

Sida Yu

Design of Multi-Vehicle control system for mapping and monitoring

Master's thesis in Marine Technology

Supervisor: Martin Ludvigsen

November 2021

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Marine Technology



Norwegian University of
Science and Technology

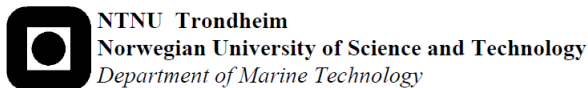
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MASTER THESIS IN MARINE CYBERNETICS

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Title: Design of Multi-Vehicle control system for mapping and monitoring.
Sida Yu (Student number: 592587)

Background

Remotely Operated Vehicles (ROVs) have been widely used in ocean mapping. However, A low-cost mini ROV can not carry big scale sensors like UHI (underwater hyperspectral imager) for better mapping. To deal with this problem, two mini remotely operated vehicles (ROVs) were assembled into a larger vehicle. For we would like to change the devices on this vehicle for different mission, which will cause huge change of the ROV dynamic parameters. dynamic parameters play an important role on the GNC system (Guidance, Navigation and control system).

an easier method to estimate the dynamic parameters for vehicle with different devices is needed to replace towing test. In this thesis, we will grab data from free running test and decay test. Using these data, an optimal method or machine learning method will be used for parameters estimation.

After the system is implemented, a robust GNC system will be developed to deal with different missions for the vehicle.

work scopes for the thesis

1. literature review key words
 - ROV and Double Blueye
 - Towing test
 - free running test
 - system identification
 - machine learning
 - Robust GNC system
2. Simulation Work
 - build up a system for calculate rigid body parameters
 - implement the optimal problem code and ML code for hydrodynamic parameters
 - Build up the GNC system and simulation environment.
 - try slam and mapping as positioning system to grab data
3. Experiments Work
 - Towing test to get the hydrodynamic parameters

- free running test to check the error between model and real robot. if error is big, do some optimal
- test GNC at TBS

The report shall be written in English and edited as a research report including literature survey, description of mathematical models, description of control algorithms, simulation results, model test results, discussion and a conclusion including a proposal for further work. Source code should be provided. It is supposed that Department of Marine Technology, NTNU, can use the results freely in its research work, unless otherwise agreed upon, by referring to the student's work.

Summary

This Master Thesis proposes a work of developing GNC system (Guidance, Navigation and control system) for Double Blueye, which is a Remotely Operation Vehicle (ROV) assembled by two Blueye Pioneers together to carry larger payload instruments. To deal with different missions in the underwater world, different devices will be removed or added on the vehicle. So Different GNC systems is needed for corresponding version of Double Blueye.

To achieve this objective, The work is divided into 3 parts of tasks: Double Blueye System Identification system, Simulation environment for Double Blueye and GNC system of Double Blueye.

1) Double Blueye System Identification system: In this part of work we built up a process of easy parameter identification for different versions of double blueyes robot, which is a combination of empirical method, free running test and decay test. In this thesis, the initial Double Blueye robot is set as an example to test the process and compared with towing test to verify the validation. To make this process easier, An ArUco position system was implemented with front camera and ArUco markers. In this way, we could test the dynamic parameters of Double Blueye in any clam and clear water environment.

2) Double Blueyes Simulation Environment : In This part of work, The digital twins of the Double Blueye and scene of MC-lab were built up on the platform of UWsim and ROS. Some sets of Hardware-in-the-loop test were simulated on this environment to check the stability and performance of GNC system

3) GNC system of Double Blueye: With known dynamic parameters, The GNC system is built up in this part. This is composed by thruster allocation, model based Extended Kalman filter and PID controller. In this work, they were tested under the previous simulation environment and Double blueye could achieve lawn motions in clam water and wave environment.

With these three parts of work well-done, It became a simple work to establish a new GNC system when devices and sensors were added or removed from Double Blueye. The new dynamic parameters will be estimated with Double Blueye System Identification system, and they will be used in the rest of two parts to get ready for field work.

