UNIVERSITA' POLITECNICA DELLE MARCHE

FACOLTA' DI **INGEGNERIA**

Corso di Laurea magistrale in **Ingegneria Meccanica**

Metodi Ibridi per Guida, Navigazione e Controllo dei ROV

Hybrid Methods for Guidance, Navigation and Control of Rovs

Relatore: Chiar.mo/a

Prof. **Sauro Longhi**

Tesi di Laurea di:

Luca Mazzanti

A.A. **2023** / **2024**

Università Politecnica delle Marche
Facoltà di Ingegneria
Corso di Laurea in Ingegneria Meccanica
Via Brecce Bianche – 60131 Ancona (AN), Italy

Abstract

With the increase in human activities in the ocean, such as oil and natural gas extraction, the need for new technologies to support these activities has arisen. For this reason, ROVs (remotely operated vehicles) have been developed—unmanned underwater vehicles capable of reaching even the deepest parts of the ocean. As technology has advanced, these vehicles have become more autonomous, reducing, at least partially, the need for human operators to manage them. In this context this thesis work was carried out, proposing a hybrid GNC (guidance, navigation, and control) system for the Blueye, a small-sized ROV. A hybrid GNC system can change the algorithms used or their parameters to increase the vehicle's efficiency and usability in the different operational conditions it might face.

To achieve these goals, the work was divided mainly into three parts:

1. Development of a simulation environment: a digital twin of the vehicle was created to verify the stability and performance of the vehicle's GNC system.

2. Development of a GNC system: the different algorithms necessary for controlling an ROV were implemented and verified.

3. Development of the Hybrid System: in this part, the concept of a hybrid methods is applied to the previously proposed GNC system. The system will be able to change controllers based on the activities it needs to perform.

All three parts of the work were developed in Python and then in ROS2 to implement them in the Blueye through a software development kit (SDK) provided by the manufacturer.

Sommario

Con l'aumento delle attività umane nell'oceano, come l'estrazione di petrolio e gas naturale, si è presentata la necessità di nuove tecnologie a supporto di esse. Per questo motivo si sono sviluppati i ROV (remotely operated vehicles), veicoli sotto marini senza equipaggio, in grado di raggiungere anche i fondali marini più profondi. Con lo sviluppo della tecnologia è aumentato il grado di autonomia di questo tipo di veicoli svincolando, almeno in parte, l'operatore umano dalla gestione del veicolo. È in questo contesto che è stato portato avanti questo lavoro di tesi che propone un sistema ibrido di GNC (guidance, navigation and control) per il Blueye, un ROV di piccole dimensioni. Un sistema ibrido di GNC è un sistema in grado di cambiare gli algoritmi utilizzati o i loro parametri in modo tale da aumentare l'efficienza e l'usabilità del veicolo nelle differenti condizioni operative che potrebbe affrontare. Per raggiungere questo obiettivo il lavoro si è suddiviso principalmente in tre parti:

1. Sviluppo di un ambiente di simulazione: un digital twin del veicolo è stato creato in modo tale da verificare la stabilità e le performance del sistema GNC del veicolo.

2. Sviluppo di un sistema GNC: i differenti algoritmi necessari al controllo di un ROV sono stati implementati e verificati.

3. Sviluppo del sistema Ibrido: in questa parte viene applicato il concetto di metodi ibridi al sistema GNC proposto precedentemente. Il sistema sarà in grado di cambiare controller in base alle attività che dovrà svolgere.

Il primo obiettivo, ovvero sviluppare un sistema GNC affidabile, è stato raggiunto in maniera soddisfacente; nell'ambiente di simulazione il Rov Blueye completa il percorso assegnato senza alcun tipo di problema e in maniera stabile. Per poter ottenere un miglior riscontro dell'efficacia e della stabilità del sistema GNC dovrebbe essere testato fisicamente sul ROV in acqua, ma per motivi di tempo non è stato possibile. Per quanto riguarda l'applicazione dei metodi ibridi, il problema principale è la limitazione data dalle ridotte dimensioni del Rov e la poca potenza disponibile, che lo rendono utilizzabile solo in condizioni di mare calmo e con poca corrente. Per questo l'unico cambio che può essere applicato è il cambio di modalità operativa. Passare da un controller PD nelle situazioni di maneuvring ad uno PID nello station keeping permette al veicolo di rimanere in posizione con una precisione maggiore, che può essere utile all'operatore nelle operazioni di ispezione. Tutte e tre le parti del lavoro sono state sviluppate in Python, e poi in ROS2 per poterle implementare nel Blueye attraverso un SDK (software-development-kit) fornito dal costruttore.

Contents

List of Figures

Chapter 1

Introduction

1.1 Background and Motivation

The ocean covers more than 70 percent of the Earth'surface. It plays a significant part to the human activities, it provides us with resources, energy, transportation, food and numerous other beneficial possibilities. Yet, only 5 percent of the ocean space is discovered. It was not possible to reach great depth, because the lack of appropriate technology. Only from the second half ot 20'th century, with the introduction of the Unmanned Underwater Vehicles (UUV), the deepest part of the ocean, for the first time in history, are now accessible for the human mankind. The discovery off the new technology, the reduced costs, the improvement of the sensors have made possible to produce underwater vehicles for commercial, research and in the latest years, for recreational use. The application range of the underwater vehicle is very broad, from the oil and gas industry to the marine biology research.
With the spread of this new technology and its applications in a wide range of fields, the variations in work tasks may vary a lot and with this the demand of a increased automation and autonomy level where the pilot aids the operation on a high level letting the operator to focus on monitoring and decision making.

1.2 Objective

The main goal of this project is to develop a robust GNC system (which include a navigation system, Guidance system and a controller), and then apply the concept of hybrid system to the Blueye ROV. In this project we will improve the performance of guidance, navigation, and control (GNC) of ROVs to handle variations in environmental and operational conditions.

1.3 Contribution

To achieve the objective explained in the previous section, the following structure and development part path will be applied: The contribution of each part of work is stated as following. Blueye simulation environment: with an already existing simulator, the simulation environment has been set up and tested.

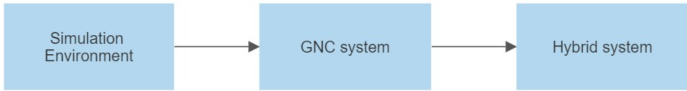

Figure 1.1: Frame of the thesis work

Blueye GNC system: In this section GNC algorithms have been developed and tested to obtain their performance.
Blueye Hybrid system: With the GNC system developed, in this part we developed an hybrid system functional and suitable for the Blueye ROV.

Chapter 2

ROV

In this chapter we are going to explain what is a ROV, how this vehicle has been developed in the years, in which fields is used, and his main component. Furthermore, we will analyze what the word "autonomy" means. In the end of the chapter is being described the Blueye ROV, used in this thesis.

2.1 What is a ROV?

Currently, underwater vehicles fall into two basics categories: manned vehicles and unmanned underwater vehicles (UUVs). UUVs can be divided in other two categories: Autonomous Underwater Vehicles (AUV) and Remotely Operated Vehicles (ROV). The main difference between AUV and ROV is the presence (or absence) of a direct hardwire (for communication and/or power) between the vehicle and the surface. Although the absence of a tether, AUV's degree of autonomy is not much higher that one incorporated in a ROV. Both classes of vehicles are often run by pre-planning a mission, which implies the definition of a list of operations which are defined by operators prior to the mission start and are carried out automatically. The ROV falls within a broad range of mobile robotic vehicles generally termed "remotely controlled mobile robots". The motion of the vehicle can be via autonomous logic direction or remote operator control depending upon the vehicle's capability and the operator's degree of input. The power of the vehicle can be on board (i.e., battery or engine powered), offboard (i.e., power delivered through conductors within the tether), or a hybrid of both (e.g., onboard battery powered with a power rechange transmitted remotely through the tether). The presence of tether allows to conduct, ideally, infinitely long operations. Approximately, a ROV is a camera mounted in a waterproof enclosure, with thrusters for maneuvering, attached to a cable to the surface over which signals and telemetry are transmitted.

2.1.1 ROV's history and development

The first ROV prototypes born in the 'fifties. Dimitri Rebikoff is credited to have developed the first ROV (the PODDLE, in 1953), for archeological research. In the birth-phase, ROVs development has faced a lot of difficulties: "they were unreliable and too noisy, were hard to control and needed constant maintenance"[1]. Subsequently, military research has started to develop operational ROVs; the Royal Navy and the US Navy developed ROVs for recovering military equipment (e.g., mines and torpedoes) which was lost on the sea bottom. In 1966 The Navy's CURV III (Fig. 2.1) retrieved a lost atomic bomb off the coast of Spain in 1966, from 869 meters of water. With a such success and other operations achieved, the Navy expanded into more complex vehicles such as the massive Pontoon Implacement vehicle (PIV), developed to aid in the recovery of sunken Submarines, and small-size observation ROVs such as the Snoopy, one of the first portable vehicles. From 1953 to 1974,

Figure 2.1: US Navy CURV III, image courtesy of "Wikipedia"

85 percent of the vehicles were still government funded. In 1975 ROVs business has changed, the technical advancements made possible and convenient for private industry to develop ROVs; from 1975 to 1982, 96 percent of the 350 vehicles were funded, constructed, and bought by private industry. From 1982 to 1989 the ROV industry grew rapidly, because it was an actual need for the offshore industry, ROVs was used to install and maintain its infrastructure. Moreover, some companies took the advancements in technology and used them to shrink the ROV to a new class of small, reliable, observation-class vehicles, affordable for civil organization and academic institution. In the nineties ROVs industry was strong and with companies from all over the world. Furthermore, the advancements in microelectronics and sensor technology led to the development of the micro-ROVs, small dimension and less-expensive vehicles. In the last years many companies, following the direction dictated by micro-ROVs and seen the success of aerial drone, start the development of vehicles which can be accessible for hobbyist or enthusiasts.

2.2 ROV classification

The market is segmented into four broad categories based upon vehicle size and capabilities:

- Observation class ROVs (OCROV): these vehicles go to the smallest Micro-ROVs to a vehicle weight of 100 kg. they are generally smaller, DC-powered, inexpensive electrical vehicles used as either back up to divers or as a diver substitution for general shallow water inspection tasks. Their payload is often limited to cameras and a small grasper. These vehicles are usually limited to depth ratings of less than 300 m.
- Mid-sized ROVs (MSROVs): extended version of the OCROVs: heavier (from 100 to 1000 kg), are generally a deeper-rated version of the OCROVs with a hydraulic manipulator. Due to the weight of these vehicles, a launch and recovery system (LARS) as well as a tether management system (TMS) is required.
- Work class ROVs (WCROV): vehicles in this category are generally heavy electro-mechanicals vehicles running on high voltage. They have, usually, hydraulic propulsion and a 6 DOF manipulation devices.
- Special-use vehicles: vehicles not falling under the main categories of ROVs due to their non-swimming nature such as crawling underwater vehicles and towed vehicles.

It is important to say that each class contain different types of ROVs. For instance, Observation Class ROV contains Micro-ROV, described above in the ROVs history, and Hybrid-ROV mostly used in scientific research. The latter has been developed due to incremented requests for high-risk work, like underwater-ice operations. They are able of working as ROV and AUV. Basically, due to higher operational risks in certain areas, the vehicle predominately operates fully remotely, and video controlled. in event of a critical situation where the tether will be disconnected and the vehicle should switch automatically into the autonomous mode, passing back to a safe rendezvous point far out of the critical area.

2.3 ROVs applications

2.3.1 Science

The main aim of ROVs for science application is to gather sensor data and take samples for the understanding of the subject environment. Usually, heavy work is not required in science mission, hence the actuators and manipulators can be small. Typical vehicles for these missions are the OCROV and/or MSROV with high data-throughput capabilities and small electrical manipulators and effectors.

2.3.2 Fishering and aquacolture

Given that the world population is increasing, as well as the food demand, fish farming has become more pronounced in the production of food stuff for the world's customers. ROVs are useful for the production support (for instance checking nets for holes, assuring the integrity of moorings for the farm) or regulatory compliance assurances by policing authorities.

2.3.3 Military

The predominant usage of ROVs in a military application involve mine countermeasures (MCM), object retrieval/recovery and inspection/security tasks. MCM missions are conducted with disposable ROV which triggers an explosion. For the object retrieval, a heavy-duty WCROV is needed along with hydraulic manipulators and deep-water capabilities. The inspection vehicle is clearly an OCROV with minimal sensor.

2.3.4 Homeland security

Homeland security needs involve the periodic inspection of various vulnerable locations for structural integrity (periodic ship hull and pier inspections) and presence of security threats. Often, these operations are performed with OCROV.

2.3.5 Oil and Gas drill support

ROVs for drill support are used observation of the sea-floor environment, mounting of well seals, and guiding of tooling and drilling equipment. They have become a requirement as the search of hydrocarbons has pushed into deeper waters of the oceans. The typical ROV configuration are a larger MSROV or a light WCROV, equipped with a hydraulic manipulator.

2.3.6 Inspection, repair, and maintenance

The inspection, repair and maintenance market include several industries like offshore wind farms, fish farms and civil engineering projects. For basic visual operations, a small OCROV will be sufficient.

2.3.7 Construction

ROVs in deep-water construction mission typically are tasked with setting and pulling rigging, guiding large construction pieces into place, and moving heavy pieces.

2.4 ROVs main components

2.4.1 Propulsion system

As a part of any mobile robotic system, some means of locomotion is necessary in order to move the robotic system and guarantee maneuvering and controllability. In free swimming ROV technology, thrusters rule. The propulsion system significantly impacts the vehicle design. The types of thrusters, their configuration usually take priority over many of the other components, the number and the position on the frame define the number of DOF that the operator can actively control. Thrusters are in most cases electrically driven propellers or, rarely, hydraulic driven propellers. Electric motors come in many shapes, sizes, and technologies, each designed for different functions. The most common thruster motor on observation-class ROV system is the DC motor (e.g., DC permanent magnet, DC brush-less, AC motors), Hydraulic motors are, usually, employed for special applications.

2.4.2 Lighting

The lights provide illumination for the camera underwater. Sunlight disappears rapidly underwater and many ROVs mission occur at depths that are normally in complete darkness. The main types or classes of artificial lamps/light sources used in underwater lightning are incandescent, fluorescent, high-intensity gas discharge and led (Fig. 2.2).

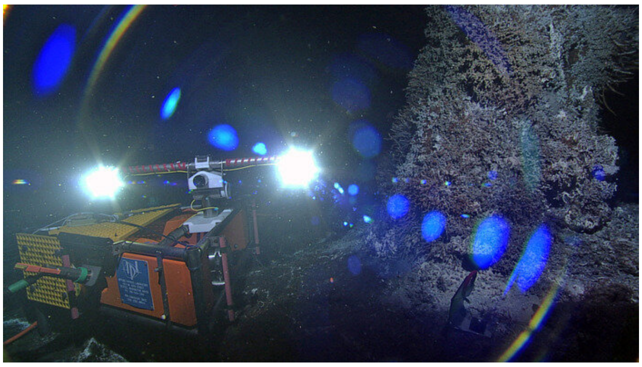

Figure 2.2: LED-ligths, image courtesy of "www.subcimaging.com"

2.4.3 Manipulator system and tool pack

The manipulator has become an essential tool of underwater vehicles for performing underwater works such as drilling, cutting in coordinate tasks, sampling in the fields of scientific research and ocean engineering. Observation class ROVs often have a simple grabber used for sampling useful for scientific research. Work class ROVs manipulators shall be bigger, more precise, and able to conduct difficult tasks. Manipulators can be electric or hydraulic, and for the Work class ROVs, they contribute significantly to the vehicle's weight.

