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DESIGN OF A PREDICITIVE CONTROL FOR A DYNAMICALLY POSITIONED SHIP

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Predictive control of the dynamically positioned ship

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This project is dedicated to my parents that have managed to give me the opportunities they could not have or even aspire.
To Prof. Roman Śmierzchalski that has trusted in me and given me the knowledge to cover this project.
To Dr Anna Witkowska that has provided me with the necessary tools to develop this project and has helped me accomplish satisfactorily to valid solutions.
To all of you thank you.

Preface

Dynamic positioning systems in ships is becoming an essential integrated system in present vessels. Due to an arise in the offshore industry for searching oil in deeper waters where moorings are becoming impractical. Maintaining a fixed position or managing to follow a desired path is an application that more and more is becoming crucial to be precise. This paper focuses on this type of application, to contribute to the modern ways of operation of the offshore industry.

DP systems require an understanding of the dynamics of the vessel and the actuators and thrusters involved. A control of these last elements is the main research of this paper. Most control systems normally do not attend to the dynamics of the actuators system and do not have a knowledge of the characteristics of the process. This project presents a solution for a control allocation in the form of a MPC controller that takes in account the dynamics of the actuator system, optimizing an objective function with applied constrains.

Modern Predictive Control constitutes a relatively modern solution to the control allocation problem. It manages to understand the process that has to be controlled and proceeds to predict well-founded solutions with a well defined process model. This approach can be easily transposed to various industrial systems that contain linear actuator dynamics. This paper focuses on an existing supply vessel and performs a comparison between two solutions for the control allocation problem.

This document is divided into six chapters, each one containing the essential knowledge to understand the control strategy developed in this project. In chapter 1, a brief description on the automated vessel industry and its future perception is done, naming some of the most important applications. Chapter 2 gets into the topic this project is based, *dynamic positioning.* An understanding of its principles is presented, with the variations present systems have between each class of control. In chapter 3, the vessel which is subject of automation, is presented and how to develop its model to simulate is described. Each sub-system of the vessel's motion is rigorously descripted. The next chapters are about the control design and its implementation. Chapter 4 describes the MPC control. This control is specially designed for this project and its theoretical aspects are described in this chapter. Chapter 5 extends to the implementation of the MPC controller designed and a description and implementation of the controllers that take part in a DP system (*DP controller and Control Allocation).* To conclude, chapter 6 presents the results of the simulation in Matlab. In this chapter a comparison between two control allocation solutions is done. The advantages and disadvantages of each solution, errors made and future approaches are commented in the last conclusion chapter.

Key Words:

Dynamic positioning, control allocation, MPC, ship control, marine systems, GNC systems.

Contents

Chapter 1: Introduction

1.1 Offshore Industry

The offshore industry has been developing since the seeking of new energy sources at high seas. Transporting resources has increased with the broadening of the markets. For these reasons, optimize the principal ship manoeuvres are the principal case of study in the offshore industry. These manoeuvres include port entries and exits, position keeping for drilling applications or loading and offloading supplies at offshore platforms and path tracking applications. The offshore petroleum industry has been the pioneer to evolve in these applications, leaving a grand legacy on vessel automation. More often, modern applications involving unmanned vessels (ROVs) are being the major cause of improving the control of automatic vessels. However, the oil and natural gas industry companies are still the dominant developers and users of automation systems.

Offshore oil extraction has been exploited since the 1940s. Originally oil extracting platforms where fixed on the seabed, but when extraction moved to deeper waters, floating production systems became in use. Tankers and supply vessels communicate these platforms with the mainland. The principal vessels that have implemented modern automation in the offshore industry are:

- Drilling Vessels
- Support Vessels (supply)
- Offshore floating platforms
- Pipe-laying and construction vessels
- Dredging Vessels
- Tankers
- Submarines
- Semi-submersibles
- ROVs & UUVs
- Floating air fields

Different offshore applications demand specialized systems. Throughout history the tendency has been to implement segregated systems, while nowadays the trend is to have a unified system that can handle most of the applications. Concerning the offshore industry, the major applications which have been exploited are the path tracking and positioning. Depending on the type of vessel and its function different manoeuvres are needed at different speeds and conditions, making to the manufacturers a difficult task to obtain a unified system that can be implemented in different vessels and functions. New ways of control are trying to solve this issue. Modern MPC’s and genetic algorithms are appearing in this area, making a new era in vessel automation. Particular systems have been simulated on various vessel models achieving good control results, but tend to lose efficiency when greater velocity ranges are implemented.

With the advance of technology new features appear, more precise and more reliable. This means a gradual improvement on navigation systems. The development from simple course holding systems to proper autopilots and dynamic positioning systems have evolved relatively fast in a short period of time. It is a fact that more deep water applications, safety, optimal path tracking and restrictions on seabed mooring are benefiting the improvement on these systems. It will not be long for yachts and pleasure crafts to start using simpler versions of these systems. This constitutes a favourable vocation drive, as it is a relatively new field which tends to increment and improve year by year.

Figure 1.1 *- Offshore Industry (KONGSBERG)* [21]

The automation of an industrial vessel presents new opportunities of operations. It allows a fast change of operation without the inconveniences of undoing physical moorings or picking up anchors. It also provides a rapid integration to a workspace that includes other vessels. Deep water applications, with DP, do not constitute any difficulties of position keeping and vessels can operate without loosing time in moorings and laying anchors. Moreover, path tracking has become more efficient as new technologies can search for the optimal path. The disadvantages of an automation lie in a greater fuel consumption. For this reason, many manufacturers have as their objective an efficient control with many methods of "relaxing" the automation action. Depending on the application it can be convenient not to make the control to act forcefully, but allow some disturbances to act and leave the control not to act in between some boundaries. Furthermore, the expense in automating a heavy industrial vessel, nowadays, is still considerably high.

1.2 State of Art

In the present literature about the topic, there are various authors that have set the foundations about dynamic positioning. The works developed by Thor I. Fossen and Tristan Perez [5] are some examples. Many students at he NTNU in Norway have contributed to the study and investigation on this subject and similar cases of ship automation. Since the 1960s where offshore drilling went to deeper waters many authors have strengthen the information regarding this topic. In order to develop this project, the main authors referenced are basically modern authors that have collected most of the information in their books and articles.

Thor I. Fossen and his books about ship motion, hydrodynamic forces and control systems have been the fundamentals for this project. *Guidance and Control of Ocean Vehicles* [2] defines the methodology to develop a vessel model along with the environmental disturbances a ship has to deal with. It also presents the various forms of controlling a ship and its applications (DP, Autopilot, Wave filtering…). It explains the concept in guidance, control and navigation, explaining in detail the three systems and how they interact with each other. In *Marine Control Systems* [3] an approach in vessel modelling using Matlab coding and control examples are shown. *Marine Craft Hydrodynamics and Motion Control* [4] is an extent recompilation of the other two books with a vast description on the elements involved in the guidance, control and navigation systems.

A student from the NTNU, Benjamin K. Golding describes in full detail the types of manoeuvres involved in the ship automation along with a high detailed description of the systems involved in the GNC systems. He also describes the function of each force generating system involved in ships motion, in his project article *Industrial Systems for Guidance and Control of Marine Surface Vessels* [6].

Many control examples are available in the present literature, which serve as inspiration for the use of different types of control methods. Their application is based on several models, but one vessel model is predominant in the literature available. This model is the one presented in Fossen & Strand, *Passive Nonlinear Observer Design for Ships Using Lyapunov Methods* [7]. Where the Northern Clipper, a supply vessel owned by Sævik Supply Management is defined. Godhavn in his article *Nonlinear and Adaptive Backstepping Designs for Tracking Control of Ships* [8] shows a backstepping control law for this model in the bis-scale system. This model in bis-scale will be the one used for the development of this project.

Examples of different control methods are the PID based dynamic positioning controller from Thor I. Fossen [1], [2] and [3], which sets the basis on DP control. Adaptive Neural Network control from Jialu Du, Xin Hu, Hongbo Liu and Philip Chen [19], that offer a new approach on learning systems for vessel control. Backstepping Observers and backstepping control by Godhavn [8] and further analysis done by Anna Witkowska [1], show a kinematic and a dynamic control. Quadratic Programming control allocation by Anna Witkowska, an optimization method that established the starting point for this project. Model Predictive Control control allocation for a thermal management system by Chris Vermillion, Jing Sun and Ken Butts [17] and Model Predictive Dynamic control allocation by Yu Luo, A. Serrani, S. Yurkovich, D.B. Doman and M.W. Oppenheimer [16] show how MPC designs can regulate efficiently the actuators signals for different systems. Aleksander Veksler, Tor Arne Johansen, Francesco Borrelli and Bjørnar Realfsen [10] show how can MPC controller embrace both dynamic positioning control and control allocation in one same MPC controller.

This project contributes in the direction of searching the optimal method for a control allocation problem. It shows a comparison between two controls with the expectancy of determine the best method from the two proposed. MPC design is a relatively new method and not much is applied in vessel automation. This project tries to establish a guidance in the use of MPC algorithms to perform a satisfactory control and aims to be a first approach for this matter, without getting in detailed industrial systems to be used. It is a theoretical understanding on the different elements involved in dynamic positioning and delivers compared simulation of both controllers.

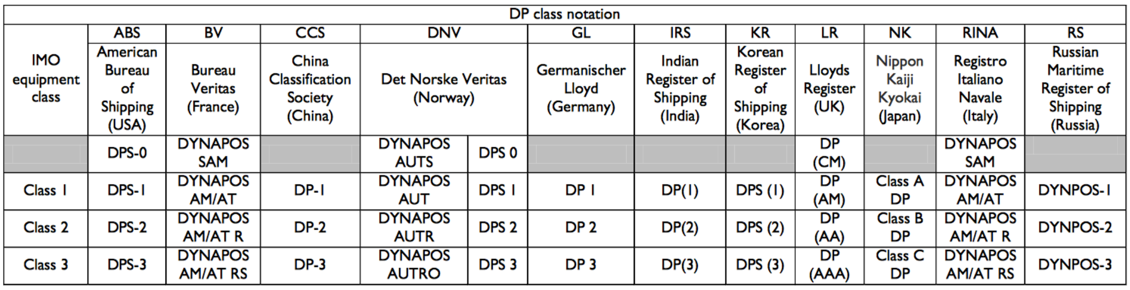
Chapter 2: Dynamic Positioning

2.1 Understanding DP

This document describes the methodology to obtain a valid simulation for a dynamic position system applied to a surface ship. Dynamic Positioning (DP) is a type of control for low speed applications on marine vehicles and unmanned aerial vehicles (drones). It allows a rigid body vehicle, that navigates through a fluid, (surface ships, submersibles, aircrafts or spaceships) to compensate disturbances generated by wind, currents or waves, in order to follow a path at slow speed or maintain a fixed position. Applications where the speed is over 2m/s (4~6 knots) DP control is not valid. This is due to the way DP control works by means of controlling the thruster's and propeller's actuators. Over this speed the bow thrusters do not have the sufficient force to control the ship's position and it is merely down to the main propeller and the rudder's angle to control the ship's position. This type of control would be named Autopilot control, which means a different type of algorithm to implement.

DP applications have two main types of control: Over-Actuated control and Under-Actuated control. Where this last option is when one or more thrusters fail to act, meaning an emergency situation. An Over-Actuated control consists of being able to control more actuators than degrees of freedom. The least actuators where DP is capable to control efficiently, a surface vessel, are when one main propeller and one bow thruster can work along with the rudder.

DP systems are integrated in the vessels with different characteristics according to a classification set by the different societies in an international committee [20].



	DP class notation											
IMO equipment class	ABS	BV	CCS	DNV		GL	IRS	KR	LR	NK	RINA	RS
	American Bureau of Shipping (USA)	Bureau Veritas (France)	China Classification Society (China)	Det Norske Veritas (Norway)		Germanischer Lloyd (Germany)	Indian Register of Shipping (India)	Korean Register of Shipping (Korea)	Lloyds Register (UK)	Nippon Kaiji Kyokai (Japan)	Registro Italiano Navale (Italy)	Russian Maritime Register of Shipping (Russia)
	DPS-0	DYNAPOS SAM		DYNAPOS AUTS	DPS 0				DP (CM)		DYNAPOS SAM	
Class 1	DPS-1	DYNAPOS AM/AT	DP-1	DYNAPOS AUT	DPS 1	DP 1	DP(1)	DPS (1)	DP (AM)	Class A DP	DYNAPOS AM/AT	DYNPOS-1
Class 2	DPS-2	DYNAPOS AM/AT R	DP-2	DYNAPOS AUTR	DPS 2	DP 2	DP(2)	DPS (2)	DP (AA)	Class B DP	DYNAPOS AM/AT R	DYNPOS-2
Class 3	DPS-3	DYNAPOS AM/AT RS	DP-3	DYNAPOS AUTRO	DPS 3	DP 3	DP(3)	DPS (3)	DP (AAA)	Class C DP	DYNAPOS AM/AT RS	DYNPOS-3

Table 2.1 - *DP classes provided by the Dynamic Positioning Committee (www.dynamic-positioning.com)* [20]

· DP-0 (*undefined class*) are systems capable of automating the heading (yaw) control. It leaves to the operator to control manually the position of the vessel, by means of joysticks. It can compensate environmental disturbances to control the heading.

· DP-1 (*class I*) are non-redundant systems with joystick backup. It is capable of controlling position and heading. The loss of position can be possible when an event of a single fail occurs.

· DP-2 (*class II*) are fully redundant systems so it will not fail by a single fault of the system. It is similar to DP-1 but with the addition of a second module to add redundancy. More sensors, and more control computers are active to perform a voting if any system fails. It requires two operator stations.

· DP-3 (*class III*) are triple redundant systems with an extended hardware configuration. It is capable of withstanding a flood or a fire in any compartment without the system failing, requiring a fire-safe compartment for a control computer.

