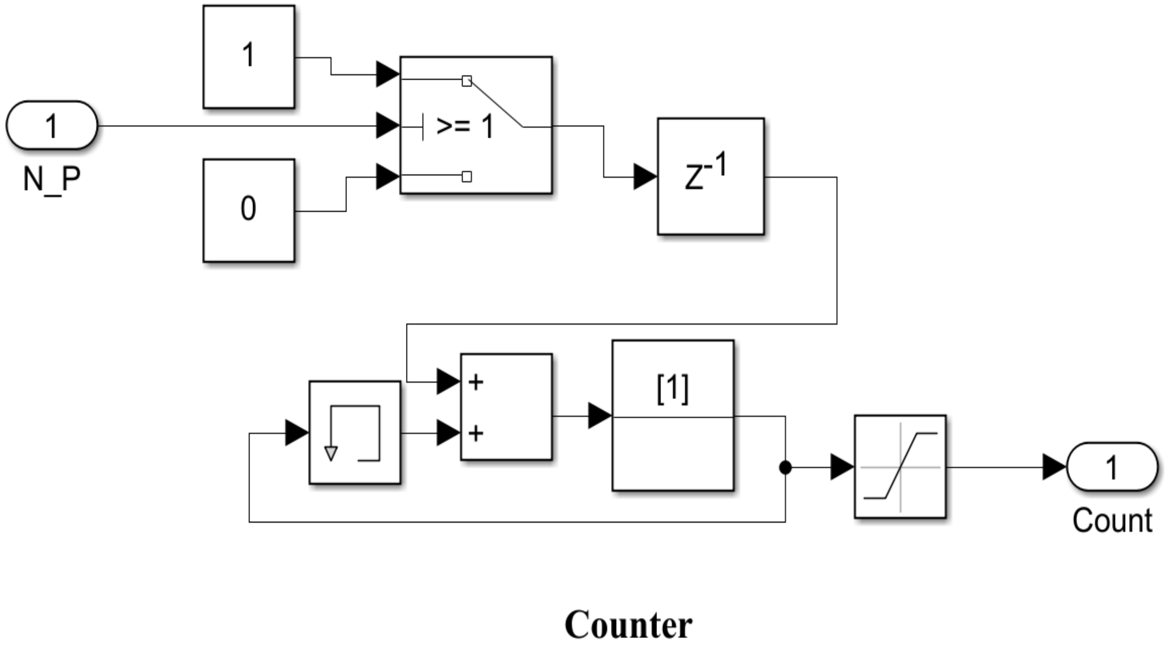

Figure 20: Internal sub-system of the counter

4.1.6 Full System Simulation Model

The system is in operation when all the sub-system blocks are connected in a proper manner and finely tuned. The system starts with the counter sending the next way point number when being triggered by the reference tracker. The spline trajectory subsystem provides the waypoints in the form of reference eta η_r to the reference tracker in accordance with the counter number. Reference yaw rate can also be observed from this block.

The η_r being fed to the reference tracker subsystem is tracked with the actual response eta η from the ship model and a change in desired eta η_d' is generated along with the change in desired velocity parameter ν_d'. These outputs after passing from integrators to provide η_d and ν_d along with standalone ν_d', are fed to the controller. Furthermore, η_d and ν_d are also feedbacked to the reference tracker to complete the closed feedback loop of this subsystem. Counter is also provided with a Next Way Point signal every time a reference point is reached

The controller is responsible for providing required torque to the model to control its maneuverability according to the desired position, angle, velocity, and acceleration parameters provided by the reference tracker. It also takes response feedback from the ship model to minimize errors.

Ship model is only receiving forces and moments in the form of torque from the controller along with feedback parameters and provides a reaction response in the form of change in positions, angle, and velocities. These parameters pass through integrators to provide current positions, angle, and velocities of the ship.

During the implementation there were number of variables set inside the system to provide physical characteristics of the ship, and the characteristics of the controller. Some of these are assumed values and many others resemble to practical values. Many of them were derived from the MSS toolbox [28] using built-in functions.

The whole system is being represented in Figure 21, which also includes the navigational guidance sub-system. In this model, scopes may also be joined at multiple points to check for outcomes. Except for the counter block, which has additional block implementations, all the sub-systems in this architecture are created using MATLAB Functions. Few of the control parameters used in this simulation model are given in Table 2. All other equations implemented are based on the derived mathematical models from chapter 3 and few are based on research work from the preliminaries mentioned in chapter 2.