2.4.4 Navigation sensor

All positioning is a simple matter of referencing a position relative to some other known position. All positioning systems, as GPS and acoustic, work in this way. Underwater navigation is vastly different than navigate above the surface. The sea space can be dark and there may be particles that makes visibility worse. Therefore, cameras are not enough, and it is necessary to make use of other technology.

2.4.5 Positioning system

• Given that GPS systems aren't functional underwater, other positioning systems have been developed. Acoustic baseline sensors like long baseline and ultra-short baseline have been the preferred positioning systems for several decades. These systems measure the time of flight for the signals, and applying the speed of sound, the range between the vehicle and a transducer is calculated. The transducers are mounted either on a support vessel (SSBL system) or positioned on the seafloor (LBL system). An important advantage of the acoustic navigation is that errors are bounded and observable. A Doppler Velocity Log (DVL) measures the doppler shift in the incoming acoustic signal reflected on the seabed or scatters in the water column. Depth is related to pressure, through the knowledge of the density of seawater. Both are easily observable with high precision, and therefore the pressure sensor is typically the main sensor for depth. In order to measure the heading of the vehicle are used heading sensors. There are three main concepts of measuring the orientation around the vertical axis: gyro-compassing by extracting the earth's rotation, using a magnetic compass, or by determining the heading vector from the relative position of one or more points. Other useful sensor type is Inertial Sensor that provides the acceleration. Combined with gyro and magnetic field, it is possible to calculate position and velocities of the vehicle, integrating the acceleration and the rate of changes of the orientation angles in the time domain. Pictures or videos can be used to control the vehicle. Some pictured elements, like features, objects, or light patterns, can be isolated and compared at following time instant to calculate their displacement, and consequently the vehicle's velocity vector [2].

2.4.6 Structural elements

- Frame: the frame provides a structure to attach the thrusters, camera, lights, tether, and other components of the ROV. Most ROVs are built with an open rectangular frame that makes it easy to build and modify, but some ROVs are built with highly specialized frames to reduce drag, improve appearance, or perform a special mission.

- Buoyancy: the objective of underwater vehicle flotation system is to counteract the negative buoyancy effect of heavier than water materials on the submersible with lighter than water materials.

2.4.7 Payload sensor

Payload sensors are measurement units that are carried by a sensor carrying platform for collecting data and images. Moving towards more autonomous vehicles with mission objectives, rather than a pre-programmed behavior, may require that these instruments are no longer passive payloads, but that their measurement are useful to the mission planning layer and the guidance.

- Camera and video: By providing pictures of the sea bottom or real-time video, they can be useful to monitor the surrounding of the vehicle or focus on some critical equipment as the manipulator. Due to light absorbance of the water underwater cameras can only show an area of few meters.

- Underwater Hyperspectral Imaging (UHI) cameras: cameras whose digital sensor provides high sensibility on the whole light spectrum, including the non-visible wavelengths. By measuring the whole light visible spectrum, the light absorption of the seabed and the seawater can be quantified and characterized. Using knowledge of the spectral distribution of the light applied many substances can be characterized.

- Imaging sonar: this kind of sensors can provide a wide overview of the area around the vehicle. A set of short acoustic pulses are emitted, those which hit objects bounce back to be received again from the sensor. The image formed by the reflections, which will be shaped by the intensity of the reflections themselves, can cover an area with a radius of hundreds of meters.

2.5 Automation and intelligence

One of the objectives of this work is to make the ROV more autonomous in order to increase efficiency, safety and make the life easier for the pilot; but what does autonomous mean and what make a system more autonomous? It is not easy to answer to these questions and it doesn't concern only engineering. To be autonomous a system it should be "intelligent" but there are many definitions of the word "intelligence" that depend by the context and the point of view. For instance, one of the statements is "To avoid a prolonged debate over how much "intelligence" is required for a vehicle to be considered "autonomous", the committee elected to include within the scope of this report all relevant vehicles that do not have a human onboard". Summarized: no human on board means autonomous system. This sentence may look like an oversimplification of the problem. In fact, a car, which can keep constant speed along highways, automatically slow down and recognize street signs and indications, it is autonomous to some extent, even though human is still required to supervise and take responsibility for the drive. Another statement focuses on the fact that an autonomous system should operate without operator input for extended periods of time, carrying out the operations and, in the end, being able to make for a successful return. Another definition of autonomous system can be sum up as “own ability to make decisions, once the vehicle senses the environment, it can reach its goals without following a pre-defined list of tasks”. Therefore, the system should:

- Sense the environment end understand what is around.
- Plan the tasks
- Act and reach the goals

In the context of this work, the last definition is the one that describes better what an autonomous should do. Following this statement, to improve ROV technology is necessary: provide tools for a better understanding of the environment, improve the decision-making process of planning tasks of the operations without human assistance and carry out the operation as efficient and safe as possible. In order to have a clear picture of autonomy in UUVs operations, they are divided in four main categories. A system may have functionality in different autonomy levels and operations shifting from different levels, for instance, in case of unforeseen events faced by the operator. Autonomy levels are characterized subject to the level of human-robot interaction (HRI), mission complexity, and environmental complexity.

- Remote control: The vehicle operates at a distance from operator. The latter directs and control all functions. System states, environmental conditions and sensor data are presented to operator (Human-in-the-loop).
- Managements by consent: system automatically makes recommendation for mission or process actions related to specific functions, where system prompts human operator at important points for information or decisions. At this level, system may have limited communication bandwidth. System can perform many functions independently of operator control when delegated to do so (human-delegated).
- Management by exception: System automatically executes mission-related functions when and where response times are too short for human intervention. Human operator may override or change parameters and cancel/redirect actions within defined time constraints. Operator’s attention is only brought to exceptions for certain decisions (human-supervisory control).
- Highly autonomous operation. System automatically executes mission- or process related functions in structured environment with capability to plan and re-plan mission or process. The human operator may be informed about progress, but the system is independent and “intelligent” (human-out-the-loop).

2.6 Blueye ROV

For this work, the ROV used is Blueye ROV (Fig. 2.3). It is a small size Observation Class ROV. Its weight is below 9 kg, therefore is suitable for transportation and operatable by one person. It has a replaceable 96 Wh lithium-ion smart battery, which allows it to perform operations lasting 2 hours in normal condition. It has been built to withstand pressure until 150 m and manage frequent dives. Its tether is thin and creates minimal drag, and it allows communication with the surface. It has four 350 W thrusters: 2 rear, 1 vertical center and 1 lateral. They allow the drone to have a max velocity of 3 knots and to operate in difficult conditions up to 2 knots current.The ROV is equipped with an IMU sensor with a 3-axis gyro, accelerometer, and magnetometer, as well as the DVL A50, which provides speed and altitude from the seabed. The drone can be controlled through smartphone or tablet, and another device can be used as observer, useful to help the pilot and optimize the research. It's used in the inspection of ships' hulls or ducts of Oil and Gas and for scientific research.

Figure 2.3: Blueye ROV, image courtesy of "Blueye.com"

Chapter 3

Simulation Environment

In this chapter we will set up a simulation environment. Starting from the study of the kinematics and kinetics we will see the behavior of the Blueye ROV under the forces acting on it.

3.1 ROV dynamic

The dynamic model is used to express and model the behavior of the vehicle over time. The dynamic model of an underwater vehicle can be divided into two parts: kinematics, which treats the geometry aspect of the motion and kinetics, which is the analysis of forces acting on the vehicle causing the motion. Depending on the function mathematical models can be formulated in two complexity models:

- Process Plant model: a comprehensive description of the dynamic of the ROV and of the environmental acting on it. It simulates the real physics of plant dynamics as close as possible, including process disturbance, sensor outputs and control inputs, is for numerical analysis of the stability and performance in closed-loop system.
- Control plant model: a simplified model used for model-based control and for analytical stability.

First, we will analyze the process plant model, due to its completeness. Then, we will pass to the control plant model and its simplification.

3.2 Kinematics

3.2.1 Reference Frames

The kinematics is a transformation between body-fixed frame and world frame for the vehicle position and velocity. The world frame of the underwater vehicle is usually set as a NED frame. NED stands for North-East-Down coordinate system $n = (x_n, y_n, z_n)$, where x_n-axis points towards true North, y_n – axis points towards East and z_n points downwards normal to the Earth's surface. The origin on is defined relative to the Earth's reference ellipsoid. The body fixed frame reference frame

$b = (x_b, y_b, z_b)$ is a moving frame that is fixed to the vehicle (Fig. 3.1). The origin is usually located at the center of the vehicle. Body-fixed frame will move together with the vehicle, the body axes are chosen to coincide with the principal axes of inertia, and they are defined as: x_b – longitudinal axis, (surge). y_b – transversal axis (sway). z_b – normal axis (heave). The direction of roll, pitch and yaw are the rotational direction around the surge, sway, and yaw direction respectively.

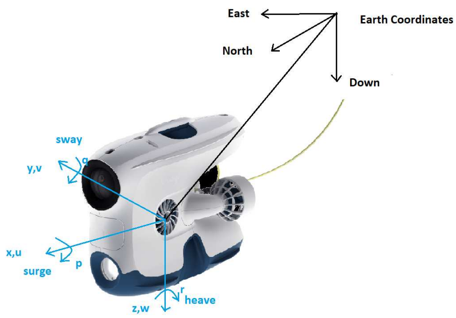

Figure 3.1: Body-fixed frame

The vectors defining the generalized vehicle' Earth-fixed position and orientation, and the body-fixed translation and rotation velocities are using SNAME notation given by:

$$\eta_1 = [x, y, z]^T, \eta_2 = [\Phi, \Theta, \Psi]^T, \tag{3.1}$$

$$v_1 = [u, v, w]^T, v_2 = [p, q, r]^T. \tag{3.2}$$

Where η_1 denotes the position vector in the Earth-fixed frame, and η_2 is a vector of Euler angles. v_1 denotes the body-fixed linear surge, sway, and heave velocity vector, and v_2 denotes the body-fixed angular roll, pitch, and yaw velocity vector. The Euler Angles result form a sequence of rotations. The rotation sequence is given by:

$$J_1(\eta_2) = C_{z,\Phi}^T C_{y,\Theta}^T C_{x,\Psi}^T \tag{3.3}$$

For 6 DOF system the Euler angle rotation matrix for linear velocities is implemented as the following equation:

$$J_1(\eta_2) = \begin{bmatrix} c\psi c\theta & -s\psi c\phi + c\psi s\theta s\phi & s\psi s\theta + c\psi c\phi s\theta \\ s\psi c\theta & c\psi c\phi + c\psi s\theta s\phi & s\psi s\theta + c\psi c\phi s\theta \\ -s\theta & c\theta s\phi & c\theta c\phi \end{bmatrix} \tag{3.4}$$

Where s(.) = sin(.), c(.)= cos(.) and t(.) = tan(.). Thus, the linear velocities of the vessel in the Earth-fixed frame are given by the transformation:

$$\dot{\eta}_1 = J_1(\eta_2) v_1 \tag{3.5}$$

The angular velocities of the vessel in the Earth-fixed frame are given by:

$$\dot{\eta}_2 = J_2(\eta_2)v_2 \tag{3.6}$$

,

where:

$$J_2 = \begin{bmatrix} 1 & 0 & -s\theta \\ 0 & c\theta & c\theta s\phi \\ 0 & -s\theta & c\theta c\phi \end{bmatrix} \tag{3.7}$$

The linear and angular velocities of the vehicle in the Earth-fixed frame is given by:

$$\dot{\eta} = \begin{bmatrix} \dot{\eta}_1 \\ \dot{\eta}_2 \end{bmatrix} = \begin{bmatrix} J_1(\eta_2) & 0_{3x3} \\ 0_{3x3} & J_2(\eta_2) \end{bmatrix} = J(\eta_2)v \tag{3.8}$$

,

3.3 Dynamics

The Dynamics describes the forces acting on the vehicle and cause its motion. The process Plant model of the ROV is composed by the kinematics and kinetics equations:

$$\dot{\eta} = J(\eta)v \tag{3.9}$$

$$M\dot{v} = -C_R(v)v - C_A(v_r)v_r + D(v_r)v_r - G(\eta) + \tau + \tau_{cable} \tag{3.10}$$

This model considers 6 DOFs, where $\eta = [x, y, z, \phi, \theta, \psi]^T$ is defined in the NED frame and $v = [u, v, w, p, q, r]^T$ is defined in the body frame. As explain above, the kinematics relates body and NED frames through the transformation matrix $J(\eta)$ [3]. v_r is the relative velocity of the vehicle with respect to the fluid and it is equal to $v_r = v\breve{\ } v_c$, where v_c is the velocity vector of the fluid. $\tau_{cable}, \tau \in R_6$ are respectively the drag force of the tether and the control force vector.$C_R(v)$ is the Coriolis Force and $C_A(v_R)$ is the Added Mass. The added mass can be seen as a virtual mass added to a system because an accelerating or decelerating body must move some volume of the surrounding fluid as it moves through it. $M \epsilon R^{6x6}$ including added mass is defined as:

$$M = \begin{bmatrix} m - X_{\dot{u}} & 0 & X_{\dot{w}} & 0 & mz_G - -X_{\dot{q}} & 0 \\ 0 & m - Y_{\dot{v}} & 0 & mz_G - Y_{\dot{p}} & 0 & mx_G - Y_{\dot{r}} \\ Z_{\dot{u}} & 0 & m - Z_{\dot{w}} & 0 & -m & mx_G - Z_{\dot{q}} & 0 \\ 0 & mz_G - K_{\dot{v}} & 0 & I_x - K_{\dot{p}} & 0 & I_{xz} - K_{\dot{r}} \\ m - M_{\dot{u}} & 0 & -mx_G - X_{\dot{w}} & 0 & I_y - M_{\dot{q}} & 0 \\ 0 & mx_G - N_{\dot{v}} & 0 & I_{zx} - N_{\dot{p}} & 0 & I_z - N_{\dot{r}} \end{bmatrix} \tag{3.11}$$

Where m is the ROV mass, I_x , I_y, and I_z are the moments of inertia about the x, y,and z axes and I_{xz} and I_{zx} are the products of inertia. The zero-frequency added mass X_u, X_w, X_q, and so on at low speed in surge sway, heave and roll, pitch, and yaw due to acceleration along the corresponding axes. The matrix $C_R(v) \in R^{6x6}$ is the skew-symmetric Coriolis and centripetal matrix of the rigid-body written:

$$\begin{bmatrix} 0 & 0 & 0 & mz_G r & -m(x_G p - w) & -m(v + x_G r) \\ 0 & 0 & 0 & mw & m(z_G r + x_G p) & -mu \\ 0 & 0 & 0 & -m(z_G p - v) & -m(z_G q + u) & mx_G p - I_z r \\ -mz_G r & mw & m(z_G p - v) & 0 & -I_{xz} p + I_z r & -I_y q \\ m(x_G p - w) & m(z_G r + x_G p) & m(z_G q + u) & I_{xz} p - I_z r & 0 & -I_x p + I_{xz} r \\ m(v + x_G r) & -mu & -mx_G p + I_z r & I_y q & I_x p - I_{xz} r & 0 \end{bmatrix} \tag{3.12}$$