Sub-systems or components			**Minimum requirements of DP class**		
			Class I	**Class II**	**Class III**
Energetic system	generation sets		non-redundant	redundant	redundant, in separate rooms (fire & flood)
	main distribution boards		1	1 with division of main lines	2 with separate main lines, separate rooms and normally open switch
	line splitting		0	1	2
	energy distribution system		non-redundant	redundant	redundant, in separate rooms (fire & flood)
	power management		not required	required with load reduction function to avoid *black-out*	required with load reduction function to avoid *black-out*
Rudders	arrangement of the rudders		non-redundant	redundant	redundant, in separate rooms (fire & flood)
Control	automatic control; number of computer systems		1	2	2 + 1 backup system
	manual joystick control with automatic maintenance course		required	required	required
	single lever for each rudder		required	required	required
Sensors	position reference system		1	3	3, which 1 of them in the alternative control station system connected directly in the maintenance system
	external sensors	wind	1	2	3, which 1 of them in the alternative control station
		position	1	3	as above
		gyrocompass	1	3	as above
MRU			1	2	2 + 1 separate room
Alternative control system for the back-up system block			not required	not required	required

Table 2.2 - *DP IMO classes requirements obtained from (Śmierzchalski, 2013)* [9]

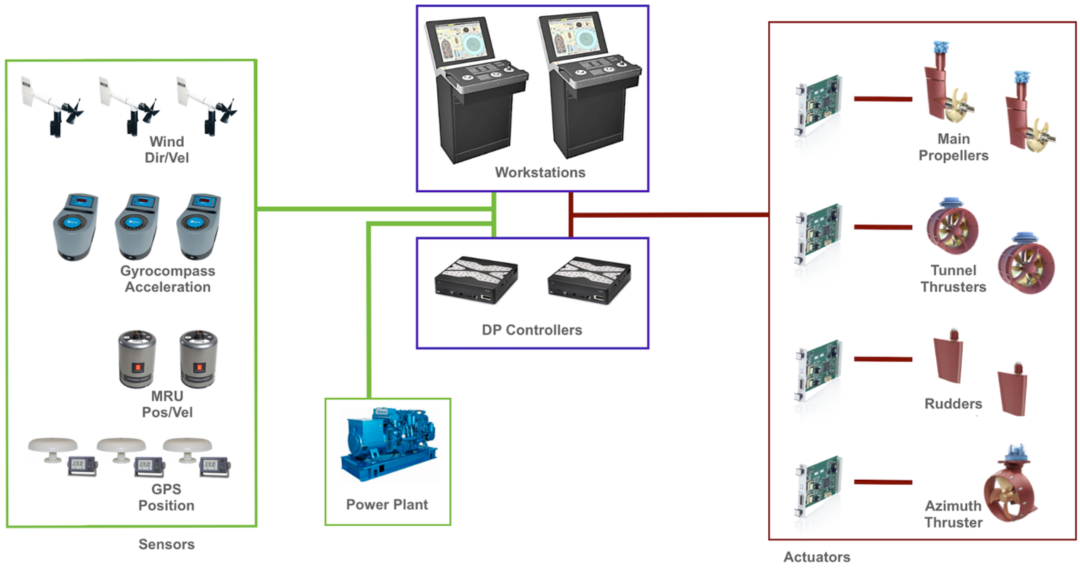


Figure 2.1 - *DP-II system architecture. Based on examples in KONGSBERG* [21]

The DP system architecture shown in *figure 2.1* is a basic scheme of the elements involved in the DP-II system. The redundant systems are needed in order to perform voting between elements to identify if any system is failing. In this way, the system can handle a single failure of an element, by identifying the failed element and avoiding its measured signal. A set of sensors are implemented to aid the system to estimate the vessel's actual state in what it is called the navigation sub-system. Moreover, they will help in the track generation as they supply environment information to the guidance sub-system. The workstations with DP controllers are the main element of the control sub-system. Also, part of the workstation would be destined for the guidance inputs and joystick control. Lastly the thruster's and propeller's action would be the output of the control, where measuring of their actual state would then be feed-backed to the controller.

2.2 Guidance, Control and Navigation

Ship control systems can be divided into three sub-systems: *Guidance, Navigation and Control*. The GNC system represented in *figure 2.2* is the control block diagram for each degree of freedom (DOF) required to control.

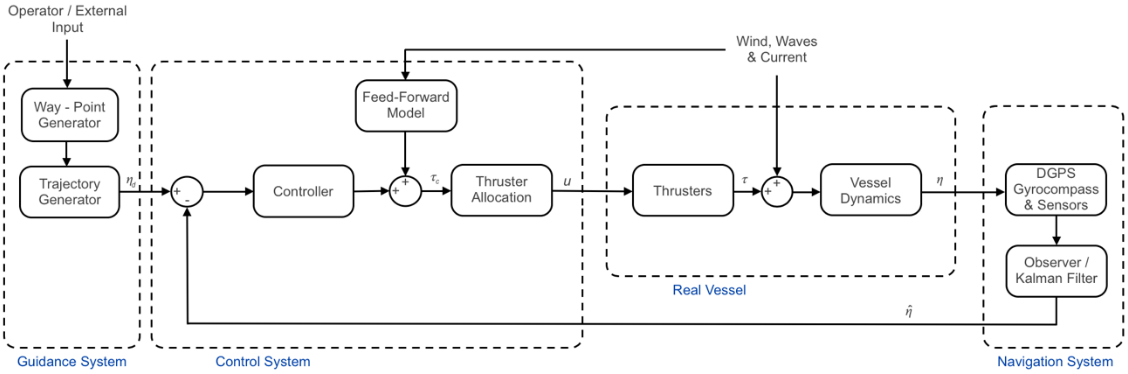


Figure 2.2 - *GNC system. Structure of a ship position control*

Guidance System

The Guidance systems is in charge of feeding the control with a desired state $(\eta, \nu)_\mathrm{d}$. It accepts inputs in the form of reference signals (operator joysticks or keyboard) and external sensors that give information about the environment (weather and position of external objects). The guidance system generates from waypoint inputs a trajectory the vessel should follow, determining a desired state vector. In closed-loop guidance the real/estimated state is fed from the navigation system, while open-loop guidance only uses sensor and reference signal inputs. (Fossen I. Thor, 2011) [4].

Control System

The Control system is in charge of interpreting the desired state from the guidance system and generating the commands to the thruster's and propeller's actuators. It receives the estimated state from the navigation observer and determines the command to compensate the error between the estimated state and the desired state. Normally there are two controls implemented, the position controller, or DP controller, and the thruster's control allocation. The first controller is in charge of the position error compensation. It sets the type of forces the vessel should experience to achieve the desired reference position. A wind model is frequently implemented to have an estimate of the wind forces that act on the vessel. It feed-forwards the wind's velocity and direction, read from the wind sensor, and translates these measurements to estimated feed-forward disturbance forces. The second controller implemented is the thruster's actuator control or control allocation. It obtains both the desired forces and the disturbance forces to perform the correct thruster's actuator signal that will produce the desired forces attending the known disturbances.

The types of control depend on the application and the quality of the control. It is increasingly being desired a unified control for most of the applications (*Autopilot, DP, Position mooring…*). The most common used controller has been the industrial PID, more modern applications have been using Least Quadratic Optimal control (LQC) or stochastic controllers. Recently fuzzy control and neural networks have been implemented and Modern Predictive Control has been simulated to achieve a unified robust controller. By unified, it is meant to obtain the controller and thrust allocation together in one controller, which by this it is obtained a controller that can understand the needs and limitations of the thrusters and setting directly the actuators commanded signal to compensate the position error [10].

Navigation System

The Navigation system determines the vessel actual state and the environmental disturbances. It uses sensors to constitute an estimate of the vessel's real position and velocity and to obtain speeds and direction of the environmental forces. The navigation system consists normally of the set of sensors to measure global position, heading angle (*yaw* ψ) and the distance travelled (Golding 2004) [6], by means of DGPS, gyrocompasses and MRU. Velocity estimations are also considered with the use of speed logs and environmental directions and speeds with environmental sensors.

The navigation system can determine the estimated state and the environmental disturbances with different methods. The **full state observer**, is an observer that both filters the wave noises to obtain the slow varying disturbances and estimates the state based on pole placement method. The **Kalman filter** acts differently as it includes feed-forward from the input and filtering of the measured output (Fossen, 1994) [2]. Computing the gain vector *k*, the Kalman filter estimates the state from a noise contaminated measurement. The method of operation is in a discrete-time scenario. The first step is to predict an estimated initial state and an estimated predicted measurement. Next is to compute the error between the real measurement and the predicted measurement and correct the state estimate. With this done it is possible to calculate predicted estimates, by knowing the corrected state estimate and the input to the system. To determine disturbance estimation, it is necessary to perform an augmented state that contains the estimated state with the disturbance states. For this, the disturbance state must be dynamically similar to the process states, so a filtering to obtain the slow varying components has to be done. With the augmented states and the process state estimations, the error between them will give out the environmental disturbances acting on the process. Kalman filters are normally implemented in linear models but are easily implemented in nonlinear models as *Extended Kalman filter*. A linear Kalman filter model design will just represent a special case of the nonlinear models.

2.3 Applications

Modern DP systems have a variety of applications. Depending on the type of vessel, some applications are essential, and some will be features depending on the DP system manufacturer. The following applications are the most common among the DP systems available.

Station Keeping

Station keeping application is focused of maintaining a vessel in a fixed position, relative to a fixed object or coordinate or relative to a moving object. The system compensates the environmental forces which will act as disturbances to the system. This type of system is essential for a DP system as it becomes the major application for offshore industry. The ability to stay at a position is a major problem in the oil and gas industry, either by means of maintaining a fixed position relative to the platform for a supply vessel or for a drilling application in a drillship, making DP systems become indispensable.

The method used up to the arrival of DP systems had been anchoring ships to the sea bed or to fixed structures. This left a limited manoeuvrability once anchored and severe forces acting on the ship and on the holding structure. In deep water applications anchoring is normally not possible. In contrast, DP systems have become increasingly efficient in maintaining a fixed position.

DP systems in station keeping application can be handled in two ways. Manual and fully automatic. In manual method the operator with the use of joysticks, or control devices, is in charge of manoeuvring surge, sway and yaw with some environment disturbance compensation (Golding, 2004). He can then decide to operate any of the 3 DOF, leaving the others to the automatic control. This is possible as the control system is designed to control the surge, the sway and the yaw separately. In fully automatic, the control will activate all navigation sensors and will manoeuvre to the desired coordinates. In addition, modern DP systems have the ability to adjust the heading to a specific yaw angle, facing the direction of the environmental disturbances, in order to result in a minimum fuel consumption.

Path Tracking

Tracking applications for DP systems is based in following a desired path at a slow velocity. Taking as inputs certain waypoints, a desired heading for each trajectory between points and the vessel's speed at the trajectories and speed turns in each waypoint. A different method is applied when *target tracking.* This means the following of a physical moving target and requires the ship to keep at a given radius from the target.

The DP control system translates the stored waypoints, in the form of Cartesian coordinates [x, y, z] and arcs related to these coordinates, to form a desired path inside a permissible radius. This path is generated by means of straight lines and circular arcs. Path generation can be done using different methods like spline interpolation or quadratic programming. Other systems like weather routing and obstacle avoidance can be incorporated in the process of path generation (Fossen, 2002) [3].

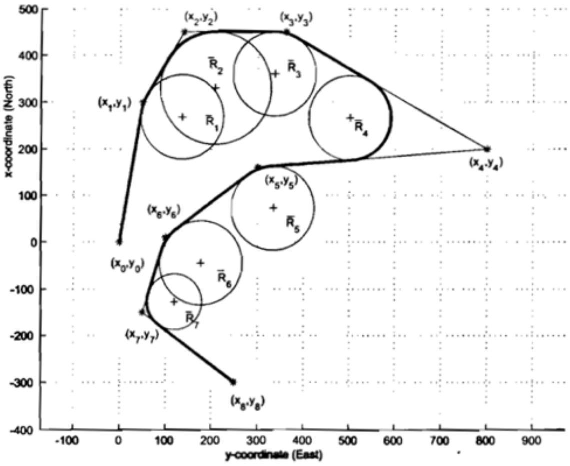


Figure 2.3 - *Trajectory planning (Fossen, 2002)* [3]

Position Mooring

Positon mooring consists in a combination between anchoring and DP control system for position keeping. This method can be also applied for vessels which drag a load and the DP system working in path tracking mode. This type of control system changes the vessel's model, as the anchoring/load adds nonlinear spring forces and moments to the vessel's dynamics. If not so, the forces applied would be interpreted by the control system as environmental forces trying to compensate them.

The mooring helps the DP system in a way it can operate at a lower gain as the mooring takes the most of the forces, leaving the DP to work to reduce the tension to the mooring (Golding, 2004).

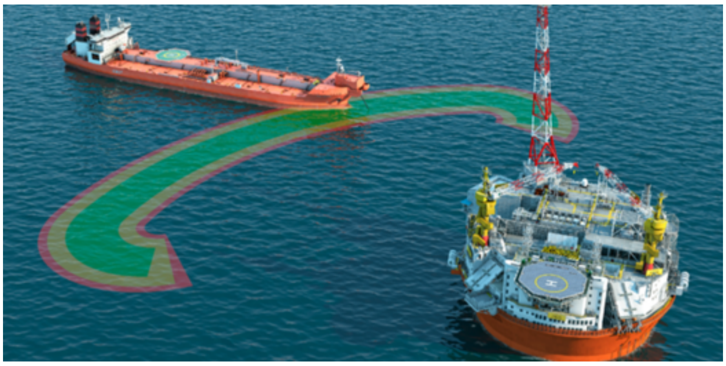


Figure 2.4 *- Position mooring (KONGSBERG)* [21]

Fuel Saving

Fuel saving feature uses different methodologies to achieve a less demanding DP control system which translates to less power usage.

Weather Optimal Positioning Control (WOPC) is one methodology which its function is to face the vessel against the direction of the environmental forces, as waves and wind direction will tend to coincide. This constitutes to a zero yaw moment and in consequence to a reduction fuel consumption, with the repercussion of disabling the fixed heading position feature.

Auto area positioning is another methodology to achieve fuel saving capabilities. It swaps position keeping to area keeping. When a strict fixed position is not required area keeping allows the vessel to keep position around a determined ‘working area’. This operation keeps DP system active at a low gain control.

To all this, *KONGSBERG* has released what it is called *GreenDP®* *System*. This system reduces the fuel consumption, resulting in a lower CO_2 emission. Its application consists in keeping the vessel safely in an area positioning. The system uses a modern predictive control to forecast the vessel’s motion, so short-term disturbances, that do not move the ship out of the operational area, are filtered out.

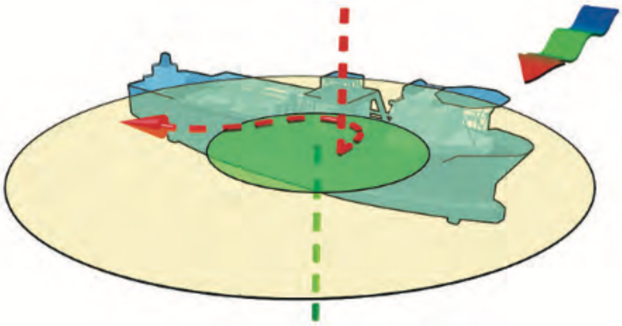


Figure 2.5 *- Area positioning GreenDP® System (KONGSBERG)* [21]

Chapter 3: Vessel Model

3.1 Vessel Description

The objective of this project is to design a DP control for a supply vessel model. The model and the further simulations have been performed with Matlab and Simulink, with the MSS GNC toolbox (Fossen and Perez, 2004) [5].