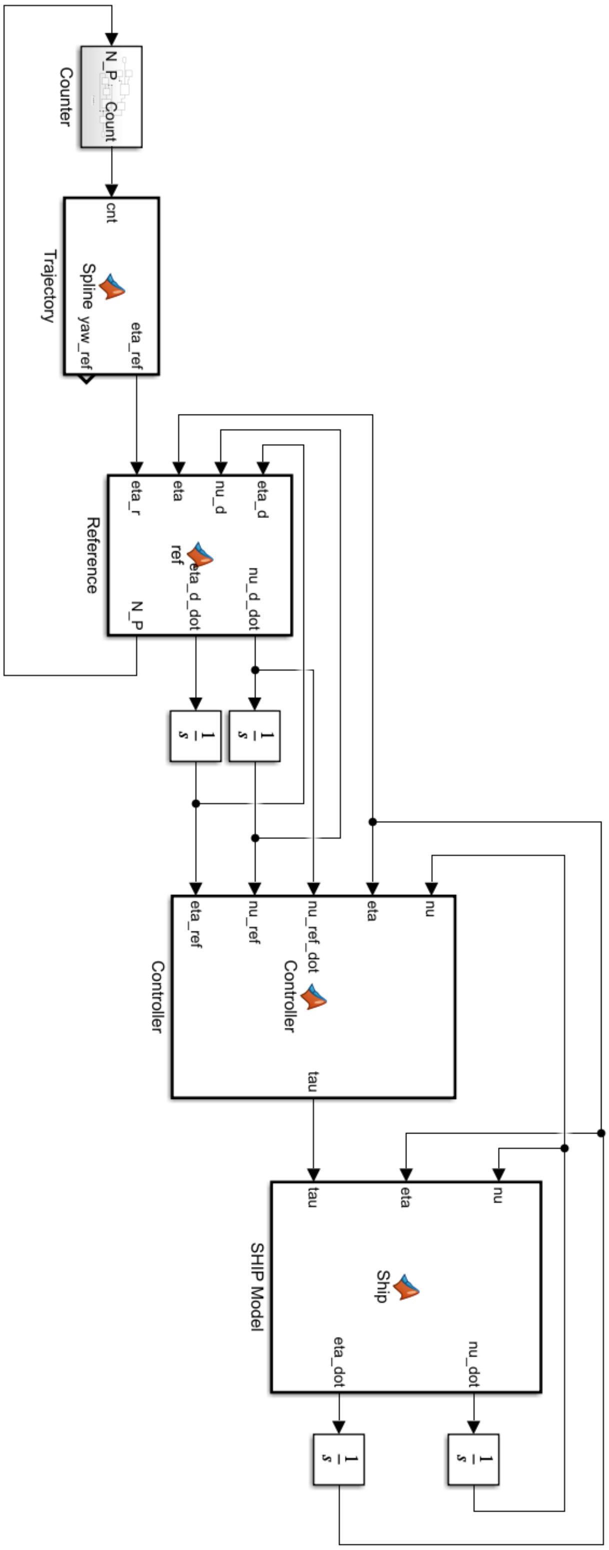

Figure 21: Full system model with navigational guidance

Table 2: Simulation parameters

PARAMETERS	NOTATIONS	VALUES
MASS OF SHIP	m	94620210
SHIP'S CENTER OF GRAVITY W.R.T. ORIGIN	r_G_x	3.93
	r_G_y	0
	r_G_z	12.5
SHIP'S CENTER OF BUOYANCY W.R.T. ORIGIN	r_B_x	3.92591
	r_B_y	0
	r_B_z	5.184459
RADII OF GYRATION W.R.T. CENTER OF GRAVITY	R44	17.01999
	R55	63.96
	R66	66.41999
ADDED MASS MATRIX	M_A(11)	4081108.255
	M_A(12)	0
	M_A(13)	0
	M_A(21)	0
	M_A(22)	50974603
	M_A(23)	293685665
	M_A(31)	0
	M_A(32)	293651430
	M_A(33)	173829237500
PROPORTIONALITY CONSTANT MATRIX	Kp(11)	4300000
	Kp(22)	4300000
	Kp(33)	1000000
DIFFERENTIAL CONSTANT MATRIX	Kd(11)	2000
	Kd(22)	2000
	Kd(33)	2000

4.2 Results

The system is currently designed to accept coordinate points from the user and after processing those points, it delivers a trajectory that follows the spline interpolation theory to give several points equally divided throughout the path.

In Figure 22, the user provided eight different coordinate points in the form of longitude and latitude, making a trajectory as shown by red dotted lines. These points were processed by the spline trajectory navigation subsystem and a new trajectory was developed as shown by the solid green line. As it can be observed, there is a ship at the starting point of the trajectory which needs to follow this smoothly interpretated path leading it to the docking station.