We may divide the effect of the current force into two parts: the potential part and the viscous part. The Coriolis and centripetal matrix of the added mass including the potential part of the current load is formulated according to

$$C_A = \begin{bmatrix} 0 & 0 & 0 & 0 & -c_{a51} & -c_{a61} & & \\ 0 & 0 & 0 & -c_{a42} & 0 & -c_{a62} & & \\ 0 & 0 & 0 & -c_{a43} & -c_{a53} & 0 & & \\ 0 & -c_{a42} & -c_{a43} & 0 & -c_{a54} & -c_{a64} & & \\ c_{a51} & 0 & -c_{a52} & -c_{a53} & 0 & c_{a54} & 0 & -c_{a65} \\ c_{a61} & c_{a62}u & 0 & c_{a54} & c_{a65} & 0 & & \end{bmatrix} \tag{3.13}$$

where $c_{a42} = +Z_{\dot{w}} w + X_{\dot{w}} u_r + Z_{\dot{q}} q,\ c_{a43} = Y_{\dot{p}} p + Y_{\dot{v}} v_r + Y_{\dot{r}} r,\ c_{a51} = +Z_{\dot{q}} q + Z_{\dot{w}} w + X_{\dot{w}} u_r\ c_{a53} = X_{\dot{q}} q + X_{\dot{u}} u_r + X_{\dot{w}} w,\ c_{a61} = +Y_{\dot{v}} v_r + Y_{\dot{p}} p + Y_{\dot{r}} r,\ c_{a62} = X_{\dot{u}} u_r + X_{\dot{w}} w + X_{\dot{q}} q,\ c_{a64} = X_{\dot{q}} u_r + Z_{\dot{q}} w + M_{\dot{q}} q,\ c_{a65} = Y_{\dot{p}} v_r + K_{\dot{p}} p + K_{\dot{r}} r.$

The damping vector may be divided into a linear and nonlinear component:

$$D(v_r)v_r = D_L v_r + D_q v_r |v_r| \tag{3.14}$$

Where the linear damping matrix, with decoupled surge dynamics, can be written as:

$$D_L = \begin{bmatrix} X_u & 0 & 0 & 0 & 0 & 0 \\ 0 & Y_v & 0 & Y_p & 0 & Y_r \\ 0 & 0 & Z_w & 0 & Z_q & 0 \\ 0 & K_v & 0 & K_p & 0 & K_r \\ 0 & 0 & M_w & 0 & M_q & 0 \\ 0 & N_v & 0 & N_p & 0 & N_r \end{bmatrix} \tag{3.15}$$

For ROV the damping matrices can be simplified into diagonal matrices. This is because these terms are the terms that dominates, and it is difficult and time consuming to determine the off-diagonal parameters. The damping equation is strictly positive since it describes energy being removed from the system.For a body that is submerged in any fluid, a buoyancy force will appear. This is a result of the displaced fluid and will act as a force of the displaced fluid. Since the center of gravity and center of buoyancy does not always coincide, these two forces will act on different locations on the body, which makes a moment arise. A submerged body is stable if the center of buoyancy is located above. This is because any perturbations from this state will create a lever arm between the forces and therefore generate moments counteracting the displacement. The net force and moments in the 6 DOF is derived as shown below:

$$G(\eta) = \begin{bmatrix} (W-B)sin\theta \\ -(W-B)cos\theta sin\phi \\ (W-B)cos\theta sin\psi \\ (y_g - y_b B)cos\theta cos\phi + (z_g W - z_b B)cos\theta sin\phi \\ (z_g - z_b B)sin\theta + (x_g W - x_b B)cos\theta cos\phi \\ -(x_g - x_b B)cos\theta sin\phi - (y_g W - y_b B)sin\theta cos\phi \end{bmatrix} \tag{3.16}$$

3.4 Simulator

To develop the Simulator, some simplification were made: the force from the cable is omitted.The added mass is assumed constant and independent from the velocities. Due to the vehicle low speed, the Coriolis force as is assumed small, thus omitted from the simulation model. Furthermore, the current force is assumed as a simple external force. For this reason it is not consider the relative velocity v_r. The buoyancy and the gravity forces are considered separately.For first, it is built the 6x6 Inertia Matrix:

$$M_I = \begin{bmatrix} m & 0 & 0 & 0 & 0 & 0 \\ 0 & m & 0 & 0 & 0 & 0 \\ 0 & 0 & m & 0 & 0 & 0 \\ 0 & 0 & 0 & I_x & 0 & I_{xz} \\ 0 & 0 & 0 & 0 & I_y & 0 \\ 0 & 0 & 0 & I_{zx} & 0 & I_z \end{bmatrix} = \begin{bmatrix} 8 & 0 & 0 & 0 & 0 & 0 & \\ 0 & 8 & 0 & 0 & 0 & 0 & \\ 0 & 0 & 8 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.087 & 0 & 0.011 & \\ 0 & 0 & 0 & 0 & 0.012 & 0 & \\ 0 & 0 & 0 & 0.011 & 0 & 0.16 & \end{bmatrix} \tag{3.17}$$

Then the Added mass matrix is summed to the Inertia Matrix. A simplification has been made, considering only the diagonal terms.

$$M_A = \begin{bmatrix} X_{\dot{u}} & 0 & 0 & 0 & 0 & 0 \\ 0 & Y_{\dot{v}} & 0 & 0 & 0 & 0 \\ 0 & 0 & Z_{\dot{w}} & 0 & 0 & 0 \\ 0 & 0 & 0 & K_{\dot{p}} & 0 & 0 \\ 0 & 0 & 0 & 0 & M_{\dot{q}} & 0 \\ 0 & 0 & 0 & 0 & 0 & N_{\dot{r}} \end{bmatrix} = \begin{bmatrix} 4.6 & 0 & 0 & 0 & 0 & 0 \\ 0 & 9.7 & 0 & 0 & 0 & 0 \\ 0 & 0 & 11.1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 10 & 0 & 0 \\ 0 & 0 & 0 & 0 & 10 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.10 \end{bmatrix} \tag{3.18}$$

Subsequently, it is necessary to initialize the Linear and Non-Linear damping matrices. The Linear Damping matrix is formed by Matlab coefficients obtained in a previous simulator in Matlab. The Non-Linear must be calculate inside the loop because it depends by the vehicle'speed.

$$D_L = \begin{bmatrix} X_u & 0 & 0 & 0 & 0 & 0 \\ 0 & Y_v & 0 & Y_p & 0 & Y_r \\ 0 & 0 & Z_w & 0 & Z_q & 0 \\ 0 & K_v & 0 & K_p & 0 & K_r \\ 0 & 0 & M_w & 0 & M_q & 0 \\ 0 & N_v & 0 & N_p & 0 & N_r \end{bmatrix} = \begin{bmatrix} 4.03 & 0 & 0 & 0 & 0 & 0 \\ 0 & 6.22 & 0 & 0 & 0 & 0 \\ 0 & 2 & 15.1 & 0 & 0 & 0 \\ 0 & 2 & 0 & 5 & 0 & 3 \\ 4 & 0 & 6 & 0 & 5 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.066 \end{bmatrix} \tag{3.19}$$

At this point we can enter inside the loop where we can calculate the position, the velocities and the acceleration of the ROV. Now we can calculate the Non-Linear matrix and sum it to the Linear-damping.

$$D_{NL} = \begin{bmatrix} 18.18|u| + 24.24u^2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 21.66|v| + 128.52v^2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 45.66|w| + 116.13w^2 & 0 & 0 & 0 \\ 4 & 0 & 6 & 5|p| & 0 & 0 \\ 0 & 0 & 0 & 0 & 5|q| & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.825|r| \end{bmatrix} \tag{3.20}$$

$$D = D_L + D_{NL} \tag{3.21}$$

To obtain the acceleration of the ROV,before, we must estimate the environmental forces: the current force, the gravity and the buoyancy force. For the current force, it must be set the direction and the force. In this case, it was chosen a force of 2 Newton from West. Then,the current vector, depending by the heading of the vehicle, is calculated:

$$\tau_c = \begin{bmatrix} \tau_{cur} * cos(\alpha - \psi) \\ \tau_{cur} * sin(\alpha - \psi) \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{3.22}$$

Where τ_{cur} is the current's force and α its direction. Then the gravity forces is written:

$$G = \begin{bmatrix} 0 \\ 0 \\ 0 \\ -B_{GZ}(m * 9.81)cos\theta sin\phi \\ -B_{GZ}(m * 9.81)sin\theta \\ 0 \end{bmatrix} \tag{3.23}$$

Where $B_{GZ} = 0.15$ is the ... The buoyancy B force is set equal to 1 N. At this point it is possible to calculate the acceleration of the ROV:

$$a = M^{-1}(-Dv + \tau + G + B - \tau_c) \tag{3.24}$$

Then, with Euler Integration, it is possible to obtain the velocity and the position of the ROV in the Body-frame.

$$v_n = v_{n-1} + adt \tag{3.25}$$

To get the position in the Earth-fixed frame is necessary, first to multiply the transformation matrix $J(/eta)$ with the velocities in the body-fixed frame, and then applying another time the Euler Method:

$$v = J(\eta)a \tag{3.26}$$

$$\eta_n = \eta_{n-1} + v * dt \tag{3.27}$$

3.4.1 Simulator result

To figure out the simulator's operate we observe its behavior checking position and velocities over time. In the first attempt (Fig. 3.2 and 3.3)we set all the thrusters force equal to 0 and observe how the current force acts on the vehicle.

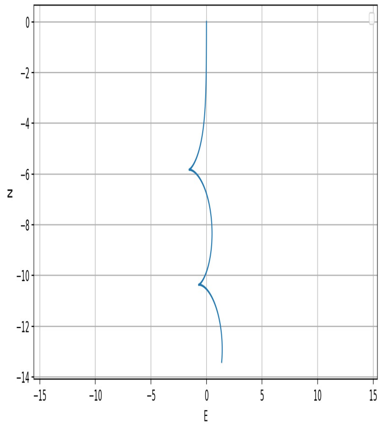

Figure 3.2: Position in the North-est frame during the test 1

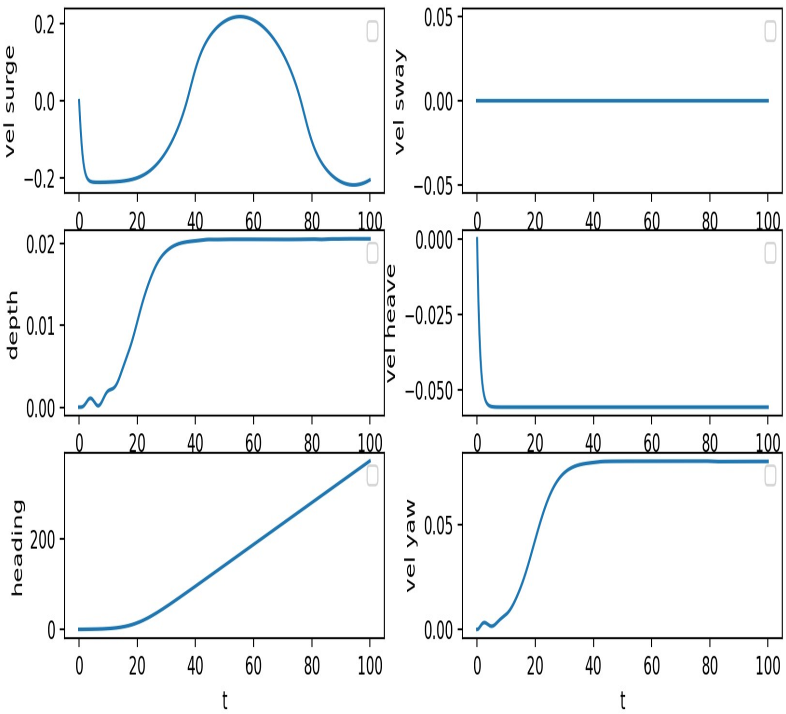

Figure 3.3: Velocity in the main directions, depth and heading during the test 1

In the second attempt (Fig. 3.4 and 3.5) we set a 10 N force in surge direction.

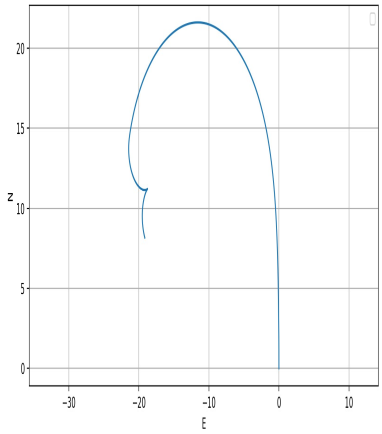

Figure 3.4: Position in the North-Est frame during the test 2

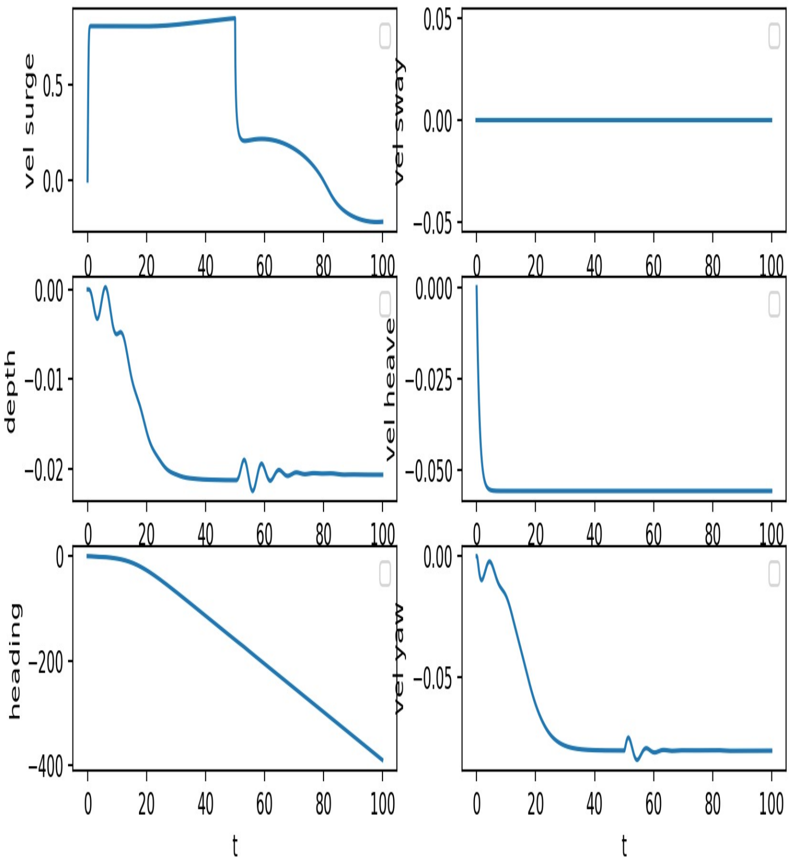

Figure 3.5: Velocity in the main directions, depth and heading during the test 2

In the last attempt (fig. 3.6 and 3.7) the force is 10 N in sway direction.
The results seem correct and reliable. The fact that the vehicle does not go straight