Figure 3.1 - *Northern Clipper supply vessel. Ship owned by Sævik Supply Management, Norway (Fossen and Strand, 1998)* [7]

The vessel in study is the Northern Clipper, shown in [7], an offshore supply ship of length: 76.2m, with a mass of: 4591t and operational mass of 6400t. The centre of the vessel's fixed frame, or body frame, will coincide with its centre of gravity (CG). In order to achieve a reliable model of this vessel, an in depth study of the vessel's motion has to be carried out. The study of motion is divided in a study of the kinematics and a dynamic study of an accelerated body.

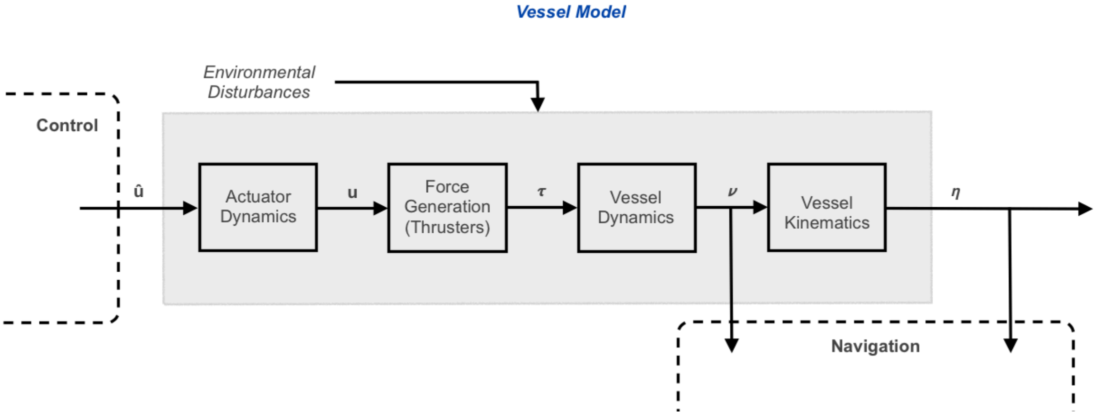


Figure 3.2 - *Vessel Model for simulation in block diagrams.*

More in detail, *figure 3.2* shows the elements involved in the vessel's model. The ship's motion is conditioned by the dynamics of the actuators system, that translates the commanded actuator signal from the control allocation, and the thruster configuration which are in charge of the force generation which will deliver the force input ($\boldsymbol{\tau}$) along with the environmental disturbances ($\boldsymbol{\tau}_e$) to the dynamics and kinematics model.

3.2 Kinematics

The kinematic study as it is defined, is the description of a moving object without taking in account the mass of the object or the forces that caused the motion. Kinematics analysis derive in describing the position, velocity and acceleration of points within a geometrically known body or object. Kinematics studies the trajectories of these points and their differential properties, aiming to provide a description of the spatial position of the body in study.

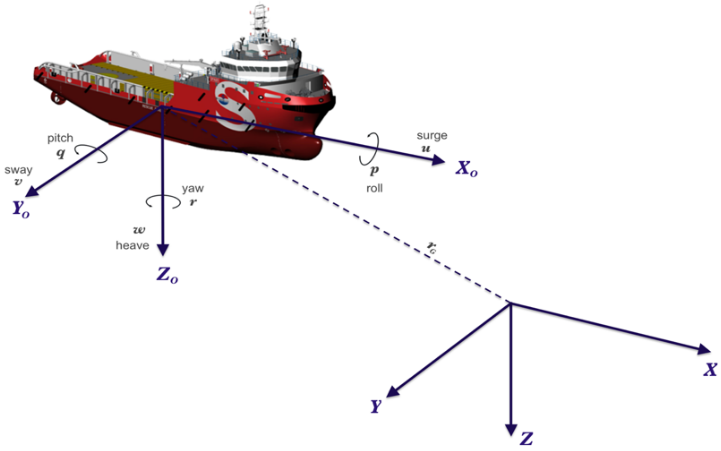
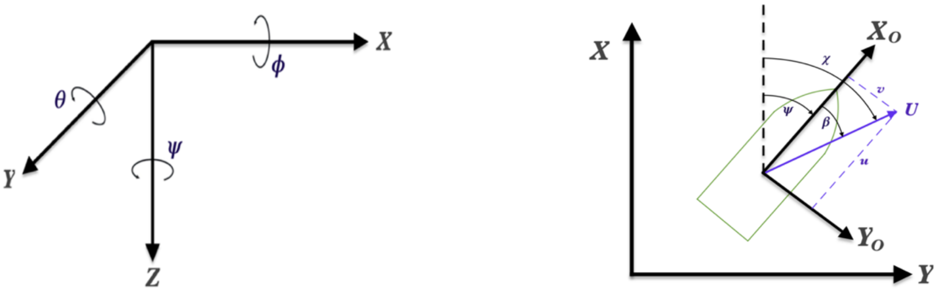


Figure 3.3 - *Reference (coordinates) frames (Body-fixed and Inertial-Earth frames) with motions and rotations in velocity terms.*

In this case, it is used Euler's equations to perform the transformation of body-fixed velocities to an absolute inertial reference frame. In *figure 3.3* it is shown the two coordinate frames used in the study of marine vehicle's motion. The moving coordinate frame, the Body-fixed frame *[X_o, Y_o, Z_o]* is fixed to the vessel. The origin O normally matches the centre of gravity (CG), in order to ease inertial calculations. This Body-fixed frame is described to an inertial reference frame *[X, Y, Z],* normally a point in the surface of the Earth (Fossen I. Thor, 1994) [2].



a) *b)*

Figure 3.4 - *(a) Angles of rotation in terms of position and orientation [roll, pitch, yaw].* **(b)** *Angles between velocity vector and both Body-fixed and Inertial-Earth frames, found in (Breivik, 2004)* [11]

Definitions

· Course angle: $\chi = \psi + \beta$ angle from Inertial-Earth frame to velocity vector *U.*
· Heading (yaw) angle: ψ angle from Inertial-Earth frame to the Body-fixed frame.
· Sideslip (drift) angle: β angle from the Body-fixed frame to velocity vector *U.*

Velocity components:
$$u = U \cdot cos\beta \tag{1}$$
$$v = U \cdot sin\beta \tag{2}$$

The motion of a marine vehicle is described by its position and velocity. The position of the vessel ($\boldsymbol{\eta}$) will be relative to the Inertial-Earth frame while the velocity ($\boldsymbol{\nu}$) will be described relative to the Body-fixed frame. The hydrodynamic forces and moments ($\boldsymbol{\tau}$) acting on a vessel are described relative to the Body-fixed frame.

- $\boldsymbol{\eta} = [x, y, z, \phi, \theta, \psi]^T$ → Position and orientation: relative to Earth-Inertial frame.
- $\boldsymbol{\nu} = [u, v, w, p, q, r]^T$ → Linear & angular velocity: relative to Body-Fixed frame.
- $\boldsymbol{\tau} = [X, Y, Z, K, M, N]^T$ → Forces and moments: relative to Body-Fixed frame.

To transform to the Euler rate vector ($\dot{\eta}$) in the Inertial-Earth frame from the Body-fixed velocity ($\boldsymbol{\nu}$) it is necessary to obtain a transformation (J_Θ) matrix relative to the orientation angles or Euler angles {*roll (Φ), pitch (θ), yaw (ψ)*}. *Euler's Rotation Theorem* states: "Every change in the orientation of two reference systems $\boldsymbol{A}$ and $\boldsymbol{B}$ can be produced by a simple rotation of $\boldsymbol{B}$ in $\boldsymbol{A}$".

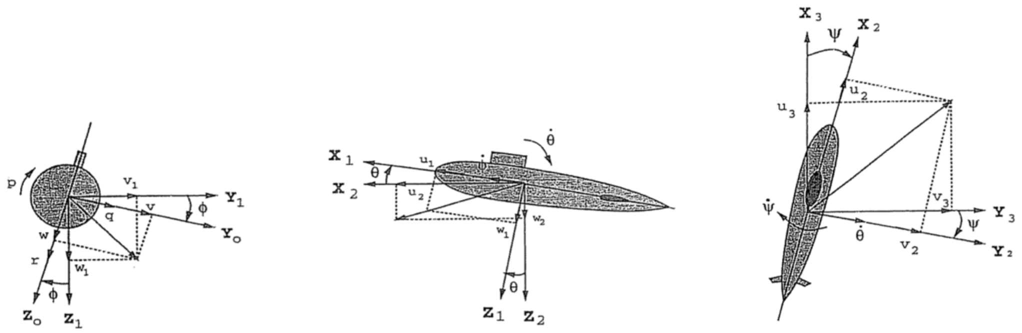


Figure 3.5 - *(a) Rotation angles or Euler angles [roll Φ, pitch θ, yaw ψ]. Transformation between Body-fixed frame and Inertial frame. Images obtained from (Fossen, 1994)* [2]

$$\dot{\boldsymbol{\eta}} = \boldsymbol{J_\Theta}(\boldsymbol{\eta_2})\boldsymbol{\nu} \quad \leftrightarrow \quad \boldsymbol{\nu} = \boldsymbol{J_\Theta^{-1}}(\boldsymbol{\eta_2})\dot{\boldsymbol{\eta}} \tag{3}$$

$$\boldsymbol{\eta} = [\boldsymbol{\eta_1}\,\boldsymbol{\eta_2}]' \qquad \boldsymbol{\nu} = [\boldsymbol{\nu_1}\,\boldsymbol{\nu_2}]'$$

$$\begin{pmatrix} \dot{\boldsymbol{\eta}}_1 \\ \dot{\boldsymbol{\eta}}_2 \end{pmatrix} = \begin{pmatrix} \boldsymbol{J_1} & O_{3x3} \\ O_{3x3} & \boldsymbol{J_2} \end{pmatrix} \begin{pmatrix} \boldsymbol{\nu}_1 \\ \boldsymbol{\nu}_2 \end{pmatrix} \tag{4}$$

$$\boldsymbol{\eta} = [x\,y\,z\quad \Phi\,\theta\,\psi]' \qquad \boldsymbol{\nu} = [u\,v\,w\quad p\,q\,r]'$$

where:

6DOF | 3DOF

$$J_\Theta = \begin{bmatrix} c\psi c\theta & -s\psi c\phi + c\psi s\theta s\phi & s\psi s\phi + c\psi c\phi s\theta & & O_{3x3} & \\ s\psi c\theta & c\psi c\phi + s\phi s\theta s\psi & -c\psi s\phi + s\theta s\psi c\phi & & & \\ -s\theta & c\theta s\phi & c\theta c\phi & & & \\ & & & 1 & s\phi t\theta & c\phi t\theta \\ & O_{3x3} & & 0 & c\phi & -s\phi \\ & & & 0 & {}^{s\phi}/_{c\theta} & {}^{c\phi}/_{c\theta} \end{bmatrix} \Rightarrow \boxed{R_\Theta = \begin{bmatrix} \cos(\psi) & -\sin(\psi) & 0 \\ \sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix}} \tag{5}$$

c=cos; s=sin; t=tan.

3.3 Dynamics

Dynamic analysis is the study of motion and the causes that cause this motion. This is the study of forces and moments that generate a movement to a body in relationship with the body's mass and inertia. It is to Sir Isaac Newton, that laid the foundations of classical mechanics with the three physical Newton's laws, that it is possible to carry out inertial studies.

Equations of Motion

The motion of a craft along a fluid can be reduced to two principle motion equations presented in (Fossen I. Thor, 1994) [2]. First one presented by the kinematics and the second equation belongs to the Newtonian and Lagrangian mechanics.

$$\dot{\boldsymbol{\eta}} = \boldsymbol{J}_{\boldsymbol{\Theta}}(\boldsymbol{\eta}_2)\boldsymbol{\nu} \tag{3}$$

$$\boldsymbol{M}\dot{\boldsymbol{\nu}} + \boldsymbol{C}(\boldsymbol{\nu})\boldsymbol{\nu} + \boldsymbol{D}(\boldsymbol{\nu})\boldsymbol{\nu} + \boldsymbol{g}(\boldsymbol{\eta}) = \boldsymbol{\tau} + \boldsymbol{\tau}_{\boldsymbol{e}} + \boldsymbol{g}_{\boldsymbol{0}} \tag{6}$$

These equations are valid for a vector state of 6 DOF.

· $M = M_{RB} + M_A$	Inertia matrix.
· $C(\boldsymbol{\nu}) = C_{RB}(\boldsymbol{\nu}) + C_A(\boldsymbol{\nu})$	Coriolis matrix.
· $D(\boldsymbol{\nu}) = D_P(\boldsymbol{\nu}) + D_S(\boldsymbol{\nu}) + D_W(\boldsymbol{\nu}) + D_M(\boldsymbol{\nu})$	Damping matrix.
· $g(\eta)$	Gravitational force.
· $\boldsymbol{\tau}$	Forces from thrusters (input to vessel model).
· $\boldsymbol{\tau}_e$	Environmental forces (disturbances).

The inertia matrix *M* of the vessel describes the dynamics of the motion when forces act on the vessel. It conditions the amount of forces and moments needed to produce an acceleration on the body, it presents the vessel's resistance to translational motion and rotational motion. It depends on the mass and its distribution, the geometry of the vessel and the axis of inertia chosen, for this reason, it is unique for each vessel. It contains components relative to the dynamics of a Rigid Body (RB) and an additional component due to forced oscillations of the environment, called Added Mass (A) component. The damping matrix *D* is due to the oscillatory movement a body is put through when waves, currents or wind act on it. It depends on the geometry of the body and the velocity through the fluid. The hydrodynamic damping components are the potential damping (P), skin friction damping (S), wave drift damping (W) and damping due to vortex shedding (M). The Coriolis matrix *C* appears when any body moves, at a considerable speed, through a fluid within the earth's rotational motion. As the inertia matrix it contains components relative to a rigid body and the added mass component due to the forced oscillation.