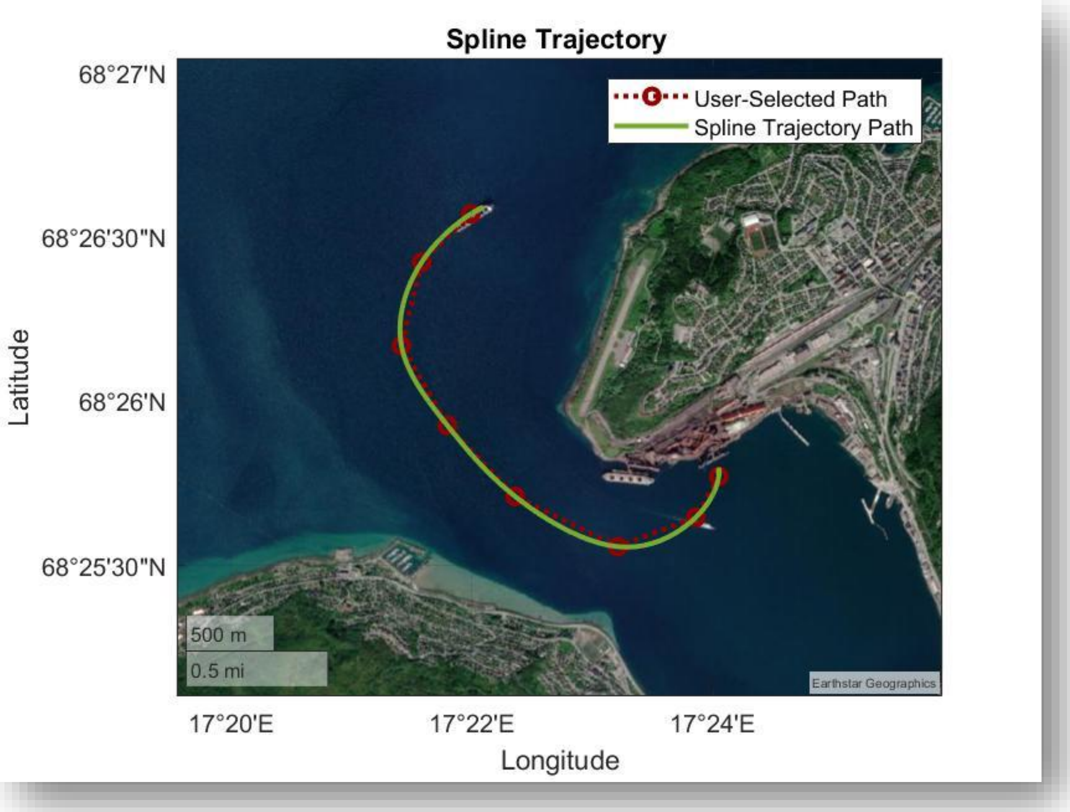

Figure 22: Spline trajectory for navigating the ship

When this trajectory is fed further to the model. The ship creates a response as shown in Figure 23. It closely resembles to the trajectory already generated by the navigational subsystem. Hence it proves the stability of the system to some extent. Further improvements will make the system act perfectly under different circumstances.

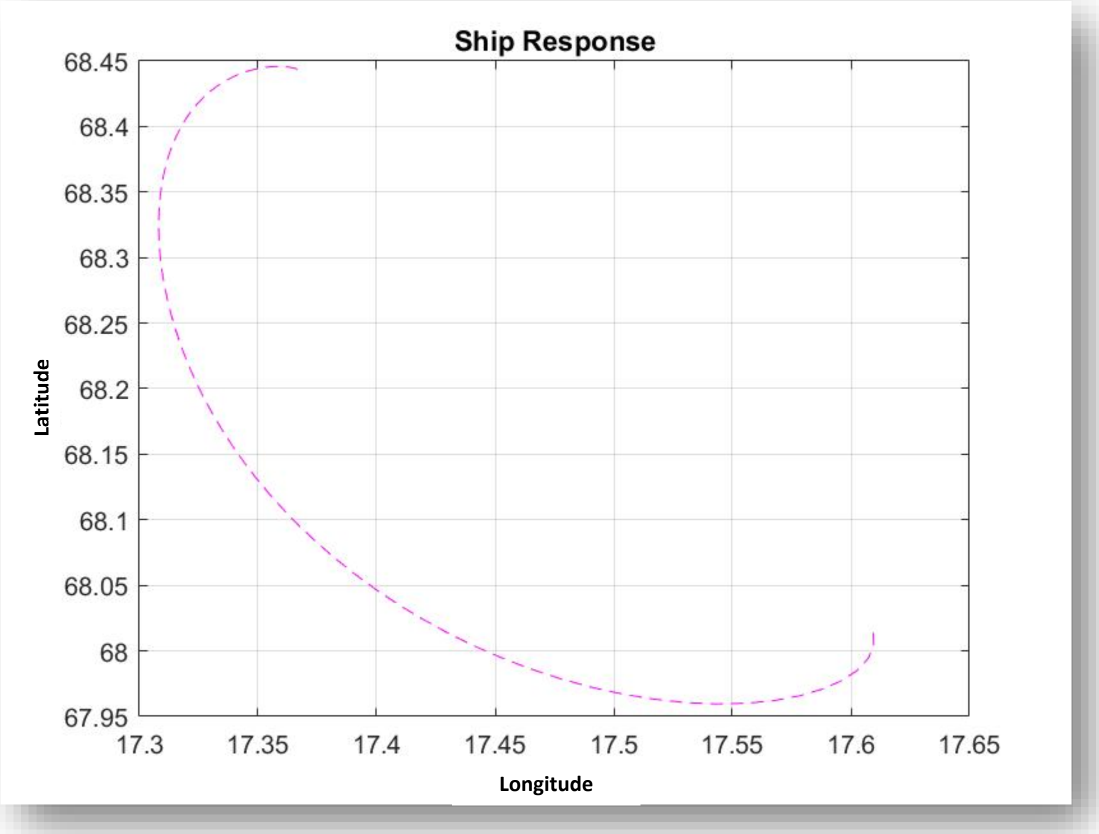

Figure 23: Ship response for given spline reference

To follow the trajectory, the ship must maneuver on some angle every time to have a smooth operation. To achieve this, a suitable rate needs to be defined, the navigational system that is being used also predicts the angle at which the ship must turn every moment. Accordingly, the ship takes the turns with the combination of its thrusters and rudders. Figure 24 represents the yaw rate at which the ship needs to take turns to make its movement efficient and be on the track. This yaw rate has been divided into one hundred equal time samples. These are the same number as the points being generated by the spline trajectory subsystem. Each reference parameter passed by this subsystem includes the respective yaw angle as well. The yaw rate is presented in degrees for easy observations but for the system, it still works in radians as all the calculations are being done in radians. Even for other results, the calculations are happening in radians and when they are to be presented for observation, they are first converted into easily readable forms.