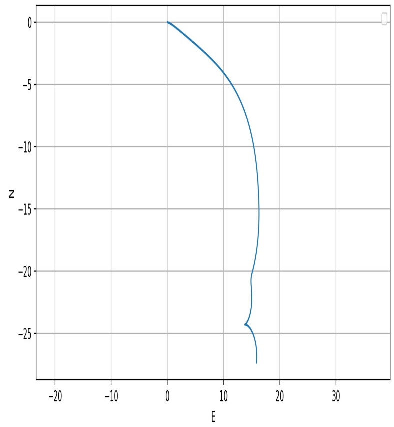

Figure 3.6: Position in the NE frame during the test 3

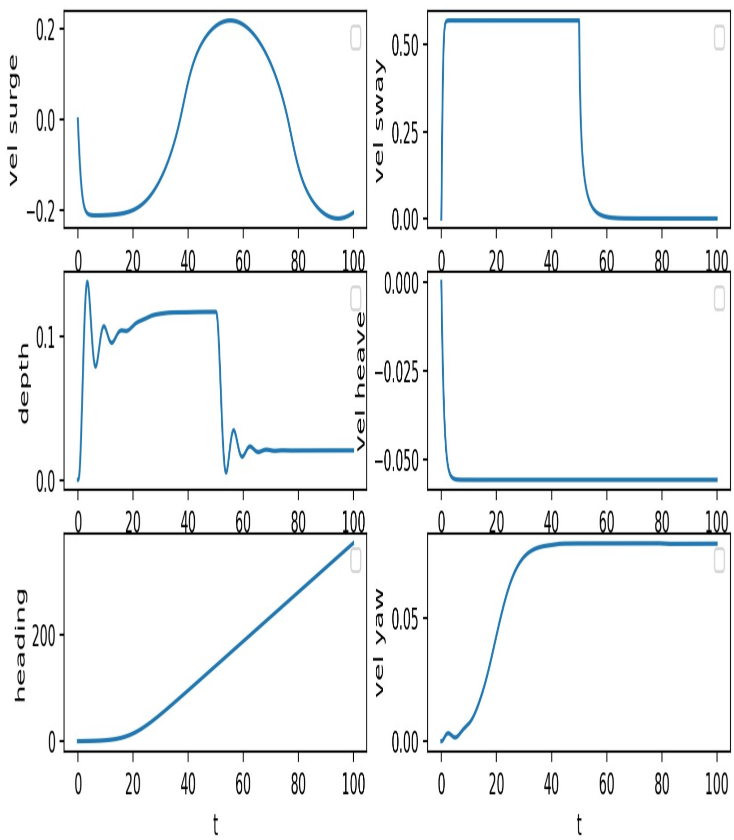

Figure 3.7: velocity in the main directions, depth and heading during the test 3

and it turns, also if the force is in only one direction, is due to the values out of the diagonal in the linear damping matrix, that stand for the coupling with pitch due to surge.

3.4.2 Proportional Controller

In order to demonstrate another time the validity of the Simulator, a proportional controller has been developed. It works only in the horizontal plane. To control also the depth, it would be necessary another controller. For first, it is necessary to set the gain of the controller, the references of position and velocity in all direction and the time of the simulation. The theory of a controller will be explain better in the next chapter At this point, the steps inside the loop are:

1. Obtain the position and the velocities of the vehicle from the simulator.

2. Calculate the errors of the position and the velocities in all direction. Then, the error of the position is transformed in the body-fixed frame.

$$E_{pos}(t) = R_{psi}(\eta_n - \eta_{ref}) \tag{3.28}$$

$$E_{vel}(t) = v_n(t) - v_{ref}(t) \tag{3.29}$$

Where:

$$R(\psi) = \begin{bmatrix} cos\psi & sin\psi & 0 \\ -sin\psi & cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{3.30}$$

3. At this point, it is possible to calculate the forces to apply. It is important to impose limit at the forces, setting the real forces that the vehicle can apply, in order to make the simulation factual. Subsequently, the loop will restart updating the position and the velocities of the vehicle with the forces impose by the controller.

$$\tau = -K_p E_{pos} - K_d E_{vel} \tag{3.31}$$

3.4.3 Results with feedback control

In the first test the vehicle must proceed 10 m in north direction. As can be seen from the images below (fig. 3.8, 3.9 and 3.10) the result is good with an error of few meter's tenths.

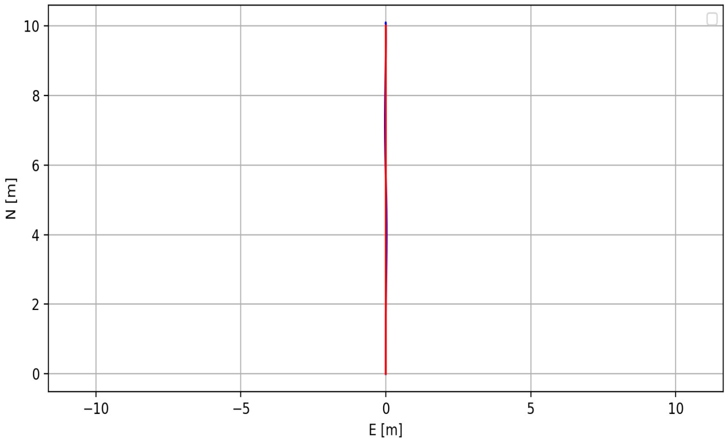

Figure 3.8: Position in the N-E frame

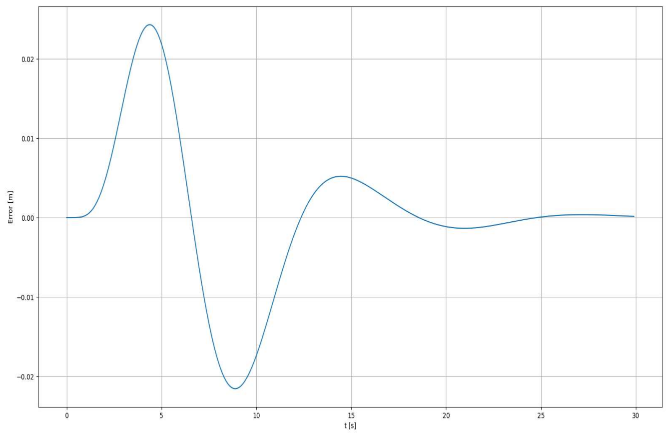

Figure 3.9: Error compared to the path to follow

In the second test the vehicle must proceed 10 meters towards East. Also in this case,as we can see in the figures 3.11 and 3.12, the result is good, with a bigger error, however below 1 meter. Probably due the fact that, at the beginning, the vehicle must change the heading, turning of 90 degrees, increase the instability and the difficulty of maintaining the right path. As visible in the Fig.3.13, the change of heading is performed quite quickly and with good precision.

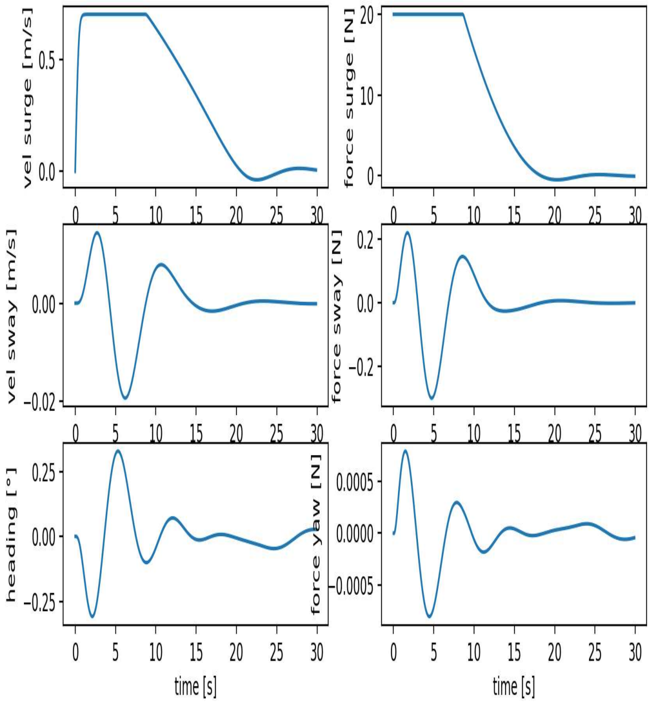

Figure 3.10: velocity in the main directions,heading and force during the path

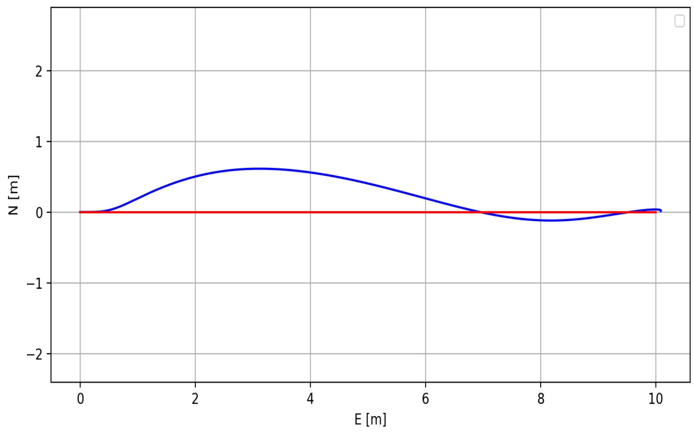

Figure 3.11: Position in the N-E frame (in blue). In red the path to follow

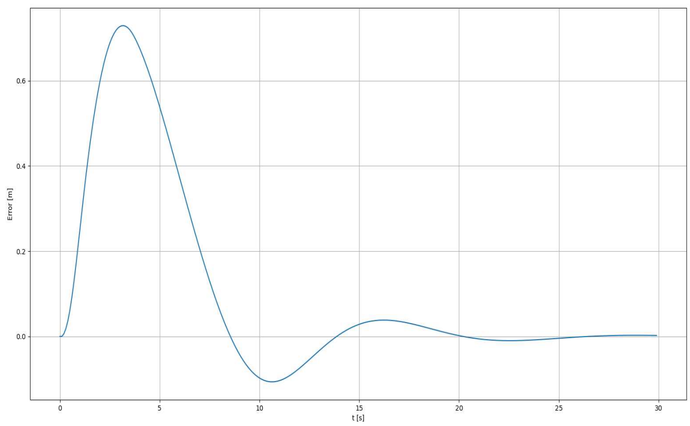

Figure 3.12: Error compared the path to follow

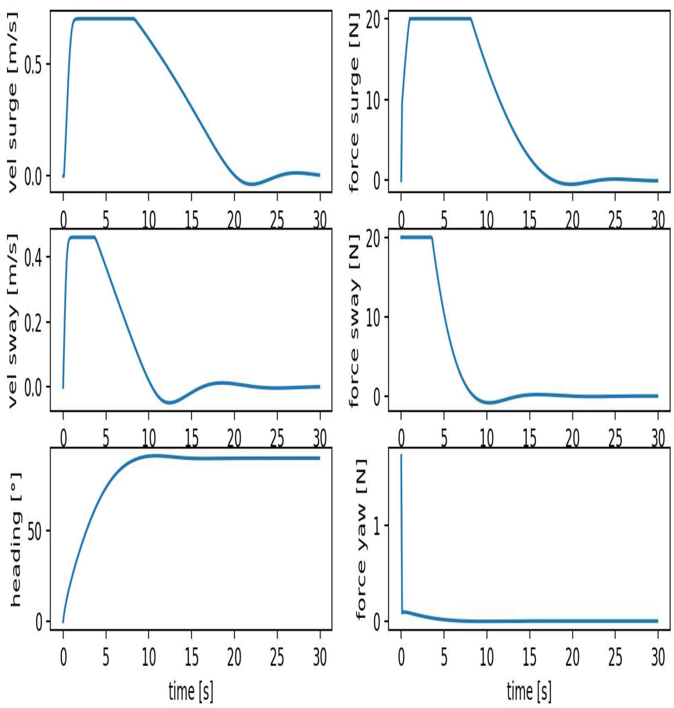

Figure 3.13: velocities,heading and force during the test

In the last test (fig.3.14 and 3.15), the vehicle must proceed 5 meters towards north and 5 meters towards east. Compared to the previous test

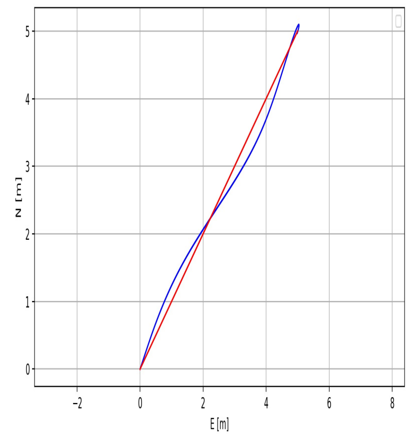

Figure 3.14: Position in the N-E frame (in blue). In red the path to follow

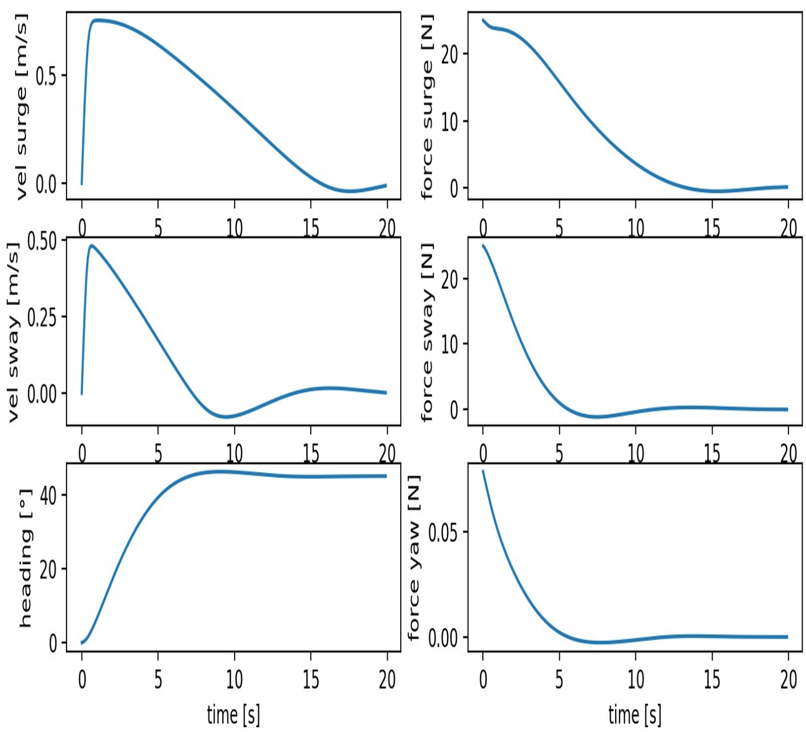

Figure 3.15: velocities,heading and force during the test 3

3.4.4 Conclusion

These tests are the first attempt to see how the simulator works and if the data is reliable, but the results from the proportional controller are good and show the correct functioning of the controller and the simulator.