As it is a surface vessel the study will be focused in **3 DOF** (*surge, sway and yaw*). It is considered a nonlinear Damping matrix containing velocity terms in order to foresee a unification system which can control in a wider velocity range.

$$\cdot\ \boldsymbol{\eta} = [x, y, \psi]^T \qquad \cdot\ \boldsymbol{\nu} = [u, v, r]^T \qquad \cdot\ \boldsymbol{\tau} = [X, Y, N]^T \tag{7}$$

(a, b, c)

- $M = M_{RB} + M_A = \begin{bmatrix} m - X_{\dot{u}} & 0 & 0 \\ 0 & m - Y_{\dot{v}} & mxG - Y_{\dot{r}} \\ 0 & mxG - Y_{\dot{r}} & I_Z - N_{\dot{r}} \end{bmatrix}$ (8)

- $C(v) = \begin{bmatrix} 0 & 0 & -(m - Y_{\dot{v}})v - (mxG - Y_{\dot{r}})r \\ 0 & 0 & (m - X_{\dot{u}})u \\ (m - Y_{\dot{v}})v + (mxG - Y_{\dot{r}})r & -(m - X_{\dot{u}})u & 0 \end{bmatrix}$ (9)

- $D(v) = D_{linear} + D_{non-linear} = \begin{bmatrix} -X_u - X_{|u|u}|u| & 0 & 0 \\ 0 & -Y_v - Y_{|v|v}|v| & -Y_r - Y_{|v|r}|r| \\ 0 & -N_v - N_{|v|v}|v| & -N_r - N_{|v|r}|r| \end{bmatrix}$ (10)

The values of these parameters have been obtained from the model of a supply vessel by (Fossen 1998) [7] and (Godhavn 1998) [8]. The Coriolis term can be assumed zero as at low speed applications it does not affect significantly the vessel's motion. Further improvements have been made by (Witkowska & Śmierzchalski 2018) [1]. The resulting Bis-system matrixes:

- $M'' = \begin{bmatrix} 1.1274 & 0 & 0 \\ 0 & 1.8902 & -0.0744 \\ 0 & -0.0744 & 0.1278 \end{bmatrix}$

- $N'' = \begin{bmatrix} 0.0358 + 1.3|u''| & 0 & 0 \\ 0 & 0.1183 + 25.0|v''| & -0.0124 - 10.0|r''| \\ 0 & -0.0041 - 10.0|v''| & 0.0308 + 5.0|r''| \end{bmatrix}$

- $N'' = D'' + D_{nl}''$

$$\boldsymbol{M''\dot{\nu}} + \boldsymbol{N''(\nu)\nu} = \boldsymbol{\tau} + \boldsymbol{\tau_e} \tag{11}$$

3.4 Thruster Configuration and Actuator Dynamics

The thruster configuration determines the way in which the forces and moments are generated. Its arrangement depends on the vessel's design and will be focused on the vessel's operational requirements. This configuration is represented by the matrix (T), which depend on the distances between the propellers and the CG axis. If the thruster design contains any azimuth thruster, this matrix (T) will also depend on the angle (β) of this thruster. For this reason, this matrix is normally defined by $T(\beta)$. The thruster allocation will determine the forces and moments generated from the actuators signal (u) by the equation (12). The matrix (K) is a weight matrix that defines the magnitude of effect (force coefficients) of each element (thrusters and rudders) to each force component $[\tau_X, \tau_Y, \tau_N]$'. This vessel contains 2 main propellers, 2 bow tunnel thruster and 2 rudders. Each one represented as a column in $T(\beta)$.

The actuators represent the thruster's, propeller's and rudder's drivers. They set the amount of force generation for each propeller and the position for each rudder that should be adopted in order to achieve the desired forces from the *DP controller*. As any complex electronic device these actuators have a settling dynamics that depend on its time constants (T_i) and past values. The actuator's dynamics will determine the real value of (u), that will be interpreted by the thrusters, from the commanded signal (u_c) defined by the *control allocation.* This relationship of state and desired signal is determined by equation (13).

$$\boldsymbol{\tau} = \boldsymbol{T}(\boldsymbol{\beta})\boldsymbol{K}\boldsymbol{u} \tag{12}$$

$$\boldsymbol{T_i}\dot{\boldsymbol{u}} + \boldsymbol{u} = \boldsymbol{u_c} \tag{13}$$

$$\cdot\ T(\beta) = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 1 & 1 \\ l_1 & l_2 & -l_3 & -l_4 & l_5 & l_6 \end{bmatrix} \qquad \cdot\ K = diag([K_1, K_2, K_3, K_4, K_5, K_6]) \qquad (14)\ (15)$$

$$T_i = diag([T_{i1}, T_{i2}, T_{i3}, T_{i4}, T_{i5}, T_{i6}]) \tag{16}$$

The bis-system values for the thruster configuration model and the actuator dynamics by (Witkowska & Śmierzchalski 2018) [1]:

$$\cdot\ T'' = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 1 & 1 \\ 0.0472 & -0.0472 & -0.4108 & -0.3858 & 0.4554 & 0.3373 \end{bmatrix}$$

$$\cdot\ K'' = 10^{-3}\, diag([9.3, 9.3, 2.0, 2.0, 2.8, 2.6])$$

$$\cdot\ T_i'' = diag([1.7940, 1.7940, 1.7940, 1.7940, 1.7940, 1.7940])$$

The vessel model implemented for simulations is described in *Annex – Vessel Model.* The Matlab code contains the presented matrices and their relationships in a state space model.

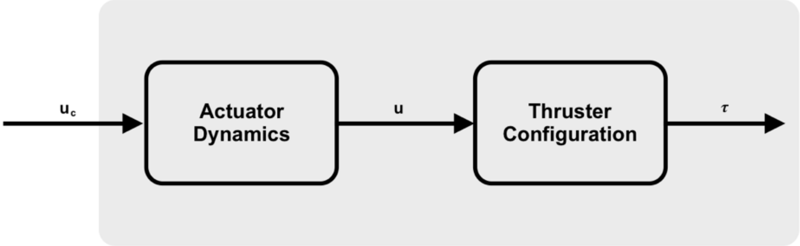


Figure 3.6 - *Actuator dynamics and thruster configuration block diagram.*

3.5 Environmental Disturbances

The environment affects the vessel's motion exerting forces and moments as disturbances. The environmental disturbances create the ship to have a fast varying component (*high frequency motions*) and a slow varying component (*slow frequency motions*). The Kalman filter separates these two types of motion to only feedback the low frequency motions. High frequency motions would create too much control and consequently a wear of the thrusters. The environmental disturbances to be considered are:

· Wind

· Waves (wind induced)

· Ocean currents

These disturbances are added to the model by the *principle of superposition* [2]. Wind and waves will create a force ($\boldsymbol{\tau}_e$) and the ocean currents will create velocities ($\boldsymbol{\nu}_c$) added to the model.

Wind

The wind exerts forces and moments to the ship by a mean wind velocity and a varying component called *gust*. The motions to be fed-forward are the low frequency motions. As said, wind forces are fed-forward to the control system. This can be done easily as wind disturbances can be easily measured by means of a wind velocity and direction sensor.

Wind spectra:

To model the wind's motion, the variations of the wind are described by a wind spectrum. Different formulations have been made by different authors in different conditions, land-based or sea-based formulations.

Harris spectrum (land-based):

$$S_w(w) = k\frac{5286 V_w(10)}{\left[1+\left(\frac{286w}{V_w(10)}\right)^2\right]^{5/6}} \tag{17}$$

· k = turbulence factor.
· $V_w(10)$ = average wind speed at 10m above surface (knots).
· w = frequency of wind oscillations (rad/s).

Spectral formulations are non-linear approximations. In (Fossen, 1994) [2] there is a 1st order linear approximation:

Wind forces and moments:

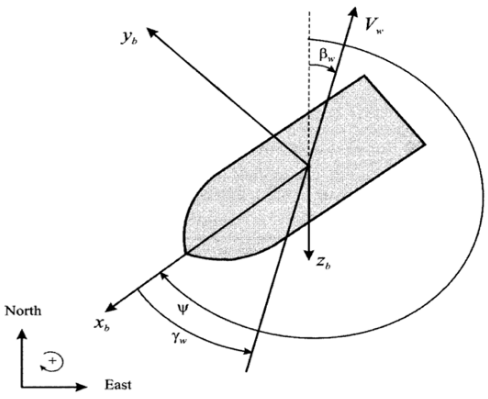


***Figure 3.7 -** Wind velocity vector (V_w) and wind direction (β_w) and angle of attack (γ_w))respect to Earth-Inertial frame (Fossen, 2011)* [4]

The wind forces and moments create a tension vector (τ_{wind}) depending on the wind's velocity and direction, which can be measured using a *anemometer*.

· Wind velocity at height z(m) or velocity profile:

$$V_w(z) = V_w(10) * \left(\frac{z}{10}\right)^{1/7} \tag{18}$$

The tension vector created on the vessel in motion will depend on the *Resultant* wind speed and angle of attack, being:

· Relative velocities:

$$u_{wr} = u - V_w \cos(\beta_w - \psi) \quad ; \qquad v_{wr} = v - V_w \sin(\beta_w - \psi) \quad ; \qquad (19)\ (20)$$

being *u* and *v* the ships velocity in surge and sway respectively.

· Relative wind speed and angle of attack:

$$V_{wr} = \sqrt{u_{wr}^2 + v_{wr}^2} \tag{21}$$

$$\gamma_{wr} = -\mathrm{atan}^2\left(\frac{v_{wr}}{u_{wr}}\right) \tag{22}$$

· Wind forces and moments:

$$\tau_{\mathrm{wind}} = \begin{bmatrix} X_{\mathrm{wind}} \\ Y_{\mathrm{wind}} \\ N_{\mathrm{wind}} \end{bmatrix} = \begin{bmatrix} \frac{1}{2}\rho_{\mathrm{air}} V_{\mathrm{wr}}^2 C_X(\gamma_{\mathrm{wr}}) A_{\mathrm{FW}} \\ \frac{1}{2}\rho_{\mathrm{air}} V_{\mathrm{wr}}^2 C_Y(\gamma_{\mathrm{wr}}) A_{\mathrm{LW}} \\ \frac{1}{2}\rho_{\mathrm{air}} V_{\mathrm{wr}}^2 C_N(\gamma_{\mathrm{wr}}) A_{\mathrm{LW}} L_{\mathrm{OA}} \end{bmatrix} \quad (23)$$

being C_X, C_Y and C_N wind coefficients for surge, sway and yaw respectively and A_{FW} and A_{LW} frontal and lateral projected areas.

Waves (wind generated)

Wind generated waves produce forces with slow varying components and an oscillating component. The oscillating component is due to the proper wave frequency, which is normally removed by what is called *wave filtering.* The control system can not take in account this forces as it would deteriorate the thrusters due to an exceeding control action. The slow varying force due to wave drift forces are considered 2nd order forces which are fed-back to the control system in order to be compensated as a disturbance. As wind, waves are characterized by a wave spectrum and are normally represented by a sum of wave components (Fossen, 1994) [2].

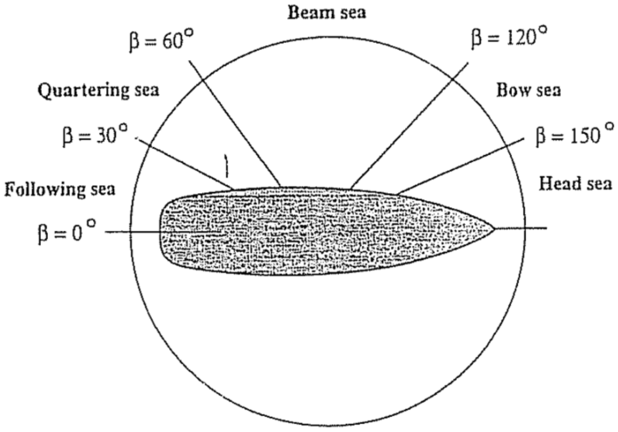


Figure 3.8 - *Encounter angle (β) for wave forces and moments (Fossen, 1994)* [2]

For ships with velocities greater than zero (U > 0) the frequency of the waves is described by an *encounter frequency*:

$$w_e = w_0 - \frac{{w_0}^2}{g} U cos(\beta) \quad (24)$$

· w_0 = wave frequency (Hz).
· U = vessel's speed (m/s).
· g = acceleration of gravity (m/s^2)

An approximation to the *wave spectrum* including the frequency of encounter is described in the form of transfer function:

$$h(s) = \frac{K_w s}{s^2 + 2\xi w_e s + {w_e}^2} \tag{25}$$

The wind forces and moments are described in terms of the spectrum and a slowly varying bias term (d_i):

$$\tau_{\text{wave}} = \begin{bmatrix} \text{X}_{\text{wave}} \\ \text{Y}_{\text{wave}} \\ \text{N}_{\text{wave}} \end{bmatrix} = \begin{bmatrix} \dfrac{{K_w}^{\{1\}} s}{s^2 + 2\lambda^{\{1\}} w_{e1} s + {w_{e1}}^2} w_1 + d_1 \\ \dfrac{{K_w}^{\{2\}} s}{s^2 + 2\lambda^{\{2\}} w_{e2} s + {w_{e2}}^2} w_2 + d_2 \\ \dfrac{{K_w}^{\{6\}} s}{s^2 + 2\lambda^{\{6\}} w_{e6} s + {w_{e6}}^2} w_6 + d_6 \end{bmatrix} \tag{26}$$

Where w_i $(i = 1, 2, \dots, 6)$ are Gaussian white noise processes. This processes uses the frequency of encounter w_{ei} $(i = 1, 2, \dots, 6)$ for a moving ship with (U > 0). For a stationary vessel the frequency used should the proper wave frequency w_0. The wave spectrum parameters ($\lambda^{\{i\}}$ and w_{ei}) should represent the real sea state, while the amplitude of the wave is adjusted by ${K_w}^{\{1\}}$.