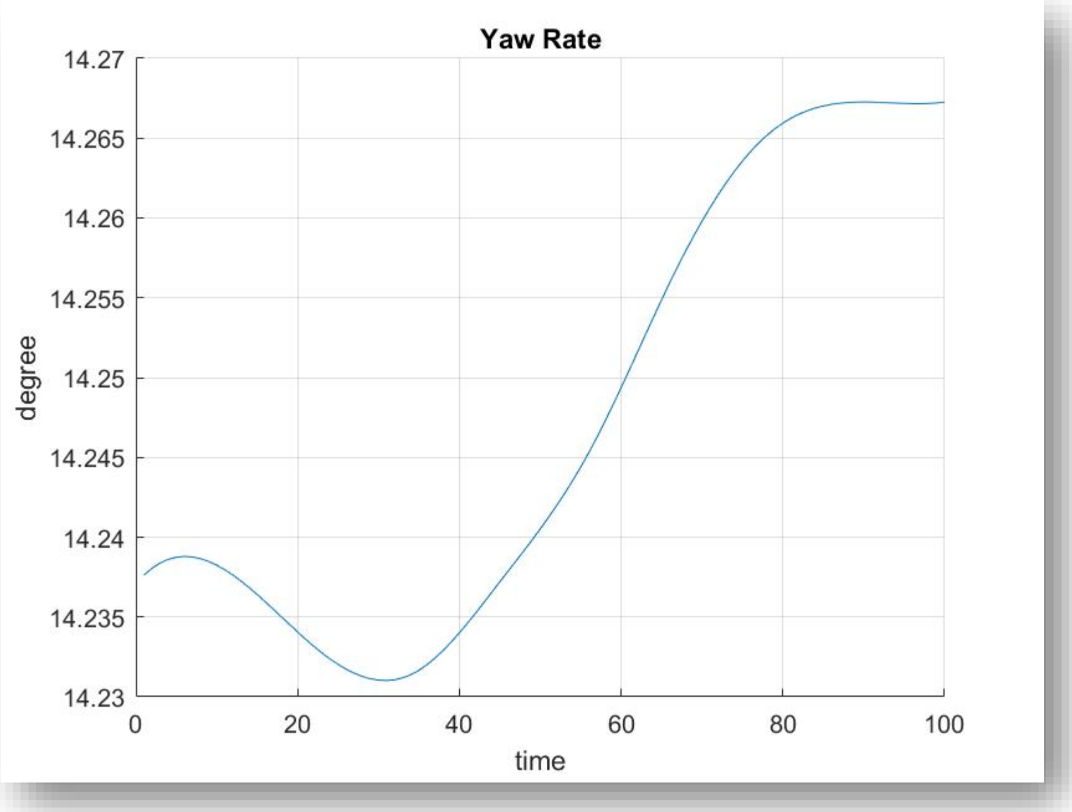

Figure 24: Yaw rate

To check whether the system is operating according to the requirements, it is useful to compare the results of the input fed to the system and the response got from it. In this case, eta is the main component of operation as the whole operation is defined on the positioning of the vessel. Figure 25 is showing that comparison between eta responded by the ship and the reference eta fed to the system by spline navigational subsystem. In the figure, the solid lines are representing the actual responded eta from the ship model and the dotted lines are representing the reference eta. The blue line is representing position of surge going in x-direction and it can be observed that the results almost same as can be seen from Figure 22 and Figure 23. Similarly, the position of sway in y-direction that is shown by green color, is also in accordance with previous results in Figure 22 and Figure 23. Also, the results shown in red color, representing yaw angle shows similar characteristics.