Chapter 4

Guidance, Navigation and Control

In this chapter we will see how the GNC module has been developed and tested, evaluating and choosing the algorithms with the best performance for our vehicle.

4.1 Guidance, Navigation and Control

Guidance, Navigation and Control (abbreviated GNC) is a branch of engineering dealing with the design of system to control the movement of vehicles. GNC system for underwater vehicle found its development in the latest years, before, the only automatic controls present on ROV, were auto heading, auto depth and auto altitude. The Blueye ROV, used in this project, is still sold with these three controls. The GNC system (as can be seen in Fig.4.1) system consists in three modules:

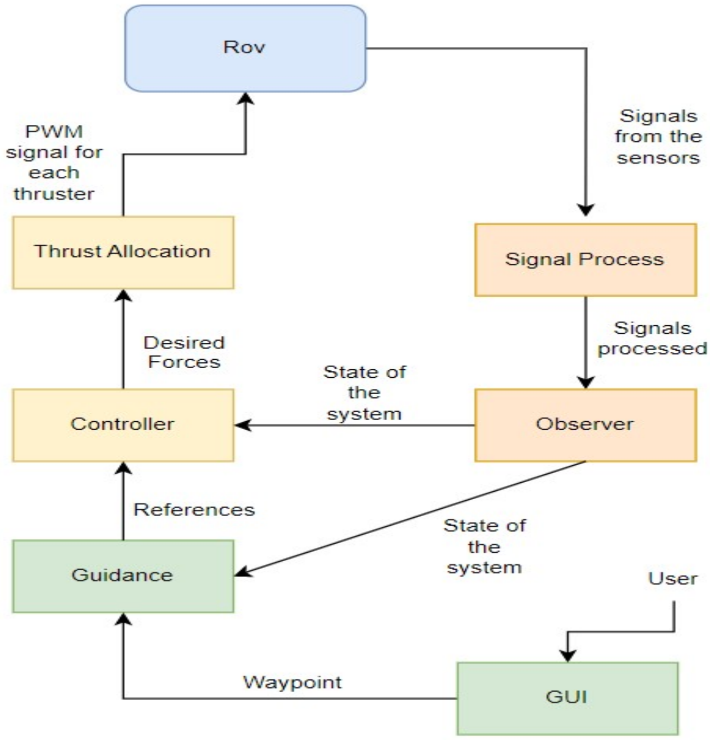

Figure 4.1: GNC scheme

1. Navigation: receives the signals from the sensors on the vehicle and returns the state of the system. COnsists mainly in the signal filter block and the observer.

2. Guidance: on the basis of the commands given by the operator returns the reference trajectory to the control module. In this thesis the operator set the waypoints that shape a path.

3. Control: received the reference trajectory from the guidance module and the state of the ROV from the navigation module send the signals to the actuators with the desired forces.

4.2 Navigation Module

The objective of the Navigation module is to provide the state of the system. It is made up by the signal process block and observer. The signal process block will receive the raw signals from sensors, elaborate it and send it to the observer. The observer will process the signal and the desired force to estimate the current state of the ROV. A measured signal often contain noise which a negative impact on the controller performance if no precaution is taken in the dynamic positioning. The quality of the input signal is crucial to the performance of the rest of the system. Inaccurate state estimation can cause the guidance system to generate wrong or discontinuous reference trajectories and consequently inaccurate moments and forces. Any anomaly of the input signals should be detected, isolated, and missing information should be filled in. The design of the observer module becomes critical for underwater vehicle due to limitations imposed by the water media, which puts strict constraints on the communication links between the operators and the vehicle itself. Therefore, the main purpose of the observer module is:

1. Reconstruction of non-measured data. For many applications important process states are not measured. The reasons could be that no convenient sensors exist, or simply that cost reasons motivate to not install the sensor. In such the main purpose of the state estimator is to reconstruct the unmeasured signal and perform filtering before the signals are used in the feedback control system.

2. Dead reckoning. All kind of equipment will fail according to some failure rate. Experience from the industrial applications has shown that one of the most frequent control system failures are caused by sensor failures. In safety critical marine applications, a sudden drop out of the control system may lead to dangerous situations, if not an adequate substitution will take place.

3. Wave filtering. Wave filtering can be defined as the reconstruction of the Low Frequency motion components from noisy measurements of position and heading by means of analog or digital filters. For most positioning applications the WF motion is not subject for control, often because that does not matter for the motion, or the vehicle does not have enough power and thrust capacity for doing any noticeable compensation. The latter is the most usual reason, hence, there is no point to waist fuel and cause additional wear and tear of the propulsion equipment.

There are mainly three different methods in marine control for position and velocity state estimation:

1. Extended Kalman Filter design: the traditional Kalman filter based estimators are linearized about a set of pre-defined constant yaw angles, typically 36 points in steps of 10 degrees, to cover the whole heading envelope between 0 and 360 degrees. When this estimator is used in conjunction with a linear quadratic

gaussian (LGQ), PID, or H controller in conjuncture with a separation principle, there is no guarantee for global stability of the total nonlinear system. The price for using linear theory is that linearization of the kinematic equations may degrade the performance of the system. Besides, the number of filter gains and switching transitions between the various sector are large.

2. Nonlinear observer design: the nonlinear observer is motivated from passivity arguments. Also the nonlinear observer includes wave filtering, velocity and bias estimation. In addition it is proven to be global asymptotic stable, through a passivation design. Compared to the Kalman filter, the number of tuning parameters is significantly reduced, and the tuning parameters are coupled more directly to the physics of the system. By using a nonlinear formulation, the software algorithms are simplified.

3. Adaptive and nonlinear observer design: the nonlinear and passive observer is further extended to adaptive wave filtering by an argumentation design technique. This implies that the wave frequency model can be estimated recursively on-line such that accurate filtering is obtained for different sea states. However, conducting DP operations in extreme seas, as proposed in Sorensen (2002), has shown that adaptive wave filtering may degrade the performance significantly using the same observer.

The chosen algorithm for the system's observer is the Extenden Kalman Filter.

The Extended Kalman Filter (EKF) is a recursive algorithm used to estimate the state of a nonlinear dynamic system described by the following equations:

$$\mathbf{x}_k = f(\mathbf{x}_{k-1}, \mathbf{u}_{k-1}) + \mathbf{w}_{k-1}, \tag{4.1}$$

$$\mathbf{z}_k = h(\mathbf{x}_k) + \mathbf{v}_k, \tag{4.2}$$

where:

- $\mathbf{x}_k$ is the state vector at time k,
- $\mathbf{u}_k$ is the control input vector,
- $\mathbf{w}_k$ is the process noise, assumed to be Gaussian with zero mean and covariance $\mathbf{Q}_k$,
- $\mathbf{z}_k$ is the measurement vector at time k,
- $\mathbf{v}_k$ is the measurement noise, assumed to be Gaussian with zero mean and covariance $\mathbf{R}_k$,
- $f(\cdot)$ and $h(\cdot)$ are nonlinear functions describing the system dynamics and the measurement model, respectively.

The EKF algorithm consists of the following steps:

1. Prediction:

$$\hat{\mathbf{x}}_{k|k-1} = f(\hat{\mathbf{x}}_{k-1|k-1}, \mathbf{u}_{k-1}), \tag{4.3}$$
$$\mathbf{P}_{k|k-1} = \mathbf{F}_{k-1}\mathbf{P}_{k-1|k-1}\mathbf{F}_{k-1}^{\top} + \mathbf{Q}_{k-1}, \tag{4.4}$$

where $\hat{\mathbf{x}}_{k|k-1}$ is the predicted state, $\mathbf{P}_{k|k-1}$ is the predicted error covariance, and $\mathbf{F}_{k-1}$ is the Jacobian of $f(\cdot)$ evaluated at $\hat{\mathbf{x}}_{k-1|k-1}$.

2. Update:

$$\mathbf{K}_k = \mathbf{P}_{k|k-1}\mathbf{H}_k^{\top}\left(\mathbf{H}_k\mathbf{P}_{k|k-1}\mathbf{H}_k^{\top} + \mathbf{R}_k\right)^{-1}, \tag{4.5}$$
$$\hat{\mathbf{x}}_{k|k} = \hat{\mathbf{x}}_{k|k-1} + \mathbf{K}_k\left(\mathbf{z}_k - h(\hat{\mathbf{x}}_{k|k-1})\right), \tag{4.6}$$
$$\mathbf{P}_{k|k} = \left(\mathbf{I} - \mathbf{K}_k\mathbf{H}_k\right)\mathbf{P}_{k|k-1}, \tag{4.7}$$

where $\mathbf{K}_k$ is the Kalman gain, $\mathbf{P}_{k|k}$ is the updated error covariance, and $\mathbf{H}_k$ is the Jacobian of $h(\cdot)$ evaluated at $\hat{\mathbf{x}}_{k|k-1}$.

4.3 Observer test

The function $f()$ was derived from the control plant model with 6 degrees of freedom. The control plant model is a mathematical model that describes the vehicle dynamics, simplified compared to the process plant model, so that it can be implemented in the control system.

$$f(x,u) = \begin{bmatrix} J(\theta,\phi,\psi)\nu \\ -M^{-1}D(\nu) - M^{-1}R^T(\psi)G\eta + M^{-1}R^T(\psi)b + Bu \\ -T_b^{-1}b \end{bmatrix}, \tag{4.8}$$

The observer has access to the following measurements vector:

$$\mathbf{h}(\mathbf{x_k}) = \begin{bmatrix} x \\ y \\ z \\ \dot{x}_{DVL} \\ \dot{y}_{DVL} \\ \dot{y}_{DVL} \\ a_x \\ a_y \\ a_z \\ \alpha_x \\ \alpha_y \\ \alpha_z \end{bmatrix}$$

where:

- $(\dot{x}_{DVL}, \dot{y}_{DVL}, \dot{z}_{DVL},)$ are the surge and sway speed components provided by a A50 Doppler Velocity Log (DVL); those measurements are referred to the BODY frame.
- z is the depth, measured by a 100 bar pressure gauge;
- (a_x, a_y, a_z) are the surge, sway and depth acceleration components provided by the IMU); those measurements are referred to the BODY frame.
- $\alpha_x, \alpha_y, \alpha_z$ is the yaw rate provided by a silicon rate sensor (gyro).
- x, y, z are the position in the NED frame. While Z is measured with pressure sensor, position in the NED FRAME is obtained with the integration of the linear velocity in the NED frame applying the Euler Method:

$$v = J(\eta)a \tag{4.9}$$

$$\eta_n = \eta_{n-1} + v * dt \tag{4.10}$$

To complete the observer we need the sensor parameters Q, R.

Table 4.1: Measurement Data

Measurement	**Sensor**	**R**	**Q**
Heave	Pressure	0.017	1e-10
Acceleration	IMU	1e-3	1e-6
Linear Velocity	DVL	0.308	1e-10
Angular Velocity	IMU	3.08e-5	1e-10

Only after testing the guidance algorithms, the Observer has been added at the simulations. Previously, to perform the tests of the guidance algorithms, the vehicle speed and position information were taken directly from the simulator, given that the addition of the observer, and the noise added to the measurements to test it. In the Figure 4.2, the Rov's trajectory adding the observer at the system(in yellow) is not precise and continue as the trajectory obtained with the controller input provided directly from the simulator (in blue), but the final result is acceptable and the ROV still complete the path in a stable way .

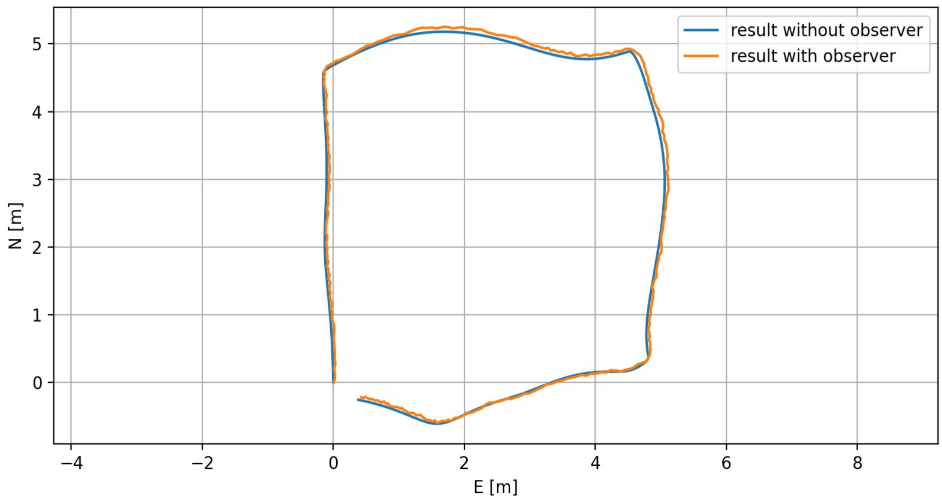

Figure 4.2: Velocity, heading and force applied by the ROV

4.4 Control Module

This module consist of two node: the controller and the thrust allocation. Get as input the state estimation from the navigation module and the desired state from the guidance module. Provide as output the signal with the desired force for each thruster.

4.4.1 Controller

The controller is an important part of GNC, which provided the desired forces in each axis by minimize the error between the measured or estimated current state and the desired state. With the feedback from the navigation system, a PD controller is implemented here. The inputs for the controller are P_{obs} and $P_{desired}$, the current state and the desired state of ROV in the NED frame. So the error in NED frame is:

$$e_{NED} = P_{desired} - P_{obs} \tag{4.11}$$

For the desired force of the ROV is in the body-fixed frame, so we need to transfer the error vector from NED to body-fixed frame:

$$e_{body} = J(\eta)^{-}1 * e_{NED} \tag{4.12}$$

where $J(\eta)$ is the three-Dof rotation matrix. In this way the controller is designed as following equation:

$$F_{general} = K_p e_{body} + K_d \frac{de_{body}}{dt} \tag{4.13}$$

where
$F_{general}$: desired force on each Dofs
e_{body} : error value in body-fixed frame
K_p : proportional gain
K_d : derivative gain

4.4.2 Thrust allocation

This node takes the desired forces from the Controller and calculate the force for each thruster. In this thesis, the pseudo inverse method will be applied:

$$F_{general} = T * K * u \tag{4.14}$$

Where $F_{general}$ is the applied force along the body frame axis, that in this case is: $[surge_{force}, sway_{force}, heave_{force}, yaw_{force}]$, given that the ROV is assumpted stable in pitch and roll. As already said, these value is given out by the controller. The vector u represents the rotation velocity of each thruster. The K matrix represent the map from rotation velocity of thrusters to the force.

4.5 Guidance Module

Guidance is the process of calculating the changes in position, velocity, altitude and and/or rotation rates of a moving object required to follow a certain trajectory and/or altitude profile based on information about the object's state of motion. The guidance has as inputs the state of the vehicle from the Navigation module and the waypoints set by the user. In this thesis are being studied two different ways of set a trajectory. The first one contents three nodes: the first is node where the user set the 3D-waypoints list. The Line of Sight node set the 6DOF waypoints and transfer them to the references node, which will generate a path from the start point to the setpoint.