Ocean Currents

The Ocean currents are added to the model by taking in consideration the currents velocity (ν_c). The current velocity depends on the phenomena that produces the motion.

$$\nu_c = \nu_{tidal} + \nu_{local\ wind} + \nu_{nonlinear\ waves} + \nu_{ocean\ circulations} + \nu_{storms} + \nu_{density\ currents} \tag{27}$$

Being then the relative velocity vector: $\nu_r = \nu - \nu_c$. It is possible to rewrite the equation of motion's model:

$$M\dot{\nu}_r + C(\nu_r)\nu_r + D(\nu_r)\nu_r + g(\eta) = \tau + \tau_e + g_0 \tag{28}$$

Assuming a negligible current acceleration ($\dot{\nu}_c$ = 0):

$$M\dot{\nu} + C(\nu_r)\nu_r + D(\nu_r)\nu_r + g(\eta) = \tau + \tau_e + g_0 \tag{29}$$

For a surface vessel we consider the motions in a 2-Dimensional case model. Being the transformation from the Earth-Inertial frame to the Body-Fixed frame:

$$\begin{bmatrix} u_c \\ v_c \end{bmatrix} = J_\Theta{}^T(\eta) \begin{bmatrix} u_c^E \\ v_c^E \end{bmatrix} \tag{30}$$

Environmental Disturbances Model

The model to be used in the simulations will correspond to the obtained by (Witkowska & Śmierzchalski 2018) [1] which represent the environmental dynamics, with the slow varying disturbances described by the bias term $\mathrm{b} = [b_1 \; b_2 \; b_3]^T$:

$$\boldsymbol{\tau_{env}} = \boldsymbol{J_\Theta}^T(\boldsymbol{\eta})\mathbf{b} \tag{31}$$

$$\dot{\mathbf{b}} = -\mathbf{F}^{-1}\mathbf{b} + \mathbf{Ew} \tag{32}$$

With the values of time constant	$\mathrm{F} = diag\,\{[1000{,}1000{,}1000]\}$;
and gain matrix	$\mathrm{E} = diag\{[3000{,}3000{,}30000]\}$.

The environmental model implemented in the simulations is described in the *Annex – Environmental Disturbances.* It represents a varying noise signal that goes incrementing in time.

Chapter 4: Modern Predictive Control

4.1 Multilayer Control

A control system is a system unit intended to influence a process to operate in a desired way in conformity with certain requirements. The controlled object is always affected by its surrounding environment, being these effects controlled or uncontrolled, it is to the control system the responsibility to act in accordance to compensate these disturbances. In every control unit it can be identified three types of variables:

- *Manipulated variables*: are the inputs to the object that can be controlled. An example can be an electro-valve which determines the flow of a substance, being the manipulated variable the opening degree of the valve.
- *Disturbances*: are the inputs to the process object that cannot be controlled. Examples could be noises in an electric system or environmental forces on a ship.
- *Process output variables*: are the outputs of the system which can be measured. Examples can be the flow out of a tank, the position or velocity of a ship or the voltage of a transformer.

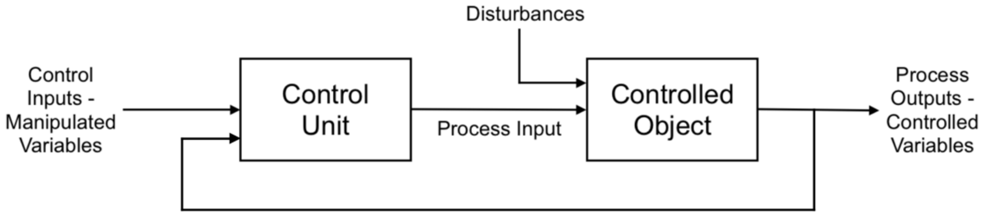


Figure 4.1 - *Scheme of a Control System*

The control to be implemented, which is the primary object of study of this project, is a multilayer control. Multilayer control is a design with a hierarchy of decision where each layer defines the reference or set-points for each subsequent system. In this way a more accurate control is acquired, simplifying the design and supervision of the partial sub-systems. In multilayer control structures the layers are divided in function of the control objectives. Control objectives are normally related to economic objectives which can be divided to partial objectives as found in (Tatjewski, 2007) [13]. In general, the three most important objectives:

1) *Safe operation*: To ensure a safe operation within the limits of the process. This objective if failed can affect the safety of the workers and means immediate stops in the process and rearrangement in the operations which will cause big economic losses. *Direct Control Layer.*
2) *Required features*: To ensure the required operation of the process within the expected quality. Also, this objective if failed will affect the quality of the final product causing also a significant economic loss. *Constrain Control Layer.*
3) *Optimization*: This objective affects the methods of operation and the effectiveness of the system. In comparison to the other two objectives, this objective if failed can cause partial economic losses, as the process or product will not fulfil economic requirements. *Optimization Layer.*

The order of importance is as enumerated above. The safety of the dynamic process is attended in the *direct control*, the only layer in contact to the controlled object. This layer is in charge of the fast dynamics of the process. The layer responsible for setting the qualities required features is the *constrain control* layer that will set the direct control's set-points ensuing a control on the slower dynamics of the process. The layer responsible to establish the optimal operating point to influence the system to obtain the desired goals is optimization layer. The goals, operation methods and production parameters have to be defined in a decision operation made by the plant management layer. This layer will be incorporated at the top of the layer structure.

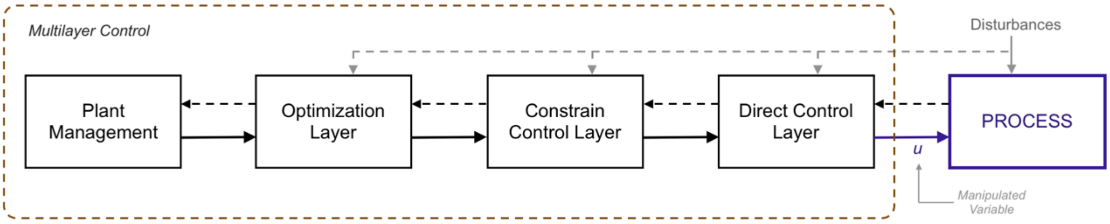


Figure 4.1 - *Multilayer control structure. Continuous lines represent the set-points and references to the next layer controllers. Dotted lines represent feedback measurements.*

The frequency of intervention of each layer goes decreasing along with the importance of the layer relative to the performance on the process. The direct control, which controls the fast dynamics, should in consequence have a fast sampling period of less than a second, in order to obtain rapid reactions of the controller. The constrain layer can have a more relaxed sampling period of about some minutes, while the optimization layer can have longer periods depending on the variations of the disturbances. Finally, the plant management will have frequencies of intervention that can last for a whole production day or more.

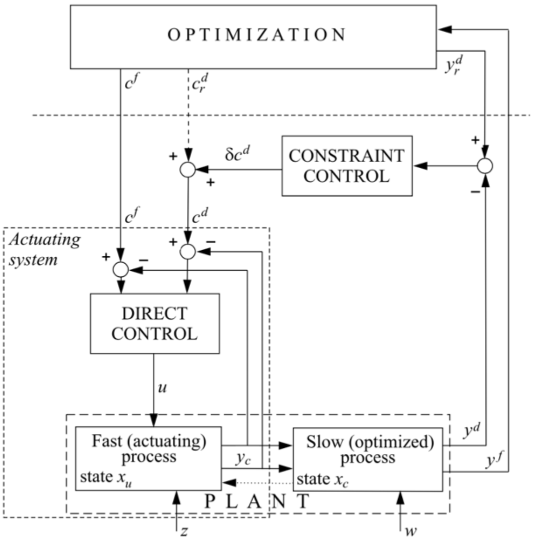


Figure 4.2 - *Multilayer control structure with decomposition of plant dynamics by (Tatjewski, 2007)* [13]

The structure is presented by (Tatjewski, 2007) [13], which shows how each layer acts on the system. It is identified the fast varying process affected by fast varying disturbances (z) and as input the manipulated variable (u) from the direct control. The output of this process (y_c) is the input to the slow varying process which is affected by the slow disturbances (w). The output of the plant process (y) is a vector $\{y^d,\ y^f\}$ of the controlled output component "d" and the free output component "f". The constrain control pursues to obtain y^d to the desired value y_r^d defined by the optimization layer. Variables denoted (c) are the set-points defined by both the optimization and constrain controllers.

These set-points should ensure a stable y_c that provides a safe control on the process and satisfies the feasibility of the process. If any of these two conditions are not satisfied the goals and parameters should be checked to accomplish a correct realisation.

4.2 Modern Predictive Control

Modern predictive control is a relatively new design of what is known as predictive control. Predictive control is based on the human's ability to take decisions, in the way that it anticipates to possible consequences of a determined action. Predictive control calculates output estimations in order to perform an optimal solution. It manages to calculate these solutions within a recessive horizon, which in each new measurement it processes new calculations with updated information.

MPC principle

The predictive control principle is shown in *figure 4.3* which is based on (Tatjewski, 2007) [13]. The predicted calculated values will be obtained for discrete intervals of time. The output (y) will be calculated every instant (k) up to the end of the horizon value (N). The value for $y(i|j)$ will be the predicted output in the moment (i) measured in the instant (j), normally referred as $y(k+p|k)$. The objective of the controller is to approximate the predicted value (y) to a reference trajectory (y^{ref}) by changing the value of the input (u). This is known as the *cost of deviation of the predicted outputs from the set-points.* The value of the predicted output $y(k+p|k)$ will depend on both past values of the input ($u(k-1)$) and future values $u(k+p-1|k)$. The inputs normally vary in sampling steps up to a control horizon (N_u) which can be shorter than the prediction horizon $N_u < N$.

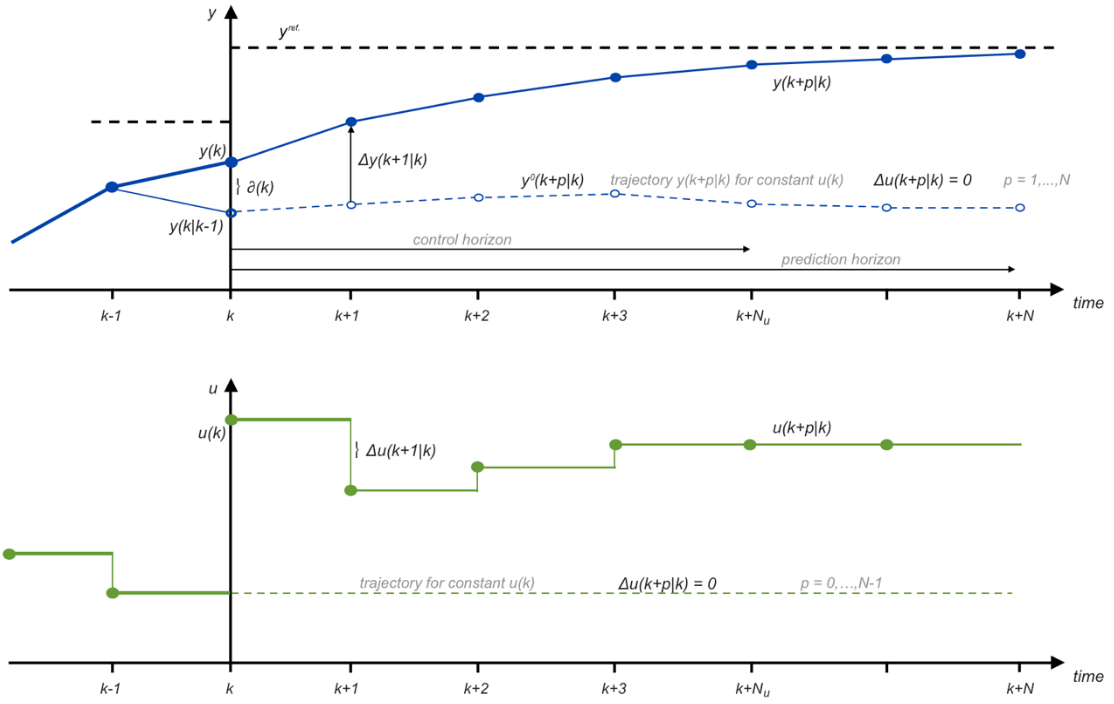


Figure 4.3 - *Predictive control principle for a SISO process. Based on (Tatjewski, 2007)* [13]

The controller determines at each sampling instant the values of the predicted outputs and control inputs by analysing a cost function or *objective function*, which will consider the penalties or costs of the deviation between the predicted output and reference value and a penalty for the control input changes.

$$J(k) = \sum_{p=N_1}^{N} \left\| y^{ref}(k+p|k) - y(k+p|k) \right\|_{\Psi}^{2} + \sum_{p=0}^{N_u-1} \left\| \Delta u(k+p|k) \right\|_{\Lambda}^{2} \quad (33)$$

Matrix Ψ and matrix Λ are weight diagonal matrices corresponding to the outputs and control inputs. They scale the influence of the different components to the cost function. In order to perform calculations, the algorithm requires a process model to obtain output values or measured variables from the control inputs or manipulated variables. For linear process models it is possible to apply the *principle of superposition* for the trajectory of the predicted outputs $y(k+p|k)$ by adding a *free trajectory* $y^0(k+p|k)$ dependant only on past process inputs and a *forced output trajectory* $\Delta y(k+p|k)$ which depends on future process inputs.

$$y(k+p|k) = y^0(k+p|k) + \Delta y(k+p|k) \quad (34)$$

As the *free trajectory* only depends on past values of the process inputs, in the algorithm they are calculated only once in each step, at the sampling instant k. It is the *forced output trajectory* which is calculated at each sampling instant $(k+p)$. For non-linear process models the process is different. It is not possible to decompose into independent components of free and forced output trajectories. This makes the problem become a non-convex optimization problem and the numerical optimization process becomes much more complex making it common to encounter local minima instead of a global optimum.

MPC algorithms work minimizing with the cost function along with a set of constrains of the output values and the process inputs. These constrains constitute an important factor when minimizing the cost function, making it possible that at a certain sampling instant k the set of results become unfeasible, an unwanted situation in MPC algorithms.

MPC control law

Predictive control has had different generations of algorithms. *Dynamic Matrix Control* is considered the first generation of MPC algorithms, then to avoid constrain problems that appeared in DMC came the *Quadratic Dynamic Matrix Control* which corresponds to the second generation of MPC algorithms. Then the *Generalized Predictive Control* was later proposed and used discrete transfer functions as process models. It developed the receding horizon predictive control and made the *Shell Multivariable Optimizing Controller* to appear and constitute the third generation of MPC algorithms. In the present days the algorithms that consider nonlinear processes are known as the fourth generation of MPC algorithms and constitute the *Modern Predictive Control* controllers. Without getting in detail of the past generation algorithms, it has to be said that the modern controllers have a big influence on their previous generations.