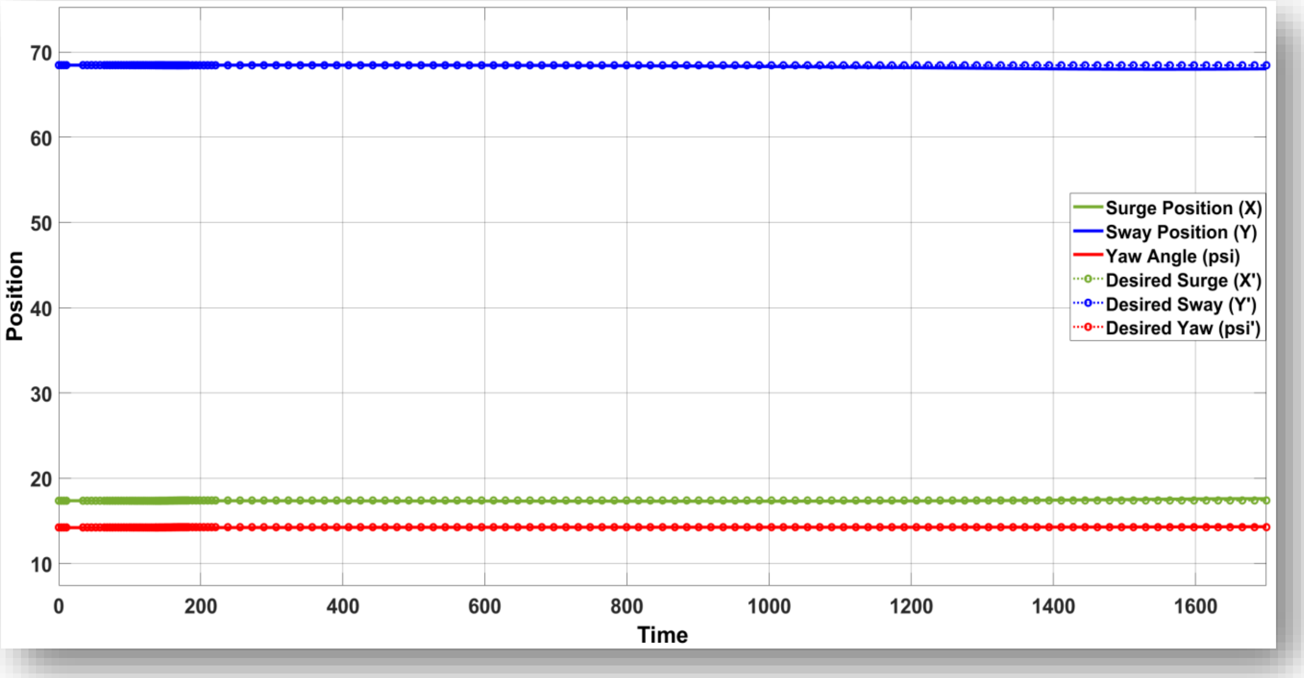

Figure 25: Eta comparison between reference & actual response

The results in Figure 25 are not visibly clear because they lie in different scale ranges. To observe them clearly, they are shown individually and after some rescaling the difference can be closely spotted. Figure 26, Figure 27, and Figure 28 are the individualized representations of each of the eta components. It can be clearly spotted from the figures that the results from ship's response are deviating from the reference results. This deviation is not too much as its on small scale. For now, it can be neglected but for future utilization of this system it can be reduced by some fine tuning of the controller parameters including K_p and K_d. Another reason for this deviation is the slow response time of the ship as it is a massive and bulky rigid body, so it takes some time to achieve the desired reference position. Also, the turning angle of the ship is longer which further adds up in the problems.