4.5.1 Line of Sight

An ROV navigating between waypoints P_k and P_{k+1} with Line of Sight is shown as following figure: From the figure we can find that the bearing between waypoints α_k

$$\alpha_k = atan2(y_{k+1} - y_k, x_{k+1} - x_k) \tag{4.15}$$

So the along the track error and cross-track error could be expressed as

$$s(t) = [x(t) - x_k]cos(\alpha_k) + [y(t) - y_k]sin(\alpha_k) \tag{4.16}$$

$$e(t) = -[x(t) - x_k]sin(\alpha_k) + [y(t) - y_k]cos(\alpha_k) \tag{4.17}$$

For the porpose of minimized the cross-track-error $e(t)$, the following command is used:

$$\chi_r = arctan(-e(t)/\delta) \tag{4.18}$$

Where δ is the look ahead distance, which is a constant.

4.5.2 2D-Line of Sight

The ROV Blueye is not controllable on pith direction. Thus the 2D Line of Sight method is chosen to track lines between waypoints. To carrying out the motion in 3D space the scheme is divided in horizontal motion and depth motion. So, it is necessary to control it separately. When it is set new waypoints $[x_i, y_i, z_i]$, the sistem will dive into the desired depth and then apply the Los algorithm and moves trough the waypoints with a constant depth.

4.5.3 Modified Line of sight

The second algorithm tested is a modification of the previous algorithm. The algorithm returns, in addition to the desired heading angle, the velocity in the body-frame in order to reach the waypoints. Starting over from the [36], the desired

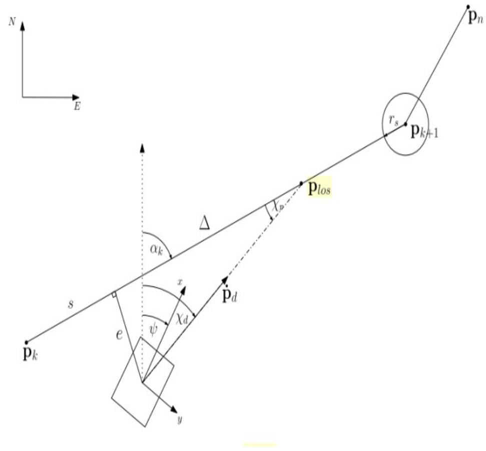

Figure 4.3: Line of Sight, Fossen 2014

velocity $\dot{p}$ is given by the desired course angle χ_d and a desired speed U_d according to

$$\dot{p}_d^n = R_z(\chi_d) \begin{bmatrix} 1 \\ 0 \end{bmatrix} U_d \tag{4.19}$$

The kinematic relationship between velocity in the NED frame and the body-fixed frame is given by

$$\dot{p}_d^n = R_b^n(\theta_{nb}) v_d \tag{4.20}$$

Thus, the desired velocity vector in the body-fixed frame is found by inverting the kinematic equation [] and inserting equation []

$$v_d^b = R_b^n R_z(\chi_d) \begin{bmatrix} 1 \\ 0 \end{bmatrix} U_d \tag{4.21}$$

One may choose the desired speed U_d as the output of a velocity reference model or via a control available to the pilot, for example.
Seen that the algorithm gives as output a reference speed, also the controller has been modified. Instead of the derivative of the position error, the controller get as input the speed error.

4.5.4 Filter based reference model

A reference model is a method to create a desired trajectory based on the desired position instead of an impulse change of position. In this thesis the filter based reference model is implemented.

$$\frac{P_{ref}(s)}{P_{desired}} = \frac{\omega^2}{s^2 + 2\delta\omega s + \omega^2} \tag{4.22}$$

4.5.5 Switching waypoint

Thor I. Fossen (2011) propose to switch wayypoint when the vehicle is either within a circle of acceptance

$$[x_{k+1} - x(t)]^2 + [y_{k+1} - y(t)]^2 < R_{k+1}^2 \tag{4.23}$$

with Radius R_{k+1} around waypoint p_{k+1}^n, or when the covered along track distance $s(t)$ is sufficiently close to the total lenght s_{k+1} between waypoints p_{k+1}^n and p_k^n

$$s(t) > s_{k+1} - R_{k+1} \tag{4.24}$$

The former strategy should be used if it is important to pass trough each waypoint, whereas the latter should be used when the waypoints simply define a path.

4.5.6 Results with LoS algorithms

As already said the Line-of-Sight algorithms used in this thesis work in the horizontal plane with a constant deep. Thus, the ROV have to reach the desired depth and, then applied the LoS algorithm.
In order to test the algorithms, it has been simulated a path with four waypoints arranged in a square separated by 30 m. The radius of circle of acceptance chosen is equal to 1 m.

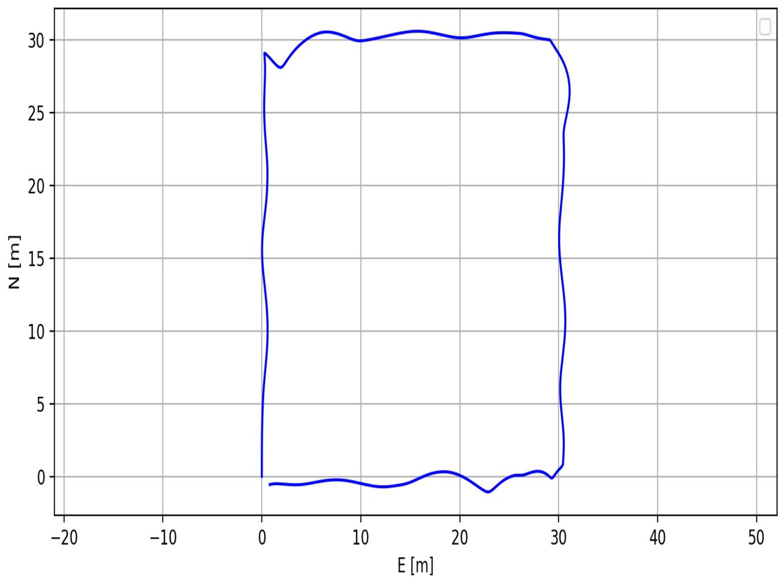

Figure 4.4: Trajectory carry on by the ROV in the simulation with the standard Line of Sight algorithm

The results from the two different algorithms can be considered similar. the parameter that greatly affects on the final result is δ. Increasing the value increase

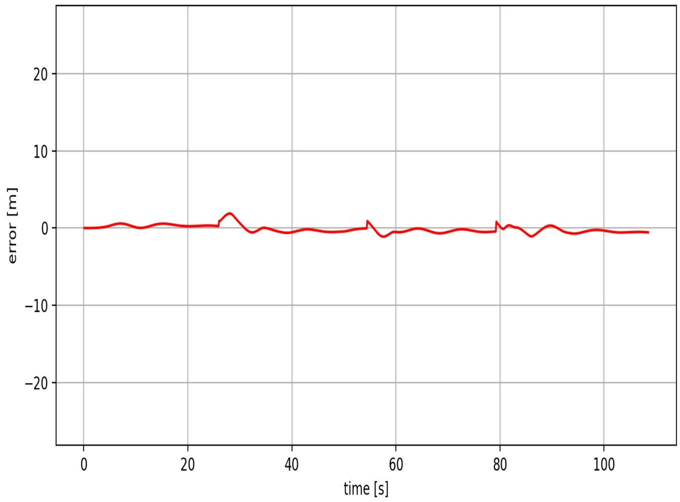

Figure 4.5: Error

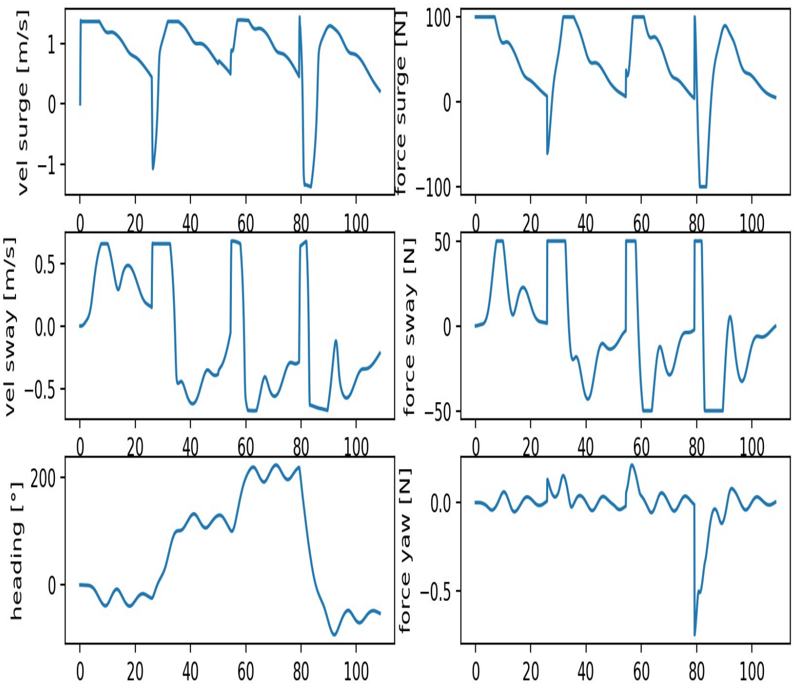

Figure 4.6: Velocity, heading and force applied by the ROV

the error from the line between two way-points but the heading is more stable and more aligned with the line form by the way-points.

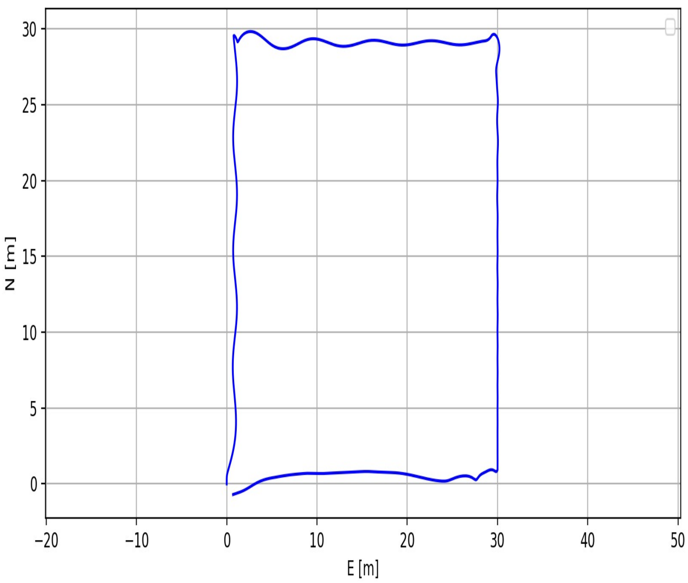

Figure 4.7: Trajectory carry on by the ROV in the simulation with the modified Line of Sight algorithm

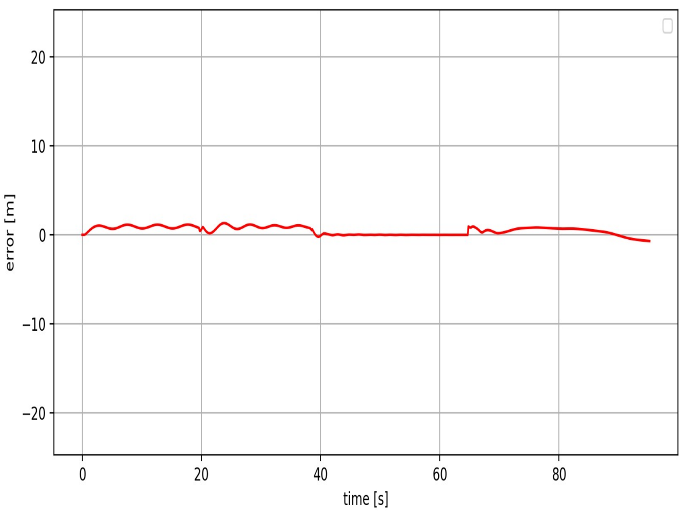

Figure 4.8: Error

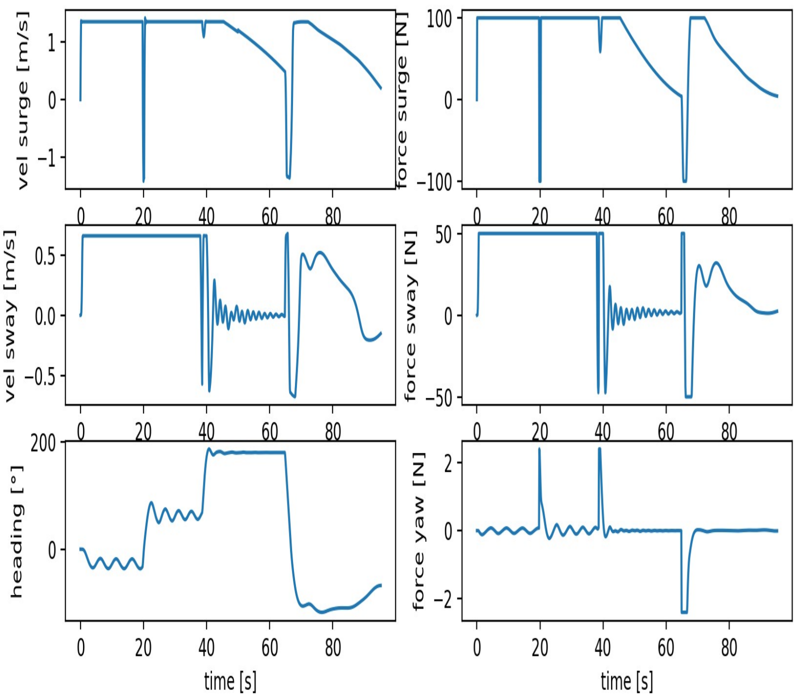

Figure 4.9: Velocity, heading and force applied by the ROV

Chapter 5

Hybrid System

Firstly, we will see study deeper the characteristics of an Hybrid system and, then, apply the concept to the Blueye ROV.

5.1 Introduction to Hybrid system

The increasing interest in autonomous marine systems and related applications has motivated, among others, the development of systems and algorithms for the dynamic positioning of marine vehicles (ships, surface vessels, underwater vehicles) under the influence of unknown environmental disturbances. A marine vehicle can work in different operational conditions concerning different aspects of the navigation. Vessels can change the use mode, consisting in different algorithms that satisfy different control objective such as station keeping, maneuvering, and target tracking which is closely linked with the vessel speed. A marine vessel can usually operate in different environment state consisting of wind, waves and current state. Because different physical effects matter for the various vehicle operational conditions, there are distinct models and control strategies which are designed specificallly for each operational condition. When the controllers for each condition are combined into one control system by using performance monitoring and switching logic, dynamics arise that differential equations on their own cannot describe. Systems that include both continuous- and discrete time dynamics are called hybrid dynamical systems, or just hybrid systems, and the interaction between the different types of dynamics leads to challenging modeling and control problems [4]. The idea of hybrid-controller system is the ability to automatically switch among controllers.