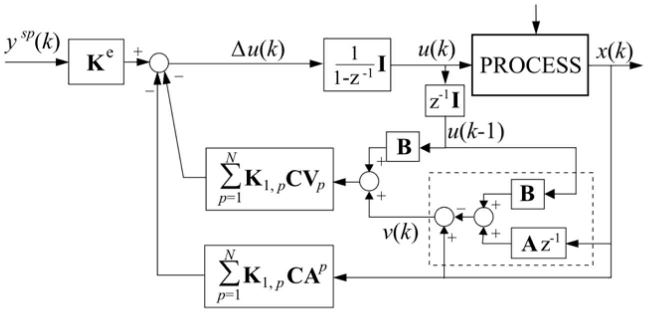


Figure 4.4 - *Unconstrained explicit MPC control law structure obtained from (Tatjewski, 2007)* [13]

The structure of the MPC algorithm shown in *figure 4.4* represents the control law of how the MPC works. It develops a process input $u(k)$ from a set-point value $y^{sp}(k)$. It operates with a linear feedback from the current measured state $x(k)$ and the last process input value $u(k-1)$. Z^{-1} represents a discrete unit step delay and $\frac{1}{1-z^{-1}}I$ represents the discrete multivariable integration. This represented control law in *figure 4.4* can be written:

$$\Delta\hat{u}(k) = K^e y^{sp}(k) - \sum_{p=1}^{N} K_{1,p}[CA^p x(k) + CV_p(Bu(k-1) + v(k))] \tag{35}$$

Where in the equation (35) we distinguish matrix K^e, a gain matrix that contains the $K_{1,p}$ values for each set-point value. Then matrix $K_{1,p}$ that depends on a dynamic matrix M that contains the step responses for each time interval $(k+p)$. A, B, C and V are structure matrices that represent the state space process model. Lastly variable $v(k)$ represents the disturbances that act on the process are fed-back as measured disturbances.

This structure of *figure 4.4* represents a linear process model. For a nonlinear model where nonlinear equations define the predicted trajectory and so the *principle of superposition* can not be held. It is practically impossible to decompose the trajectory into the free and forced components. What is common, is to perform an approximate linearization of the nonlinear model at each sampling instant and then apply the linear MPC algorithm. In *figure 4.5* the structure for a nonlinear model is presented. This method is called MPC-NSL (*Nonlinear with Successive Linearization)* and it is a suboptimal approach while the operating point stays close to certain equilibrium points.

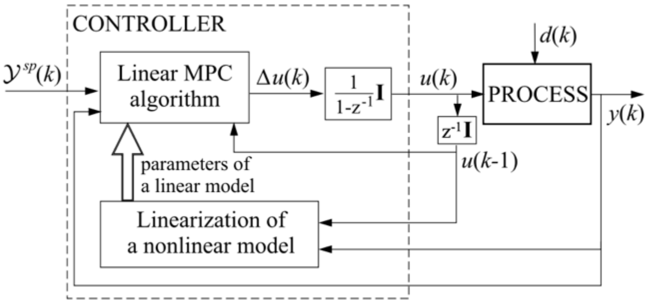


Figure 4.5 - *Structure of a nonlinear MPC with successive linearization of the process model obtained from (Tatjewski, 2007)* [13]

Chapter 5: Control Algorithm

5.1 Identification of Controllers

The controllers which are needed to be designed are the *DP-Controller* and the *Thruster Allocation Controller*. The first controller, the Dynamic Positioning Controller, is the controller in charge of defining the desired thruster forces from the position reference. This controller will be designed as a PID controller. The second control, the Thruster Allocation Controller, will be designed as an MPC controller. This controller will be in charge of setting the thrusters actuators signals from the desired thruster force in order to the forces from the thrusters and propellers resemble these desired forces.

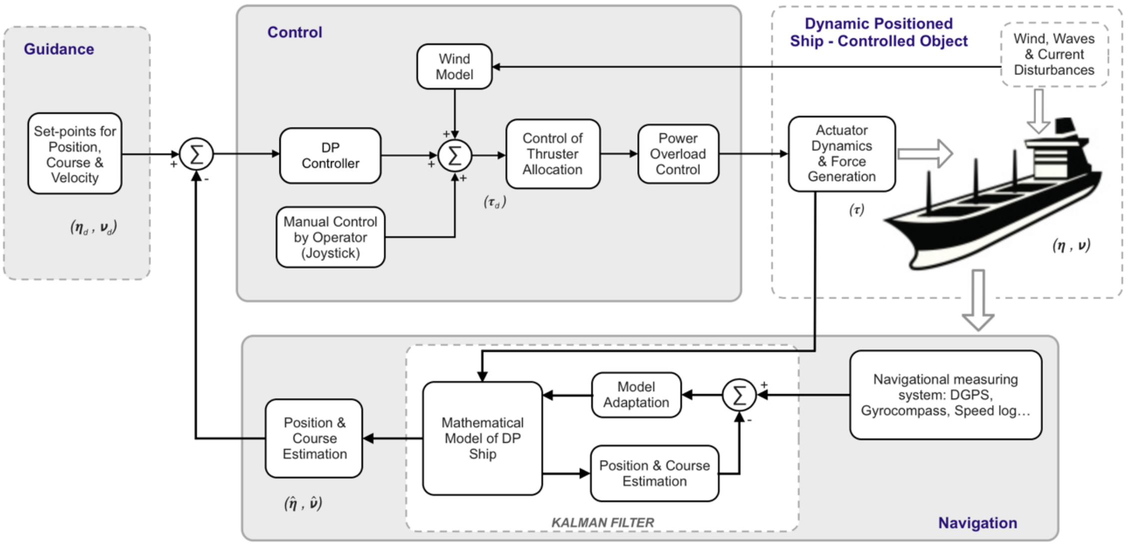


Figure 5.1 - *System structure. Based on (Śmierzchalski, 2013)* [9]

Figure 5.1 shows the control system structure. The guidance system for this case is the operator's inputs of waypoints and speed parameters which compose the *reference position*. The reference position is then compared with the actual estimated state of the vessel. This error between the desired state and actual state is the input to the DP Controller which sets the desired thruster forces to compensate the error. Depending on the mode the operator can adjust the sway or the position of the vessel manually, by means of joysticks, commanding a desired force by the Manual Control. To this set of commanded forces, it is added the wind's low varying forces that exert on the vessel and this sum of forces constitutes the input to the Thruster Allocation Controller. This controller transforms the desired forces into actuators signal. These actuators are in charge of managing the thrusters, propellers and rudders actions. The Thruster Allocation Controller must have information about the thruster's dynamics so it can perform the optimal actuators signal that will ensure that the thrusters produce real forces that coincide with the desired forces. In the MPC solution for the Thruster Allocation Controller the Power Overload Control, which saturates the actuators signal so that thruster limitations are taken in account, will be included as constrains of the predictive system.

After setting the commands of the actuators signal to the vessel, the actuator and thruster dynamics will generate a force which by adding the disturbance's forces will result in the real force acting on the vessel. This force, depending on the vessel's dynamics, will impose a motion to a new position which may or not be the desired reference position. This error has to be measured by estimating the vessel's real state by means of sensors and navigational measuring systems. These measurements will be processed by the *observer* which will determine an estimated state of the real position and velocity. In the *Kalman filter*, inside the observer, the measurements will be applied to a mathematical model included in the system. It is in this process that an estimation of the actual state of the vessel is done and again compared to the results of the navigational measurements. This is done to reinforce the estimation and to clear out noises and high frequency disturbances of the sensor's measurements.

Figure 5.2 - *Ship's Control Bridge from iXblue* [22]

5.2 DP Controller

The DP controller is in charge of setting the desired force to compensate the error between reference position and actual real position. It is the first part of the control system and it is intended to focus primarily on *dynamic positioning.* The DP Controller selected corresponds to a PID controller. PID based controllers have proved to work effectively as dynamic positioning control systems. PID controllers for dynamic positioning can be implemented as PD controller or PID controllers. The first, PD, will ensure a *directional stability*. It will maintain a parallel path to the original after a disturbance. With this type of control, it is recommended to set a variety of set-points close to each other, in order to not loose track from point to point. A PID controller provides positional motion stability. It will return to the original path after disturbance effects.

$$\tau_{PID} = -\boldsymbol{K_P} J_{\Theta}(\psi)'(\eta_{REF} - \tilde{\eta}) - \boldsymbol{K_D}\nu - \boldsymbol{K_I}\int(\eta_{REF} - \tilde{\eta})\,dt \tag{36}$$

The algorithm that the PID controller uses to set the desired forces is formulated in equation (36) presented by (Fossen, 1994) [2] and the function-block in the system is represented by *figure 5.2*.

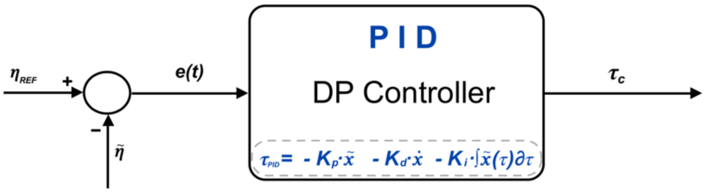


Figure 5.3 *- PID – DP controller function block*

The method used to obtain efficient values for K_P, K_D and K_I has been the optimization method implementing *genetic algorithm*. The genetic algorithm optimization calculated the parameters K_P, K_D and K_I that minimized an error function J, shown in equation (37). This objective function to minimize takes in account the error from the desired reference position $\eta_{REF} = [x\ y\ \psi]_{REF}$ and the real position $\eta = [x\ y\ \psi]$ and the rate of change of the commanded actuators, by calculating its variance (σ^2).

$$J = A \cdot \sum (\eta_{REF} - \eta) + B \cdot \sum_{i=1}^{6} \sigma^2(u_i c) \tag{37}$$

Being A and B weight parameters to enforce the position error or the actuators variance, respectively. The implemented code is presented in the *Annex – Genetic Algorithm*. The resultant values obtained that best fitted in the model for various path tracking applications are for a PD - Controller:

$$K_P = \begin{bmatrix} 0.129 & 0 & 0 \\ 0 & 0.126 & 0 \\ 0 & 0 & 0.010 \end{bmatrix}; \qquad K_D = \begin{bmatrix} 3.491 & 0 & 0 \\ 0 & 3.482 & 0 \\ 0 & 0 & 0.200 \end{bmatrix}; \qquad K_I = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix};$$

5.3 Thruster Allocation Controller

The Thruster Allocation is the part of the control destined to design the propeller's and thruster's actuator signal. The input to this control system will be the desired or commanded thruster force (τ_c), determined by the DP controller. The control allocation will determine the commanded actuator signal (u_c) as the output of the system. The objective is to design a MPC based controller for this purpose. The designed MPC controller will be compared to an already functional controller provided by Dr. Witkowska based on a *quadratic programming* optimization method. The thruster control allocation must be aware of the capabilities and limitations of the propellers and thrusters design, in order to perform optimal performance and not tear the elements involved in the force generation. In addition, the actuators limits must be taken in account so the optimization algorithm does not look for unfeasible solutions.

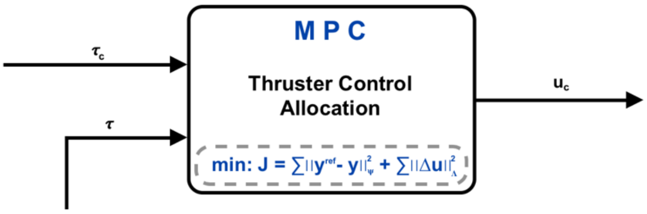


Figure 5.4 *- MPC – Control Allocation function block*

Modern Predictive Control controllers translate these limitations as a set of constrains which the objective function to minimize is subject to. Other control methods to perform this have to add saturation blocks for the different elements involved in the control algorithm. The objective function implemented in the MPC controller with the respective constrains is as follows in equation (38) presented in (Tatjewski, 2007) [13]. The goal of the MPC controller is to minimize the difference between the commanded forces determined by the DP controller and the actual real force exerted on the vessel. The constrains have been implemented, as the model, in the bis-scale system and have been taken from (Witkowska & Śmierzchalski 2018) [1].

$$\min\ J = \sum_{p=N_1}^{N} \|\tau_c(k+p|k) - \tau(k+p|k)\|_{\Psi}^2 + \sum_{p=0}^{N_u-1} \|\Delta u_c(k+p|k)\|_{\Lambda}^2 \tag{38}$$

$$\text{subj to:} \qquad -1 \le u_{ci} \le 1 \tag{38a}$$

$$-\frac{7.5502\cdot 10^4}{mg} \le \tau_X \le \frac{7.5502\cdot 10^4}{mg} \tag{38b}$$

$$-\frac{2.5272\cdot 10^5}{mg} \le \tau_Y \le \frac{2.5272\cdot 10^5}{mg} \tag{38c}$$

$$-\frac{\pi}{180}\cdot\frac{4.1894\cdot 10^4}{mgL} \le \tau_N \le \frac{\pi}{180}\cdot\frac{4.1894\cdot 10^4}{mgL} \tag{38d}$$

Where N and N_u are the prediction horizon and the control horizon respectively. Being the sampling moment k and the predicted moment $(k+p)$. The weights adopted for the *measured variables* (Ψ) and the *manipulated variables* (Λ) have been assumed to fit the needs and capabilities of the force generating system. The propellers have the less penalty weight as they are the elements that work the most and exert the most influence in the force components. The tunnel thrusters have some more penalty weight as it is intended to make the propulsion thruster work more than the tunnel thrusters, but as they perform good angle control and compensate the incident lateral disturbances they have a relative small penalty weight. The rudders have the highest penalty weight as their action at low speed can be assumed ineffective, being more adequate in path tracking applications.

- Output weight (measured output):

$$\Psi = \{1\ 1\ 1\}$$

The measured output corresponds to the force in X and Y and the rotational moment in Z. They are all equal to one as there no reason for one force to be more exploited than the others. Meaning that the forces can appear in each direction without any restriction.

- Input weight (manipulated variable):

$$\Lambda = \{0.001\ 0.001\ 0.01\ 0.01\ 0.1\ 0.1\}$$

The prediction horizon and the control horizon have been chosen relatively short in order to attend to environmental disturbances that may vary in a certain moment and may cause the predicted output values to not take in account these changes if a horizon too long. This is why the prediction horizon and the control horizon has been chosen to be:

$$\mathrm{N} = 10 \qquad\qquad \mathrm{N}_u = 2$$

As measured disturbances the MPC design does not contemplate the disturbances by its own, but they are subtracted to the desired force of the DP controller. By doing this, the MPC controller assumes that the actuator signal that have to be manipulated have to give a signal that will generate a force with the disturbances force subtracted, which after are added to the vessel so we obtain a resultant force equal the desired force. In this way the disturbances are not contemplated as measured disturbances to the MPC design but are compensated with the action of the actuators.