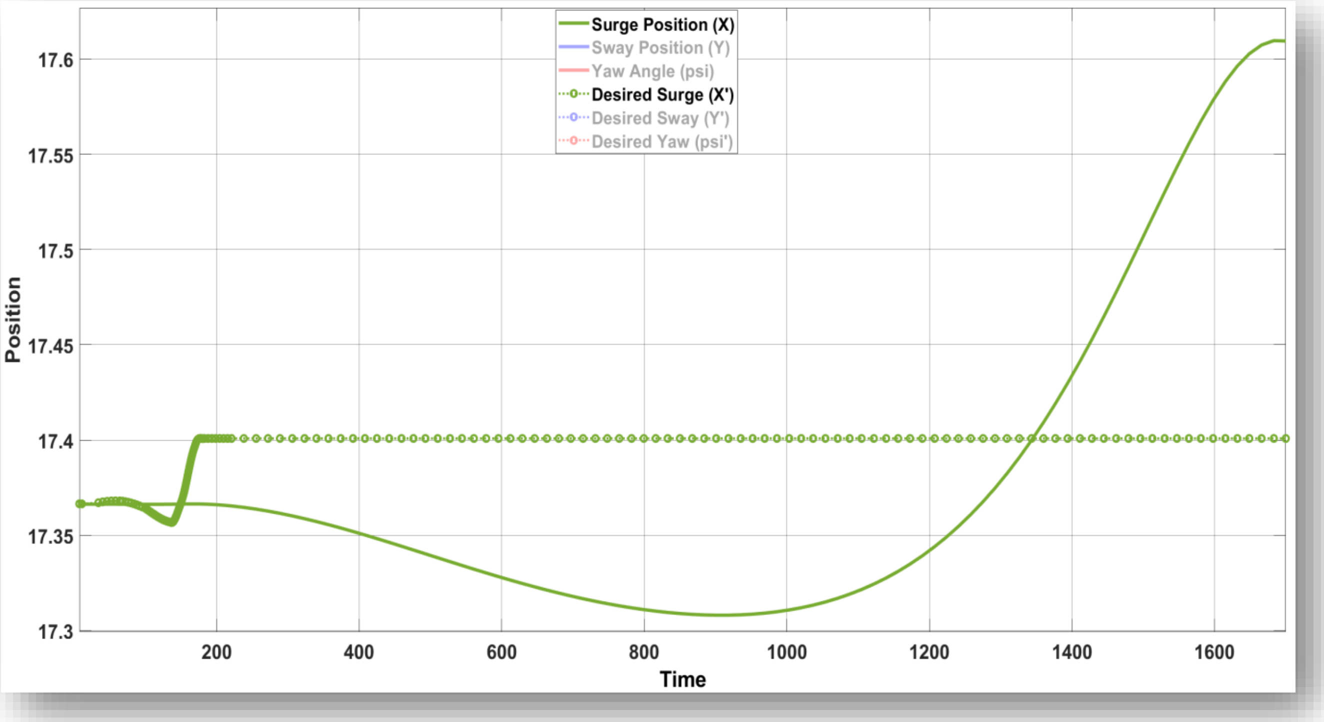

Figure 26: Surge comparison

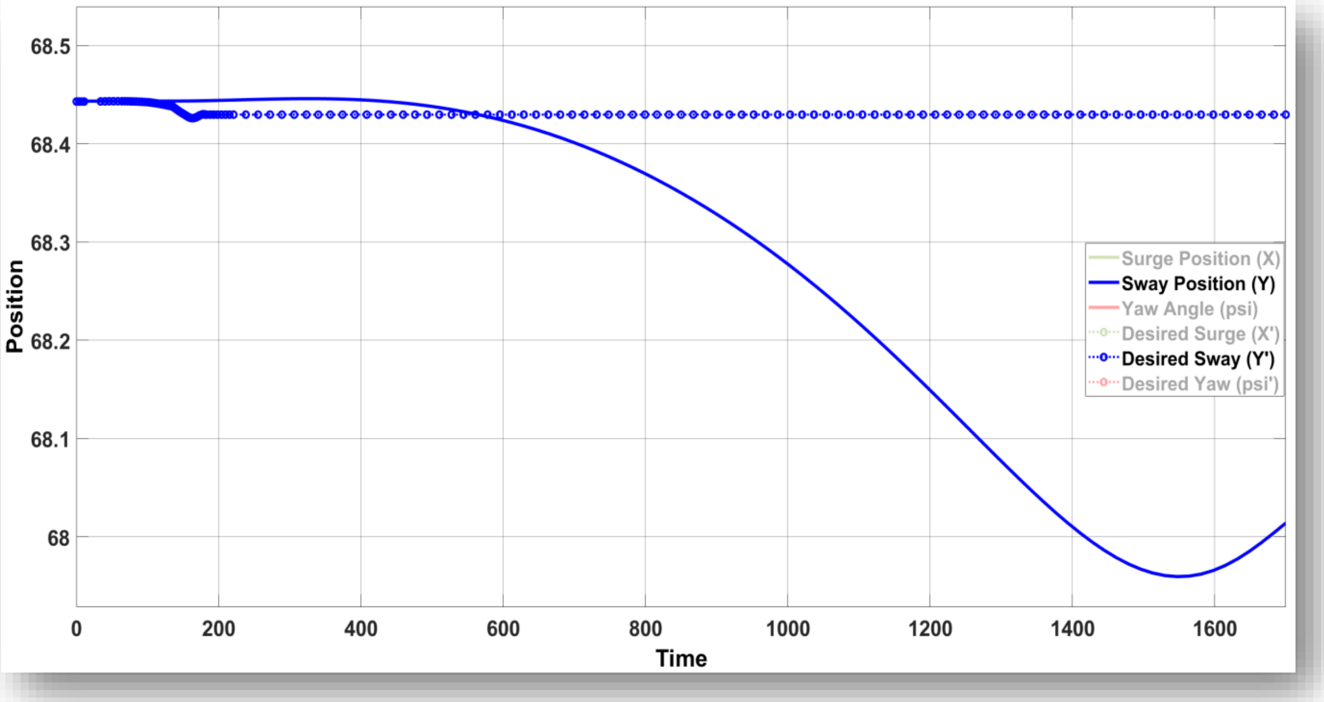

Figure 27: Sway comparison

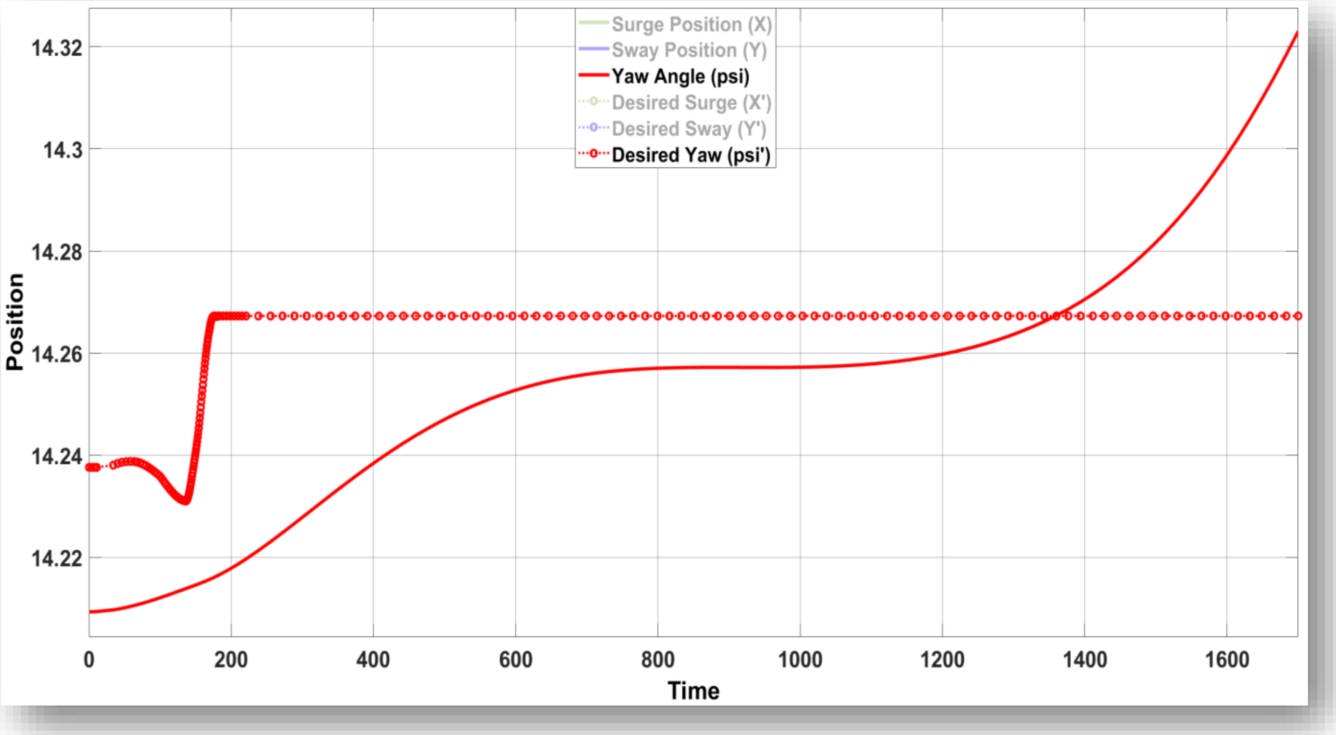

Figure 28: Yaw comparison

To drive the ship model according to the requirements, the torque is provided as an input from the controller. This torque is responsible for individual responses in each maneuvering component. For such a massive ship vessel, the amount of torque required is also massive. The torque being fed to the model consists of surge force, sway force and the yaw moment. All these are acting together to make a combined effect to push the ship in specific direction with specific velocities. When the system starts operating, the torque starts to increase in either direction or when it reaches its specific threshold, it starts to stabilize. To stabilize, often there are oscillations in the torque. In current scenario, these oscillations are slightly larger and taking longer time durations to complete each cycle. Such case can also be observed in the Figure 29, representing each component of the torque. These oscillations can also be reduced to an extent by fine tuning of the controller.