5.2 Hybrid Control System structure

A general structure for a hybrid motion control system, as shown in the image below (Fig. 5.1), can be composed by sets of candidate observers, controllers, control allocations, actuator controls, and a Hybrid and Supervisory control. The supervisory control monitors the performance of the different blocks and the switching logic chooses which algorithms to use in the closed-loop control from the candidates.

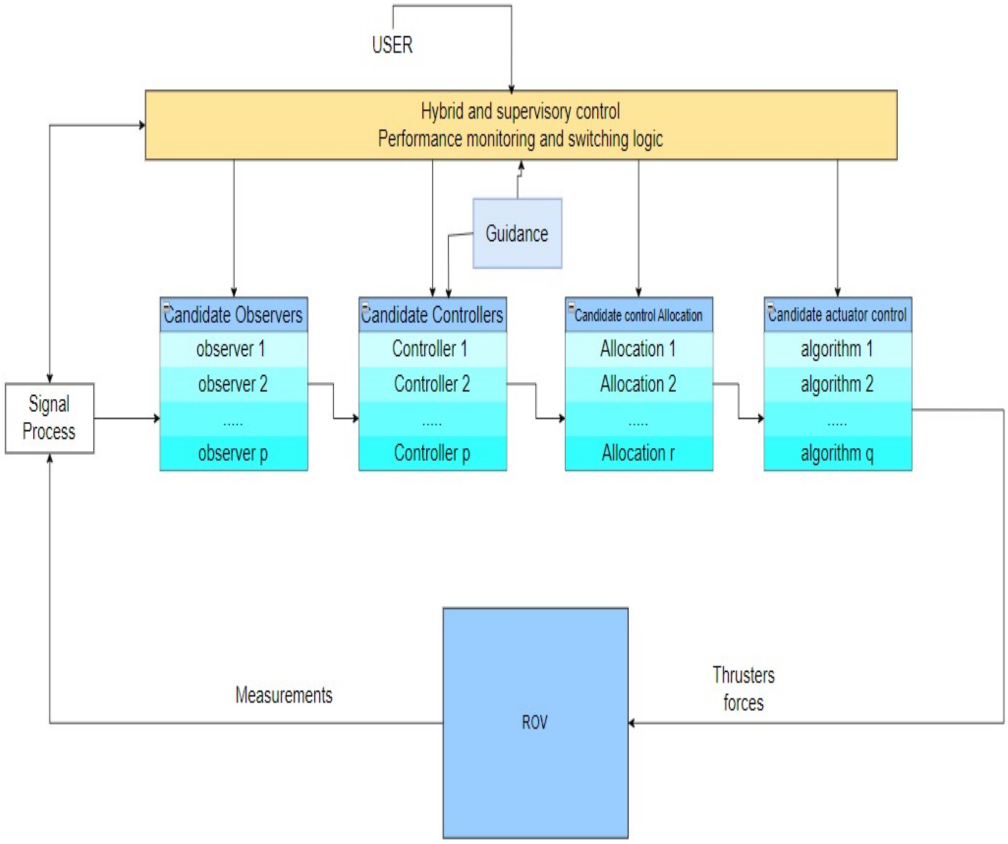

Figure 5.1: Hybrid system structure

5.3 Performance monitoring and Switching Logic

In order for a hybrid control system to be reliable, good switching criteria that are robust to measurement noise and system errors need to be established for the vessel speed, use modes, and environmental conditions. The main tasks of the performance monitoring functions are to decide which of the candidate algorithms to use in the closed loop, detect faults and provide decision support for the operator. The performance monitoring takes input from the operator, references, operating conditions, measured position, estimated position, control input, and more. To get a good picture of the overall performance, could be necessary considering several different parameters, and , as suggest Sørensen in [4], combine the norms of the different inputs in a cost function. Which variables to include, and how to weight them depends on the operational condition.
The switching logic has the task to ensure safe switching to the candidate algorithm indicated by the performance measures. A switch, here also referred to as a jump, induces a transient in the continuous-time system, which introduces additional dynamics that are not encountered in purely continuous-time system. Two cases that

may cause instability in automatic switching are: switching during transient and chattering. In the first case, the hybrid system is not allowed enough time to come to steady state, so that jumps are triggered based on the transient system behavior. This may lead to instability induced by switching. The transient could be due to initialization, a change of heading or set-point, or it could be to a previous jump. The latter case, chattering,consists in rapid switching back and forth. In order to avoid this scenario, explicit constraints on switching may be achieved through hybrid stability analysis. Constraining switches can be done though switching logic based on time, such as dwell-time or average dwell-time dynamics , or based on the system variables, such as hysteresis [5](Fig. 5.2). During dwell-time or average dwell-time

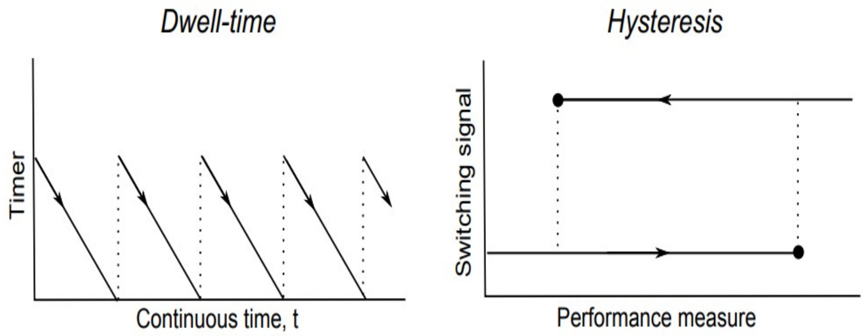

Figure 5.2: Illustration of dwell-time and hysteresis switching contraints. The timer dynamics to the left only allows periodic switches each time the timer reaches zero. The hysteresis on the right switches based on the history of the system state, or performance measure. A jump is indicated by the dotted lines. From "Marine Cybernetics, Lecture Notes, Asgeir Sorensen"

switching a timer keeps track of the time from the last switch, and does not allow a new switch until a certain time has passed. Hysteresis switching is based on the history of the variable, allowing switching only if the variable crosses a boundary with a certain direction of change. In many cases it is possible to implement both type of switching login, however the choice should complement the system dynamics as much as possible.

5.4 Hybrid system for a ROV

The main objective of this thesis is to demonstrate how the adoption of a hybrid controller system by an ROV can lead to an improvement in vehicle performance. To figure out how this type of system can be applied to Blueye it is necessary first understand the limits and uses of this tool. As already told in the introduction of this thesis, the Blueye is a small ROV, capable of moving safely only in calm waters, and it is usually used in Research or inspection in the "Oil and Gas" and Aquaculture industries. Therefore, the operating conditions in which it can be found are not many. The proposed hybrid system is composed of, in addition as well as performance monitoring and switching logic, two controllers for station keeping and maneuvering (Fig.5.3).

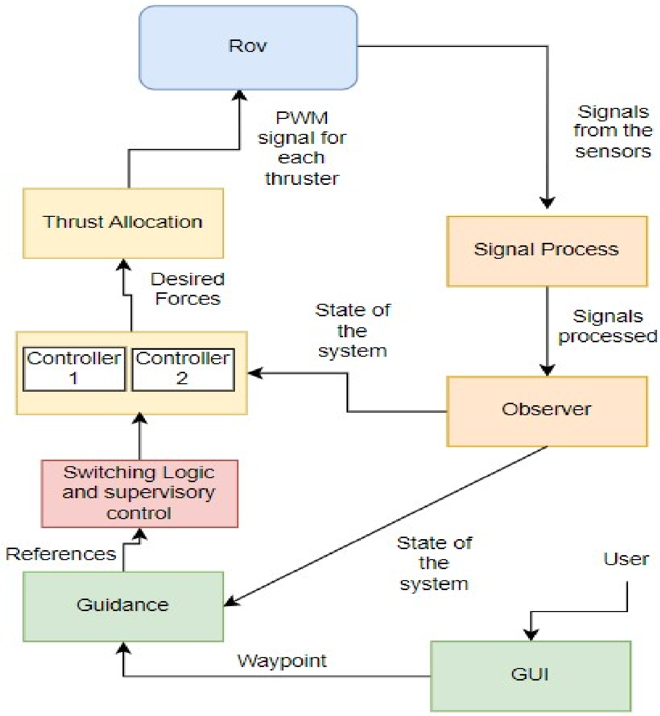

Figure 5.3: Hybrid system structure of the ROV

5.4.1 Switching logic

In this case of implementation of an hybrid system in the Blueye, the switch between controllers does not happen due to a change of the environment conditions or a change of the state of the vehicle. The choice between controller takes place according to the inputs given by the user. Trough an interface the user is asked wants to reach way-points. If inputs are given the ROV starts the task using the maneuvering controller. Once the operation has been completed or no input is given the ROV goes in the station keeping mode using the appropriate controller.

5.4.2 Station Keeping controller

The controller chosen for the station-keeping task is a PID controller.

$$F_{\text{general}} = K_p e_{\text{body}} + K_i \int e_{\text{body}}\, dt + K_d \frac{de_{\text{body}}}{dt} \tag{5.1}$$

In this case it can be noticed how the integrative term is important to reduce the accumulated error. After some tests, below there are the chosen parameters.

$$Kp = \begin{bmatrix} 5 & 0 & 0 \\ 0 & 5 & 0 \\ 0 & 0 & 0.5 \end{bmatrix}, Kd = \begin{bmatrix} 2 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 0.2 \end{bmatrix}, Ki = \begin{bmatrix} 5 & 0 & 0 \\ 0 & 5 & 0 \\ 0 & 0 & 0.5 \end{bmatrix} \tag{5.2}$$

To better evaluate the response of the controller at the current, the current force starts at the half of the simulation, and not at the beginning as in the previous tests (Fig.5.4). In the images below (Fig. 5.5 and Fig. 5.6)is possible to see the response of the ROV to the current force. The vehicle maintain the position within a range of few centimeters.

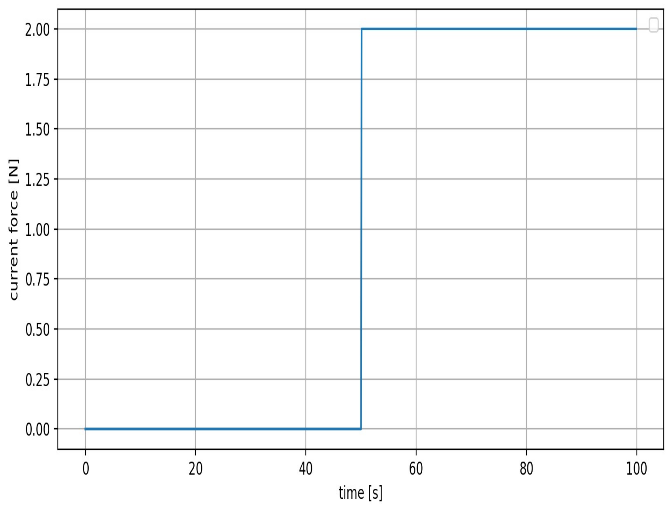

Figure 5.4: current force

In images 5.5 and 5.6, it can be seen how the use of the PID controller significantly reduces the residual error, leading to an increase in system performance. This can be very useful in situations where something is being observed with the camera.

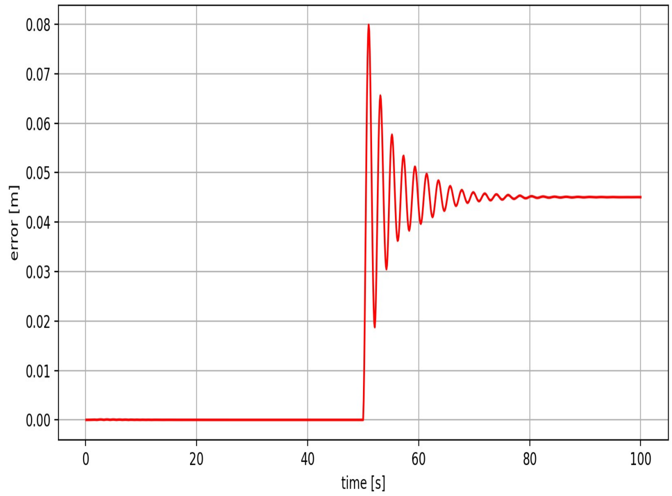

Figure 5.5: Error of the station keeping controller with the PID controller

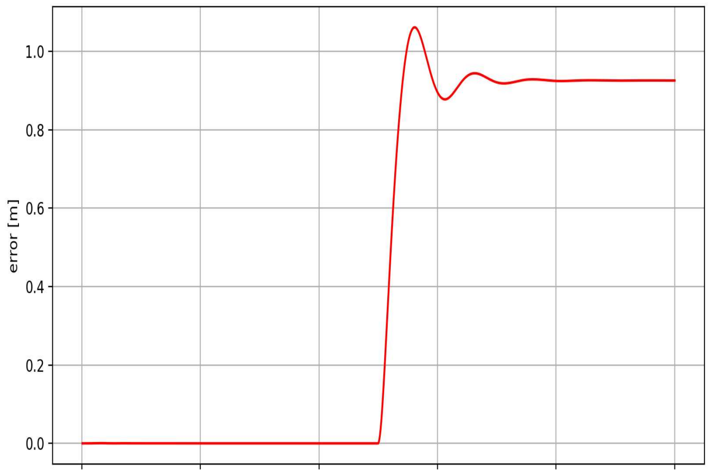

Figure 5.6: Error of the station keeping controller with the PD controller

5.4.3 Maneuvering controller

The controller chosen for the maneuvering is a PD controller. It has been removed the integrator term seen that it gets worse the performance and in the tests performed it didn't reach the way-points. In order to test the controller the ROV have to run across a path with a shape of a square 5 m x 5 m. The path is performed in a depth of a 5 m. To reach and maintain the desired depth another PD controller has been developed.

$$Kp = \begin{bmatrix} 5 & 0 & 0 \\ 0 & 5 & 0 \\ 0 & 0 & 0.5 \end{bmatrix}, Kd = \begin{bmatrix} 2 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 0.2 \end{bmatrix} \tag{5.3}$$

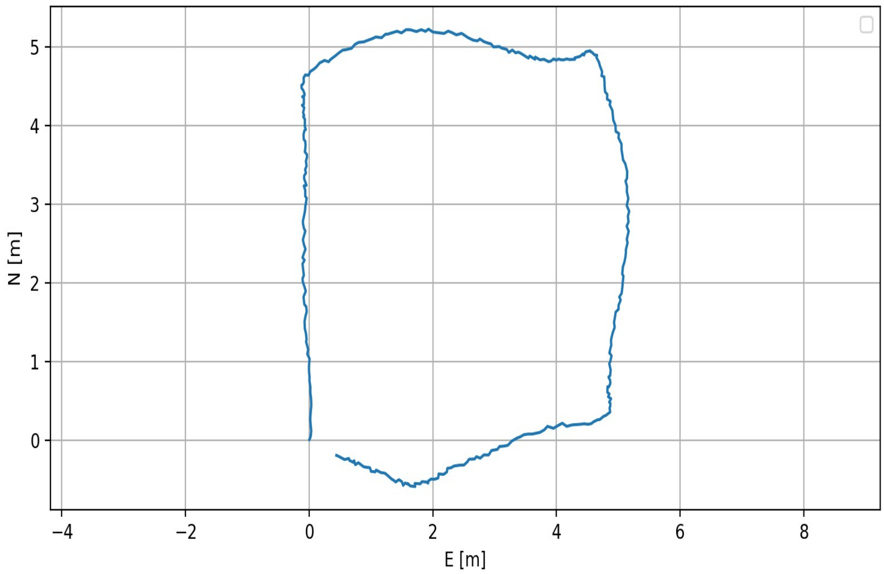

Figure 5.7: 2D path

As can be seen in the figure 5.8 and figure 5.7, the vehicle follow with good precision the chosen path. The PD controller used for depth control seems work accurately. The error (fig. 5.9) is relevant only in the waypoints and the vehicle seems more instable in the end of the path, but however with an acceptable error. From the figure 5.10 we can notice how the vehicle carried out the tasks with little effort by the thrusters and with good precision also in maintain the heading.