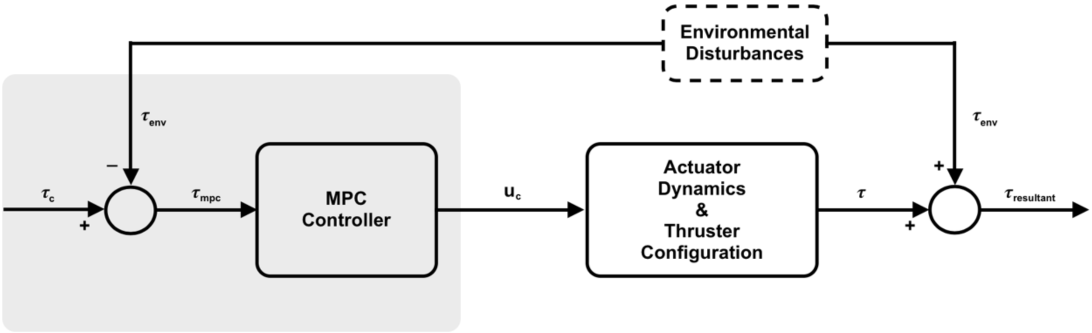


Figure 5.5 - *MPC – Environmental disturbances compensation*

The MPC controller sets the actuators signal (u_c) in order to set the force (τ) to equal the input to the MPC, in this case (τ_{mpc}).

$$\tau \approx \tau_{mpc} = \tau_c - \tau_{env} \tag{39}$$

As the disturbances are subtracted at the input of the MPC controller the resultant force after being added the disturbances should be similar to the desired forces set by the DP controller.

$$\tau_{res} = \tau + \tau_{env} \approx \tau_c \tag{40}$$

Chapter 6: Simulation Results

The results presented are a comparison between using MPC controller as Thruster Allocation and Dr Witkowska's Quadratic Programming optimization method.

Quadratic Programming Controller

In quadratic programming it is observed that the desired path is well followed with at most 1 metre of deviation. On the selected waypoints the vessel maintains position with very small displacements, but at the expense of a great use of the propellers and thrusters and practically no use of rudders, as it can be seen in *figure 6.3* where it shows the actuators signal (real actuators in red). It is when the reference angle changes, where the vessel experiences the biggest deviation from the waypoint. This is due to the use of the propellers and bow thrusters to change the ships direction that inevitably affects the ship's position. The settling times for each DOF is adequate being at its most of a 100 seconds, taking in account the movement between waypoints it is an acceptable value, as for a vessel so big and heavy the motion becomes a slow process.

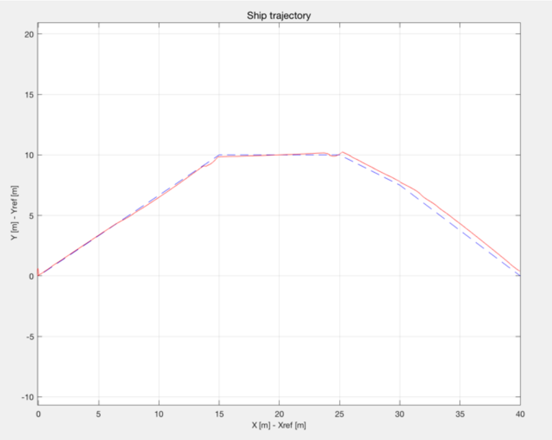


Figure 6.1 - *Ship reference trajectory (blue) and ship real trajectory (red)*

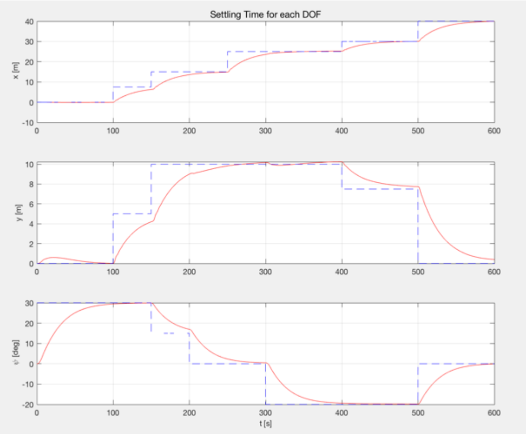


Figure 6.2 - *Settling time for each direction X, Y and for angle psi. Reference (blue) Real (red).*

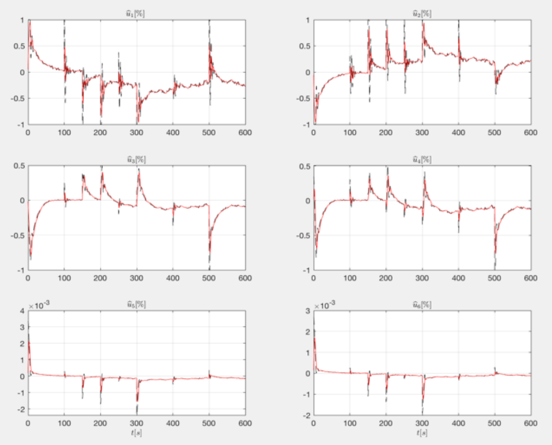


Figure 6.3 - *Actuators signal. U commanded (black) & Real U (red)*

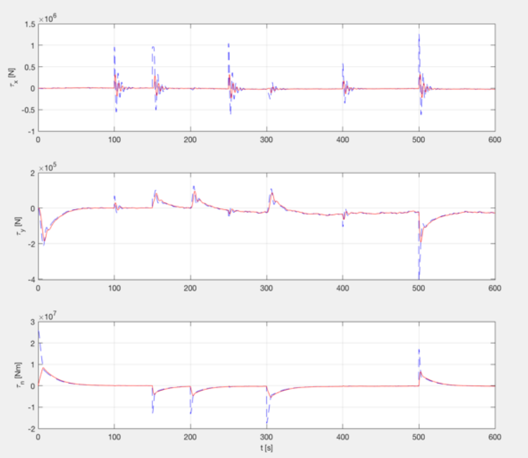


Figure 6.4 - *Forces commanded by DP controller (blue) and actual force exerted on vessel (red).*

MPC Controller

The MPC controller presents similar results to the quadratic programming method. It presents a better path tracking control, with some small deviations. It is in the middle part of the desired path where it comes down the Y value and it presents the biggest deviation. It could have been solved by letting the angle reach and settle in its reference value before commanding new *x* and *y* waypoint. In comparison with the QP controller the MPC control at the first angle change it manages to change direction without displacing the ship as much from the waypoint. Moreover, the changes in angle do not affect as much the path in X and Y as the QP controller. In addition, the position keeping in the selected points is more precise with less movement of the ship. The actuators are used in a smoother way and the rudders are being much more used, which is translated to a less use of propeller and thruster to change direction which means less fuel consumption. This is achieved as a result of the predictive values with the recessive horizon, which attends better to changes. Furthermore, the MPC controller obtains slightly better settling times.

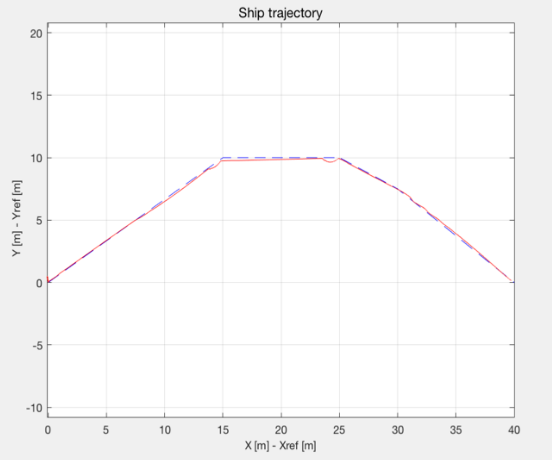


Figure 6.5 - *Ship reference trajectory (blue) and ship real trajectory (red)*

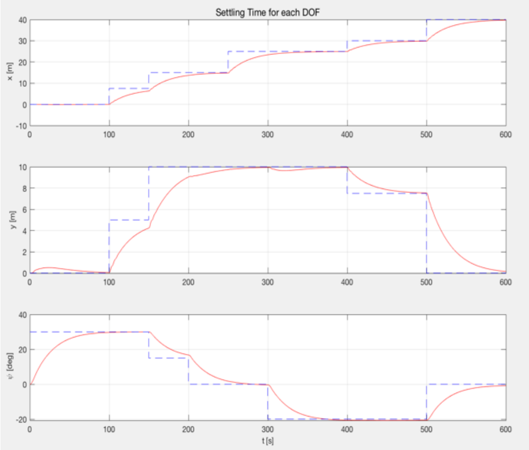


Figure 6.6 - *Settling time (Bis-Scale) for each direction X, Y and for angle psi. Reference (blue) Real (red).*

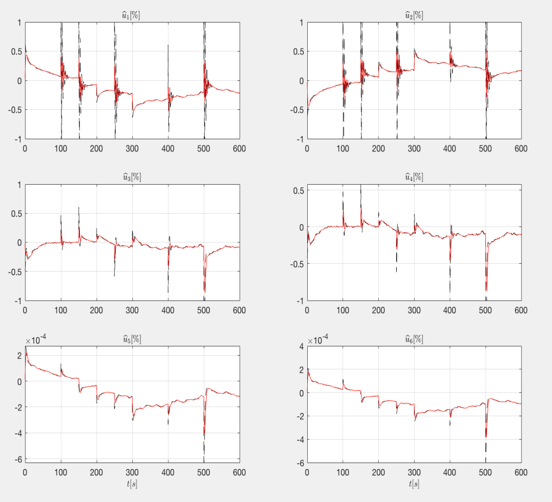


Figure 6.7 - *Actuators signal. U commanded (black) & Real U (red)*

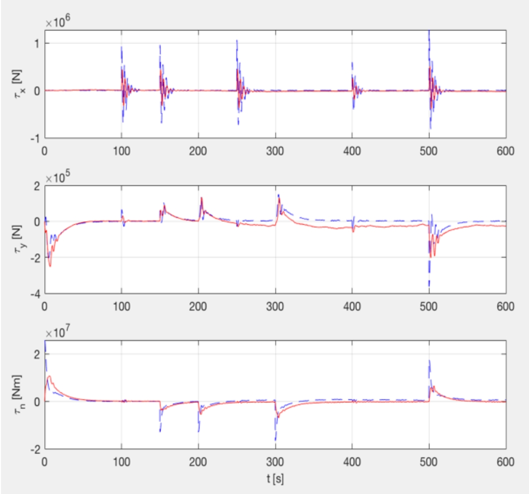


Figure 6.8 - *Forces commanded by DP controller (blue) and actual force exerted on vessel (red).*

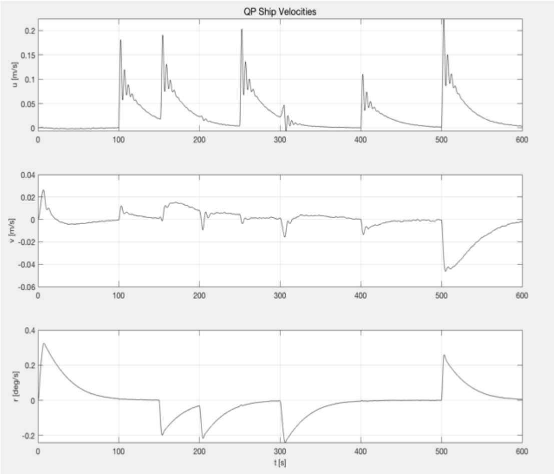


Figure 6.9 *- Velocities in X and Y and angle variation for the QP controller with time in the real scale.*

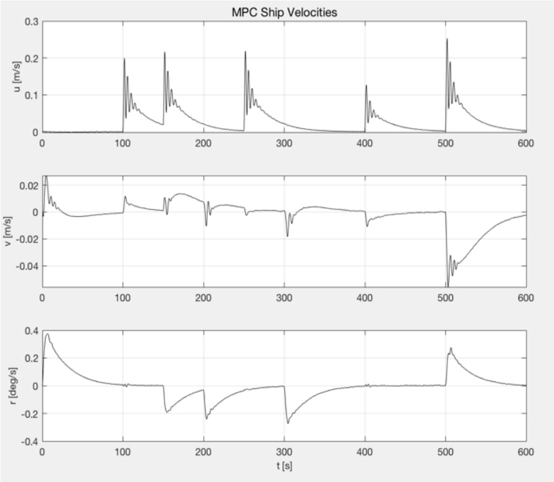


Figure 6.10 *- Velocities in X and Y and angle variation for the MPC controller with time in the real scale.*

The velocities attained by the ship for both controllers are quite similar in the large scale. They have similar shapes and present their peaks at the same time intervals, but they differ on the way they extend in the short scale. QP controller shows a smoother velocity continuity on the X axis of the ship (u velocity) getting, in some points, to negative values when position keeping, while the MPC controller shows an oscillating u velocity getting to a zero value in position keeping. Moreover, the peaks of the MPC for this u velocity are greater making the shorter settling times when the waypoint changes. In contrast with the X axis velocity, the Y axis velocity (v velocity) presents a more oscillating velocity for the QP controller and a smoother continuity for the MPC controller between peaks, but the MPC shows more oscillations at the peak points. This is probably due to the weights each controller has adopted for the tunnel thrusters. The MPC controller adopted a weight higher than the propellers and in the QP controller the weight of the tunnel thruster is the same as the propellers meaning they make it possible to vary in the same amount without inquiring in a higher penalty. This affirms the way in which the actuators signal for the QP is much more demanding than in the MPC for the tunnel thrusters.

For the angular velocity the same case happens, we obtain similar results in the large scale with the same peaks and with oscillations when the ship is keeping position, due to the environmental disturbances. This is why the tunnel thrusters present oscillatory actuators signal in both controllers, to compensate the changes in the angle that the disturbances cause. In the short scale, the QP controller present a smoother continuity, due to the fact that in the MPC controller the disturbances are being taken in account as inputs to the control system so these forces are being translated as forces to be compensated, so the vessel follows much smoother the reference path.

Conclusions

The project has shown a comparison between to solutions for a control allocation in dynamic positioning control on vessels. The solutions have been a Quadratic Programming optimization method and a Modern Predictive Control to set the actuator's signal, in order to obtain a force generated by the thruster equal or similar to the desired force the DP controller sets from the desired position waypoints. The quadratic programming controller was a courtesy from Dr Witkowska, in order to set a groundwork for the MPC controller design. In addition, the model of the vessel has also been obtained by Dr Witkowska's work in this field. Some tuning had to be done in order to set some parameters for the MPC design and to obtain some representation variables.

The solution obtained from the MPC controller is an adequate solution to the problem. It fits the requirements that the problem demanded in a satisfactory manner. By tuning the weight parameters of the manipulated variables different gain control is obtained. If incremented the problem becomes stricter in the use of the actuators and an area positioning application appears, making the solution a less fuel consuming. By lowering their value, the use of the actuators becomes less penalizing becoming more powerful in the position keeping and in consequence more fuel is consumed. Depending on the application and the vessel's environment this parameter can be tuned to fit the desired way of operation.