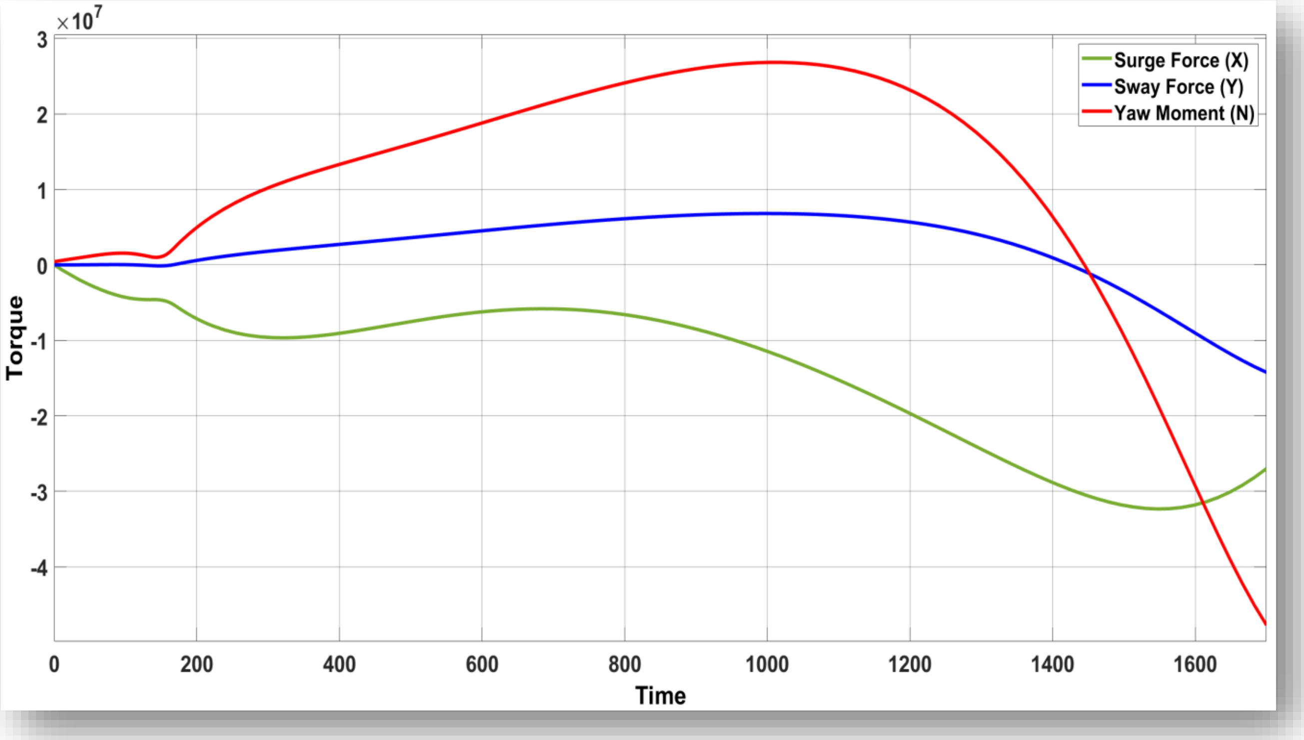

Figure 29: Torque provided by controller to the model

Due to the torque implemented there is change in the velocities of the ship model, which causes acceleration. On the other hand, these velocities produced cause a change in the position and orientation of the ship. If the velocities are changed according to the requirement, the ship can reach the desired destination position. Figure 30 is representing the ship's velocity in response of the applied torque. It can be observed that the surge velocity increase until a certain point and then starts to decrease until it reaches zero which represents the braking condition of the ship. After that it starts moving in reverse direction and to achieve this the torque needs to be in the negative direction. On the other hand, the sway velocity is increasing due to a positive torque applied and beyond reaching certain velocity, the torque goes in negative to reduce the velocity just before reaching the port. Meanwhile in the case of rotational velocity yaw, it needs to be decreased drastically and to achieve that, the torque is dropped correspondingly.