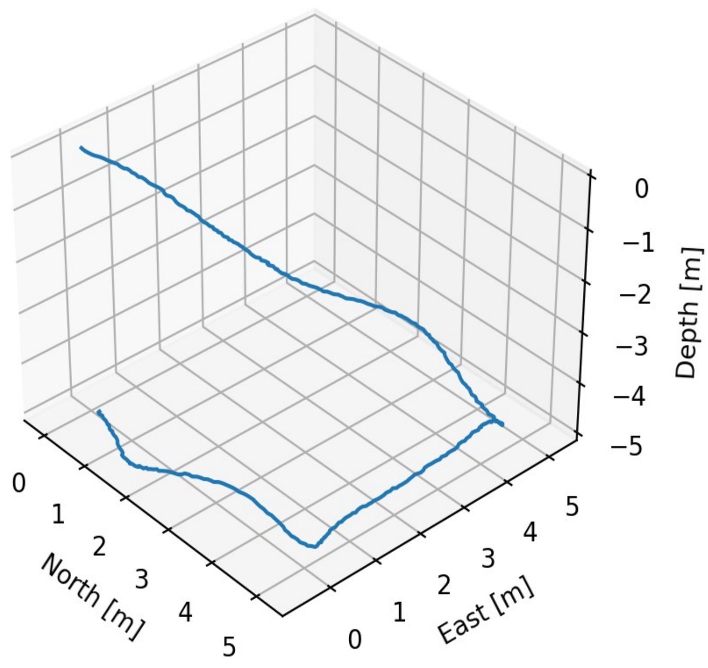

Figure 5.8: 3D path

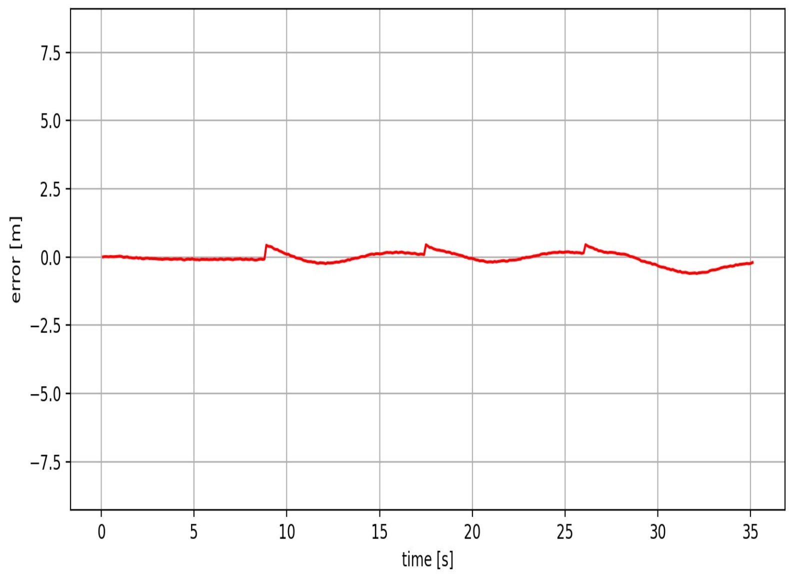

Figure 5.9: Error

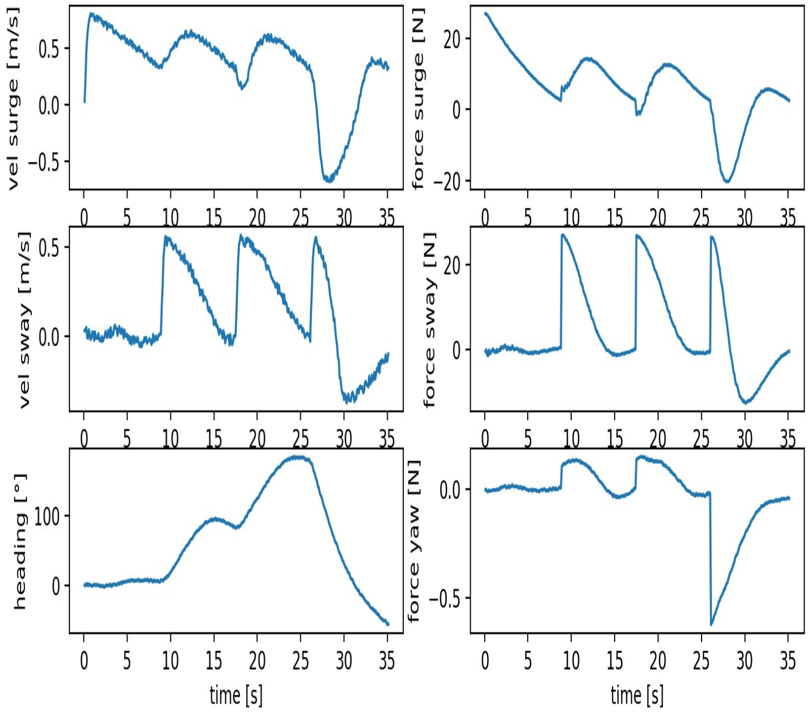

Figure 5.10: force and velocity of the ROV during the path

Chapter 6

ROS Implementation

With the intention of implement the work developed before in the Blueye ROV, some parts of the GNC system have been adapted to work in ROS2.

6.1 ROS Robot-operating system

Robot Operating System (ROS) provides libraries and tools to help software developers create robot applications. It is a flexible framework for software writing. The framework is made up by nodes, messages, topics and master. Nodes is the program to process scripts, which is connected by messages to communicate with each other. To specify the messages, each of them will have a unique topic.In this way we could allocate the work into different nodes and run them parallelly [6].

6.2 Keyboard Control

The first system developed is a simulation of the Blueye ROV that is controlled with the PC keyboard. Typing certain keys a node send a message to the simulator node with the command force in the various direction. Typing in "i" and "k" we send the control force in the surge direction, "j" and "l" correspond to the sway direction, "a" and "d" allow to set the heading and, in the end, "w" and "s" the depth. As can be seen on the figure of the nodes [Fig 6.1] the structure of the system is simple and has been chosen to understand how the ROS environment works.

Figure 6.1: ROS nodes of the keyboard control system

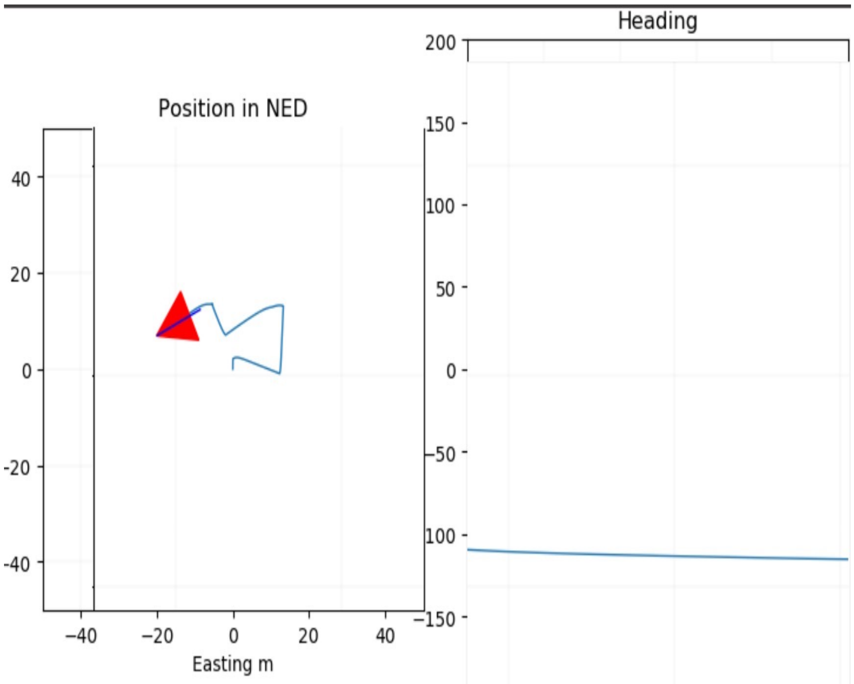

Figure 6.2: Simulator interface

6.3 GNC implementation

The second system implemented in ROS correspond at the GNC system developed in the chapter 4, containing the controller, the guidance and the navigation modules. In the images below we can see the system structure. The guidance module has been divided in two nodes. The first node allows the user to set the waypoints. The waypoints chosen will be sent to the guidance node, that will send the reference (in the various direction) to the controller.

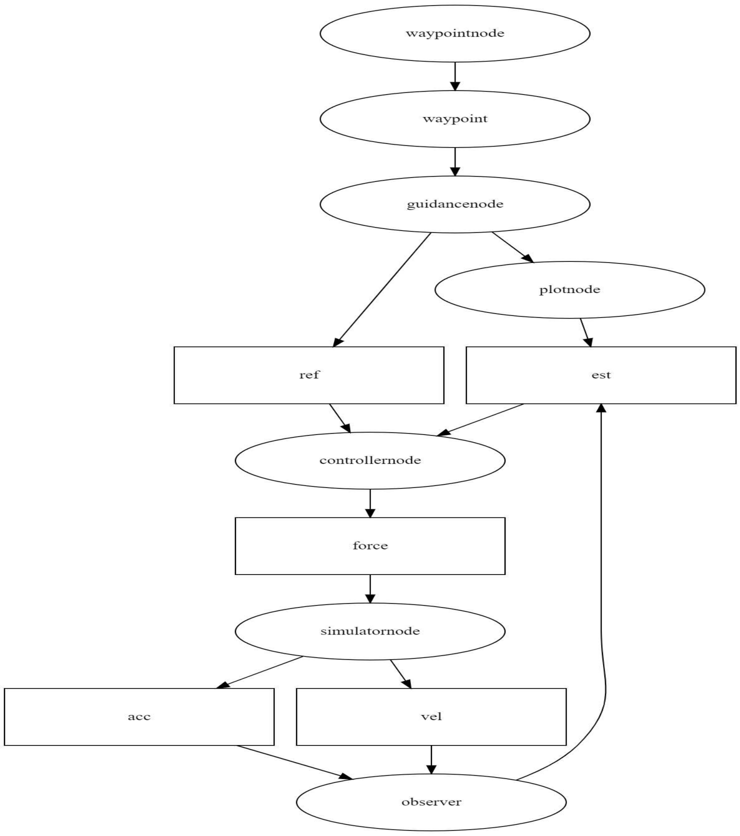

Figure 6.3: ROS nodes of the GNC system

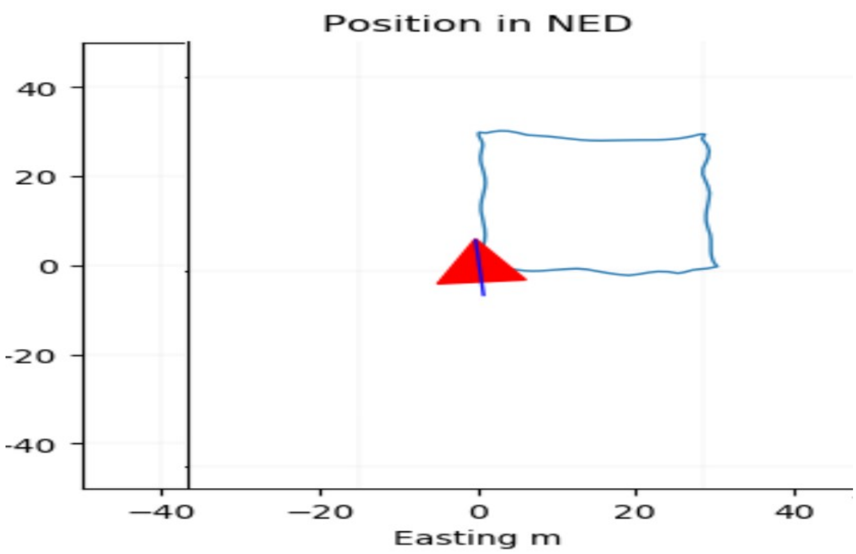

Figure 6.4: Simulator interface

Chapter 7

Conclusion

7.1 Conclusion

The main objectives of this thesis work are primarily two.

1. Create a stable GNC system that, with waypoints provided by the operator, the vehicle is able to reach them without human intervention.

2. Apply the concept of hybrid methods to the GNC system of the ROV, so that the vehicle can operate in different conditions as effectively and efficiently as possible.

The first objective, namely to develop a reliable GNC system, has been satisfactorily achieved; in the simulation environment, the Blueye ROV completes the assigned path without any problems and in a stable manner. To obtain a better assessment of the effectiveness and stability of the GNC system, it should be physically tested on the Blueye ROV in water, but due to time constraints, this was not possible.

Regarding the application of hybrid methods, the main issue is the limitation given by the small size of the ROV and the low available power, which makes it usable only in calm sea conditions and with little current. Therefore, the only change that can be applied is the change in operational mode. Switching from a PD controller in maneuvering situations to a PID controller in station keeping has shown how the system is more precise, that can be considered useful when the system has to perform inspection operations and let the operator focus on other aspects of the task.While the PID controller was found to be almost unusable for maneuvering operations, with very high error and instability.

7.2 Further Improvements

An improvement in the automation of the ROV could be the development of a system that recognizes obstacles and proposes an alternative trajectory. To achieve this, a vision system could be implemented, through which the ROV recognizes the obstacle and attempts to bypass it. The main problem is that at greater depths, visibility is poor, which could render the system useless. A more effective approach would be to use a sonar device. A 3D sonar is a type of sonar (sound navigation and ranging) system that uses sound waves to create three-dimensional images of underwater objects or environments. Besides navigation, the sonar could be used to accurately map environments and support underwater operations.

Bibliography

[1] Robert L. Wernli Sr Robert D. Christ. *The ROV Manual: A User Guide for Observation-Class Remotely Operated Vehicles*. 2007.

[2] Norgren P Ødegård Ø Cottier F. Asgeir J. Sorensen, Ludvigsen M. *POLAR NIGHT Marine Ecology – Life and Light in the Dead of Night*. 2018.

[3] T.I Fossen. *Handbook of Marine Craft Hydrodyamics and Motion Control*. 2011.

[4] Asgeir J. Sorensen. *Marine Cybernetics - Towards Autonomous Marine Operations and Systems*. 2018.

[5] João P. Hespanha. *Linear System Theory*. 2003.

[6] RyuWoon Jung TaeHoon Lim YoonSeok Pyo, HanCheol Cho. *ROS Robot programming*. 2017.