The problems encountered have been predominantly in managing to control the vessel in a suitable way. Tuning the DP controller was an aspect that project did not focus as much as the control allocation, but was a primordial feature in solving the projects problem. The method used to solve this has been the use of genetic algorithm optimization method. Other much faster methods could have been used, but this method provided a wide scope between the range of possible values and a reliability on the convergence to a global optimum. To know if optimal values had been achieved it was necessary to count with the quadratic programming control allocation as a valid control in order to set a fundamental base to start the MPC design. Moreover, different paths and scenarios have been tested in order to confirm the valid values of the PD controller in charge of the dynamic positioning controller. A bigger search for a PID system, that would control the vessel, with different type of solvers would have been an improvement in the control system, but it would have been a complex computational algorithm and of too many iterations.

The vessel's model is a nonlinear model which depends on the ship's velocity. This model has not been examined in the different manoeuvres that the MSS GNC toolbox [5] offers (TurnCircle, ZigZag and Pullout). But attends to all specifications suggested in all three Thor I. Fossen's books [2], [3] and [4]. This has not been carried out due to the characteristics of the model fits the problem for this project and many modifications to the vessel's model should have been done in order to fit the characteristics the manoeuvre's models require. This is an aspect that could be improved in order to confirm the validation of the vessel's model.

The MPC design has been performed with the Modern Predictive Control toolbox, which sets the controller by setting weight parameters, reference inputs and a definition of the plant to control. For this case the plant constituted the *actuators dynamics* and *thruster's configuration.* The use of the MPC toolbox limits the way in which the prediction horizon conditions the end result, while if the algorithm would have been coded in a Matlab script the prediction horizon could have been established to end when the difference between the predicted output and the reference trajectory met a certain small value. In addition, in each step the MPC has to be simulated in order to obtain manipulated variable values for the varying reference signal, consuming computational time.

In future approaches to this problem, the main issues that would be considered to improve are mainly control algorithms and faster coding. The DP controller should have been contemplated much more in detail. Also, the MPC controller should be designed in an iterative way, making the optimization of the cost function much more precise. Moreover, inside the cost function more parameters involving the vessels dynamics and limitations should have been considered and constrained. This control system could have been applied to other vessel to see its robustness and its polyvalence. The vessel should be made to perform the manoeuvres included in the MSS GNC toolbox in order to, as said, confirm its validation.

This project compares to solutions of *control allocation* controllers. Many other types of controllers could have been taken in account to perform a much higher degree of acceptance of the solution proposed as an MPC based controller. Even more, the solution embraces the control allocation which considers the dynamic of the thrusters and its actuators which corresponds to a linear plant. A much complex controller, which includes DP control and Control Allocation in the same MPC controller could have been tested to see its performance and compare it to the segregated control.

To conclude, this project is a first approach to dynamic positioning of ships. Future studies will be done chasing better results, with this solution as a baseline to continue with the investigation. Understanding each concept and element involved in this project is an arduous task, which involved ship’s notions and its environment, as well as a high understanding on industrial control. It is believed that these tasks have been covered in a satisfactory way and will offer a path to follow in future personal investigations.

Summary

This project has been developed in order to understand the bases of ship automation. Ships are important elements of the engineering industry and so is the problem of approximating offshore platforms and port entries and exits. This is why the project has focused on the automation applied to dynamic positioning of ships, to contribute to the contemporary investigation that many good engineers have taken part in.

The problem in which this project focuses is to find a new method of proceeding in the *control allocation* on the thruster's dynamics. The method developed to solve this problem has been the technique used by *Modern Predictive Control.* MPC is a relatively new method of controlling industrial processes. The way it is applied is by knowing the dynamics of the plant/process and advancing ahead with prediction values. In order to apply the method a profound study of vessel dynamics had to be done. Ships motion is much conditioned by the type of ship, its geometry, its mass and its distribution. In addition, ships move through fluids which influences the motion. The depth or the density of the water are high conditioners of the motion of objects through it, as it is the wind, which can't be omitted. Moreover, these fluids contain varying components that alter the forces acting on the vessel. This is why an in depth understanding of the environment and its changes has been done.

Dynamic positioning is a type of control that manages all the above aspects that a ship experiences. Its applications can be found in many types of vessels and platforms, making it an important aspect in many activities. This project required a deep understanding on how dynamic positioning worked and how it is applied to the controlled object at matter. Dynamic positioning works at low speed applications, but always with the belief of translating it to higher velocity ranges. Position keeping and path tracking is an operation that many industrial elements have to achieve at a certain precision, from deep water platforms to unmanned crafts they all share the need of being more and more automated in order to improve effectiveness and lower fuel consumptions.

The solution presented in this document is a controller based on MPC design. It has been compared to another type of control based on *Quadratic Programming* which is a type of control broadly used in this type of application. Both solutions have shown their feasibility in their application. An inclination towards the MPC controller has been declared, as it presents new features of ahead prediction and good disturbance compensation. Furthermore, it is a modern method of control, making it possible to find newer technologies in this type of controller. Its developing is still at work, making it subject to changes that will improve its performance. In order to achieve a valid solution, an intensive study of how MPC works and how to tune the controller to achieve the requirements had to be done.

To achieve the purpose of the project a valid model of the vessel in subject has been performed. The model has been implemented in Matlab, where many variables can be represented and handled. This model is presented in the Annex below. The model used is a unique model of the supply vessel *Northern Clipper*, from *Sævik Supply Management, Norway.* This vessel does not differ much from other types of supply vessels, making this project available to be transposed to other types of vessel, with the tweaking of the controllers and the changing of parameters that define the ship.

The applied control has been performed in this same Matlab environment. Making it also available to modify the parameters to meet stricter requirements. The algorithm implemented converges fast to a solution making it possible to perform various tests in different scenarios before implementing on the real vessel.

To conclude the document, conclusions have been made on how an improvement could be made and what type of problems have been encountered, in order to recommend the reader to achieve a better solution and not to fall on same errors committed in this project.

Figure S.1 – *VTT* [23] *futuristic idea of a ship's bridge*

Annex

A. Vessel Model

The vessel model implemented in Matlab obtained from Dr Witkowska:

```
function [xdot] = mariner(x,u_c,tau_dystbis)
% returns the time derivative xdot from state vector:
% x = [u v r x y psi u1 u2 u3 u4 u5 u6]'

 L    =  76.2;              % length of ship (m)
 g    =  9.81;              % acceleration of gravity (m/s^2)
 mass = 6400e3;             % mass (kg)

 x_bis = x(1:6);            % linear speed, position and course
 u_bis = x(7:12);           % actual actuators value
 u_c   = u_c;               % commanded u_c from Control Allocation

% Ship model matricses (Bis-scale)

J_bis= [cos(x_bis(6)) -sin(x_bis(6)) 0;
        sin(x_bis(6))  cos(x_bis(6)) 0;
                  0              0   1];

DN_bis=[1.3*abs(x_bis(1))           0                            0;
                  0           25*abs(x_bis(2))   -10*abs(x_bis(3));
                  0           -10*abs(x_bis(2))   5*abs(x_bis(3))];


M_bis = [1.1274         0           0;
              0    1.8902      -0.0744;
              0   -0.0744       0.1278];

D_bis = [0.0358         0           0;
              0    0.1183      -0.0124;
              0   -0.0041       0.0308];

% Thruster configuration matrix (T_bis) & Thruster force coefficient (K_bis)

T_bis =[1.0000    1.0000         0         0         0         0;
             0         0    1.0000    1.0000    1.0000    1.0000;
        0.0472   -0.0472   -0.4108   -0.3858    0.4554    0.3373];

K_bis=10^(-3) * diag([9.3 9.3 2.0 2.0 2.8 2.6]);

B_bis=T_bis*K_bis;

% Actuators time constants

Ti_bis=5.0*sqrt(g/L)*eye(6,6);

% State Space model:

A = -inv(M_bis)*(D_bis+DN_bis);
B = inv(M_bis);
```

```
ni_bis  = x_bis(1:3);      % [u_bis, v_bis, r_bis]
eta_bis = x_bis(4:6);      % [x_bis, y_bis, psi_bis]
tau_bis = B_bis*u_bis;

d_ni_bis  = A*ni_bis +B*(tau_bis+tau_dystbis);
d_eta_bis = J_bis*ni_bis;
d_u_bis   = inv(Ti_bis)*(u_c-u_bis);

xdot = [d_ni_bis; d_eta_bis; d_u_bis];
end

% To obtain the integrated form: euler2 obtained from the MSS GNC
toolbox (2008 Thor I. Fossen and Tristan Perez) [5]
x = euler2(xdot,x,h);
```

B. Environmental Disturbances

The environmental disturbances implemented in Matlab obtained from Dr Witkowska:

Both X and Y match in values in the time interval. Z components would correspond to current changes affecting the ship’s hull.

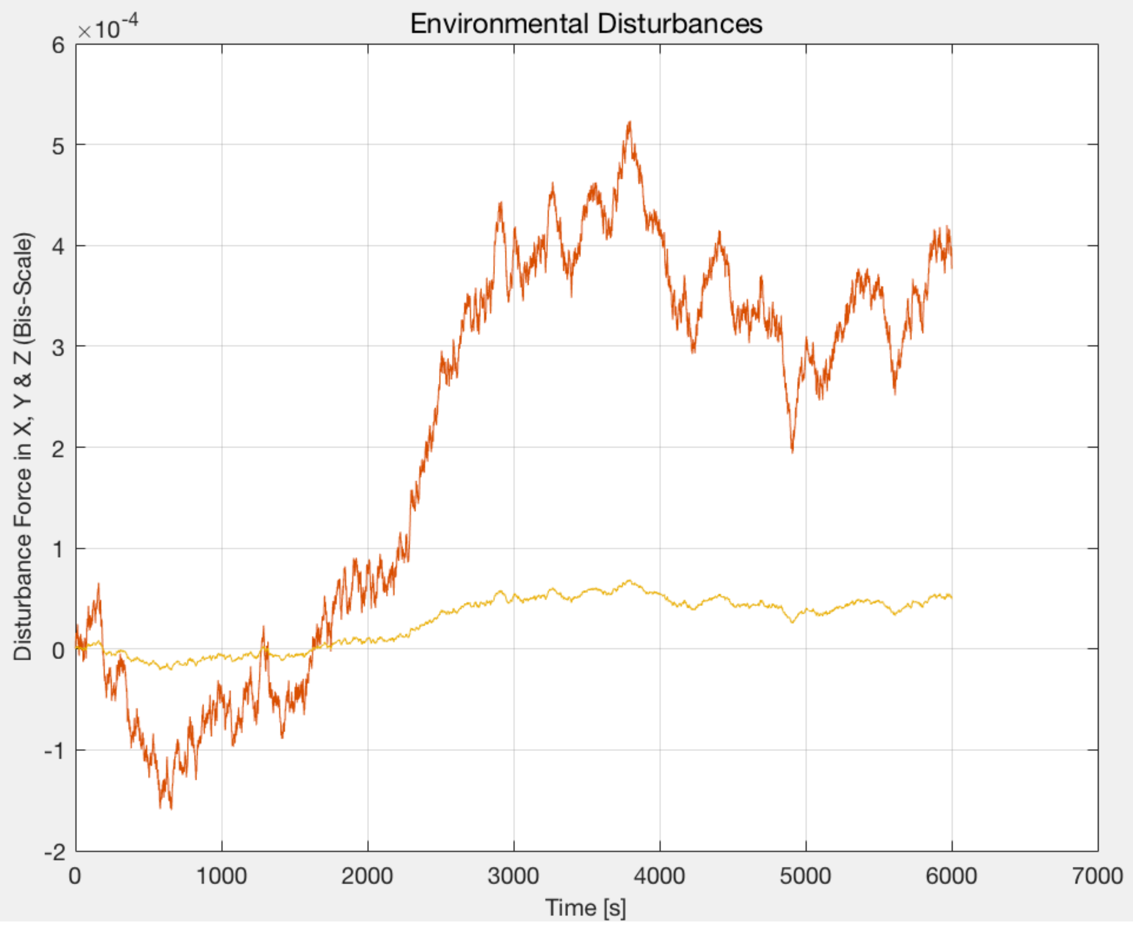


Figure B.1 - *Representation of the Environmental Disturbances X and Y have similar values(Red) Z (Yellow).*

C. MPC Design

```
MPC object (created on 16-Jun-2018 12:13:28):
---------------------------------------------
Sampling time:      0.4 (seconds)
Prediction Horizon: 10
Control Horizon:    2

Plant Model:
                                              --------------
      6  manipulated variable(s)    -->   |          tf  |
                                              |              |      -->  3 measured output(s)
      0  measured disturbance(s)   -->   | 6 inputs  |
                                              |              |      -->  0 unmeasured output(s)
      0  unmeasured disturbance(s) -->   |3 outputs |
                                              --------------
Disturbance and Noise Models:
        Output disturbance model: default (type "getoutdist(mpc1)" for details)
         Measurement noise model: default (unity gain after scaling)

Weights:
    ManipulatedVariables          : [0.0001 0.0001 0.001 0.001 0.1 0.1]
    ManipulatedVariablesRate      : [0.1000 0.1000 0.1000 0.1000 0.1000 0.1000]
    OutputVariables               : [1 1 1]
                         ECR: 100000

State Estimation:  Default Kalman Filter (type "getEstimator(mpc1)" for details)

Constraints:
  -1 <= uc1 <= 1, uc1/rate is unconstrained,        -0.1156 <= tau1 <= 0.1156
  -1 <= uc2 <= 1, uc2/rate is unconstrained,          -0.387 <= tau2 <= 0.387
  -1 <= uc3 <= 1, uc3/rate is unconstrained,        -853.16 <= tau3 <= 853.16
  -1 <= uc4 <= 1, uc4/rate is unconstrained
  -1 <= uc5 <= 1, uc5/rate is unconstrained
  -1 <= uc6 <= 1, uc6/rate is unconstrained
```

D. Genetic Algorithm

The script implemented in Matlab to optimize the parameters Kp and Kd of the DP controller.

```
>>gaSim.m
```

The script manages to find the Kp and Kd paramaters by reproducing, crossing-over and mutating 4 chromosomes in the generations introduced (maxgen). It selects values of Kp and Kd and simulates the process of the vessel to obtain a fitness function value (*J*). The reproduction method used is the *roulette wheel* and the probabilities of cross-over and mutation are to be selected by the user.

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