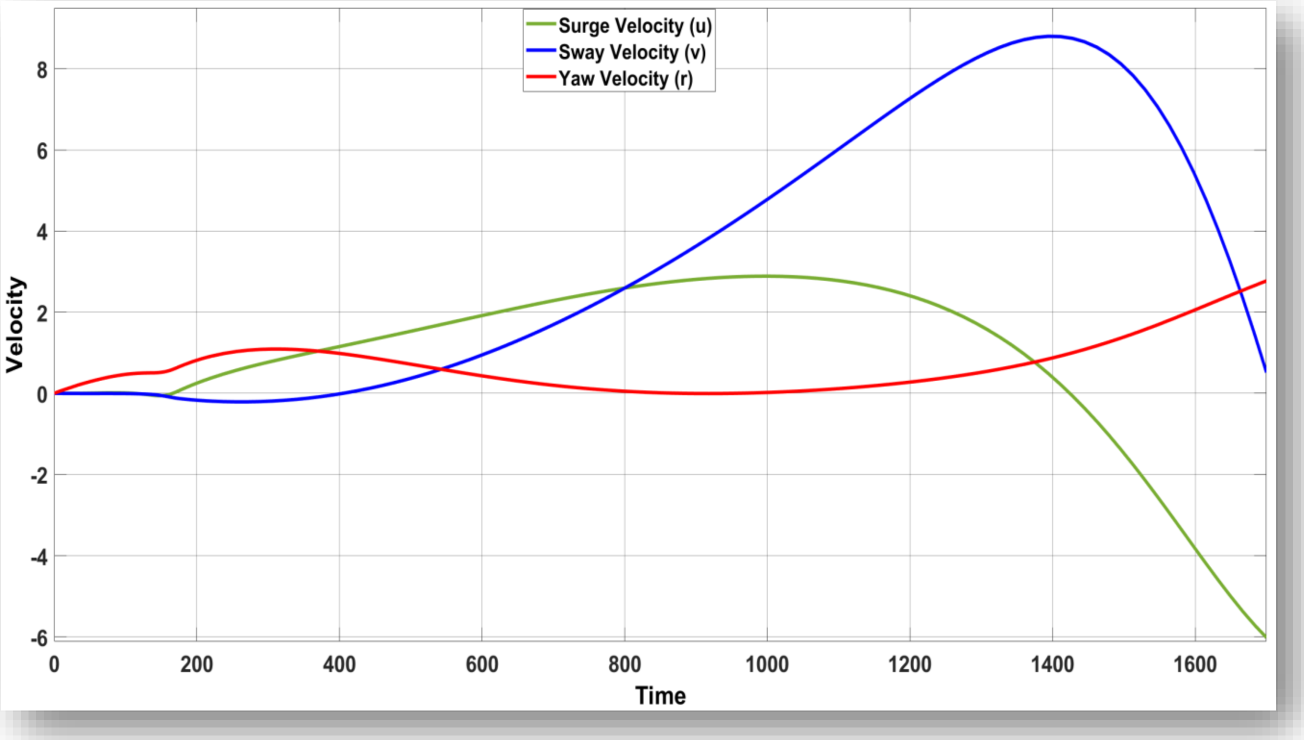

Figure 30: Ship's velocity response

By observation of all these results, it can be presumed that the system is performing as it should, but there is still a lot of room for improvement, as managing a large ship with such faults is unacceptable. The results are still good for this early stage of the project, and they will improve over time with future developments. The reference trajectory tracker sub-system requires more initiatives to improve reference frame tracking, as it now relies on approximation to determine whether the reference point has been reached. In many circumstances, this results in the system's new route point being deployed too soon, leading the system to miss crucial trajectory points due to the ship model's delayed response. Other factors must be considered to eliminate oscillations in the findings, which are responsible for the ship's constant attempt to align its real reaction with the reference results. All of this necessitates more investigation and analysis of the findings to enhance the system's reaction.

5 Conclusion

5.1 Discussion

During this thesis work, the problems related to the port docking of large vessels was studied in detailed and all related information was researched. All the incidents related to such problems were also intensely studied. Based on these studies, all the previous research works has been gone through accordingly and their suggested solutions have been taken into considerations. Furthermore, the feasibility for developing an autonomous system for docking operations of large vessels has been researched. Based on that, all required information and data has also been recovered from different literatures.

The future goals of the base project have also been defined along with the categorization of the whole process into different phases. As a part of this, some pre research work is also done, which includes the extraction of useful equations and derivation of the mathematical model.

Based on these, a simple simulation-based prototype is also made, which is helping in understanding the complexity of the project and all the possible outcomes from it. A spline-based path trajectory system is taken into consideration as a navigational system for the ship. This system is also tested with the simulation model made.

5.2 Future Work

In future, this work can be continued with the stabilization of the prototyping model and further enhancements can be made in it to make it even efficient and reliable. By using all the extracted data from this thesis work, new research can be done to overcome the obstacles and limitations faced in this project. The project will also require extraction of real-time and practical parameters to introduce realistic effects on the system. For this purpose, associated companies can be contact to gain stream of real-time practical data from them.

After successful prototyping on the simulation software, the prototype can be implemented using hardware components to test the real-world conditions and environmental impacts on the system. This will be a step forward in this project and a big achievement for the advancement of marine technologies.

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