Sammendrag

Denne masteroppgaven foreslår et arbeid med å utvikle GNC-system (veiledning, navigasjon og kontrollsystem) for Double Blueeye, som er et fjernoperasjonskjøretøy (ROV) satt sammen av to Blueeye Pioneers for å bære instrumenter med større nytelast. For å håndtere forskjellige oppdrag i undervannsverdenen, vil forskjellige enheter bli fjernet eller lagt til på kjøretøyet. Så forskjellige GNC-systemer er nødvendig for tilsvarende versjon av Double Blueeye.

For å nå dette målet er arbeidet delt inn i 3 deler av oppgaver: Double Blueeye System Identification system, Simuleringsmiljø for Double Blueeye og GNC system av Double Blueeye.

1) Double Blueeye System Identification system: I denne delen av arbeidet bygget vi opp en prosess med enkel parameteridentifikasjon for ulike versjoner av double blueeyes robot, som er en kombinasjon av empirisk metode, gratis løpende test og decay test. I denne oppgaven er den første Double Blueeye-roboten satt som et eksempel for å teste prosessen og sammenlignet med tauetest for å verifisere valideringen. For å gjøre denne prosessen enklere ble et ArUco-posisjonssystem implementert med frontkamera og ArUco-markører. På denne måten kunne vi teste de dynamiske parametrene til Double Blueeye i alle muslinger og klart vannmiljø.

2) Double Blueeyes-simuleringsmiljø: I denne delen av arbeidet ble de digitale tvillingene til Double Blueeye og scenen til MC-lab bygget opp på plattformen til UWSim og ROS. Noen sett med Hardware-in-the-loop-test ble simulert i dette miljøet for å sjekke stabiliteten og ytelsen til GNC-systemet

3) GNC-system av Double Blueeye: Med kjente dynamiske parametere er GNC-systemet bygget opp i denne delen. Dette er sammensatt av thrustertildeling, modellbasert utvidet Kalman-filter og PID-kontroller. I dette arbeidet ble de testet under det forrige simuleringsmiljøet og Double blueeye kunne oppnå plenbevegelser i muslingvann og bølgemiljø.

Med disse tre delene av arbeidet godt utført, ble det et enkelt arbeid å etablere et nytt GNC-system når enheter og sensorer ble lagt til eller fjernet fra Double Blueeye. De nye dynamiske parametrene vil bli estimert med Double Blueeye System Identification system, og de vil bli brukt i resten av to deler for å gjøre klar for feltarbeid.

Preface

This Master's thesis is a continuation of the project work carried out in the spring of 2021, and the final part of my M.Sc. in Marine Technology, with a specialization in Marine Cybernetics. It is written at the Department of Marine Technology at the Norwegian University of Science and Technology during the Fall of 2021.

First, I want to thank my supervisor Martin Ludvigsen for his guidance, insights and helpful feedback along the way. I also want to thank Torgeir Wahl, Trond Innset, Emil Bratlie and Ole Erik Vinje. Without their help in the MC-lab and their great towing test equipment, I could not accomplish the towing test of Double Blueeye. I would also like to thank Håvard Snefjellå Løvås for his help on the Double Blueeye assemble and instruction on the use of Double Blueeye in the MC-lab

Finally, I must express my profound gratitude to my parents and friends for their continuous support and encouragement.

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Chapter 1

INTRODUCTION

1.1 Background and Motivation

In the NTNU AUR-Lab, Two Remotely Operation Vehicle (ROV) Blueeye Pioneer were assembled together to a large vehicle to carry larger payload instruments. There is an interest to develop a robust GNC system to handle dynamic positioning control system. The combined vehicle is currently actuatable in five degrees of freedom (DoFs) including surge, sway, heave, roll and yaw. The vehicle, with a functioning guidance, navigation and control (GNC) system, can serve as a cheap, low-threshold platform for field-testing of GNC algorithms and sensors. Løvås, Sørensen, and Ludvigsen, 2020

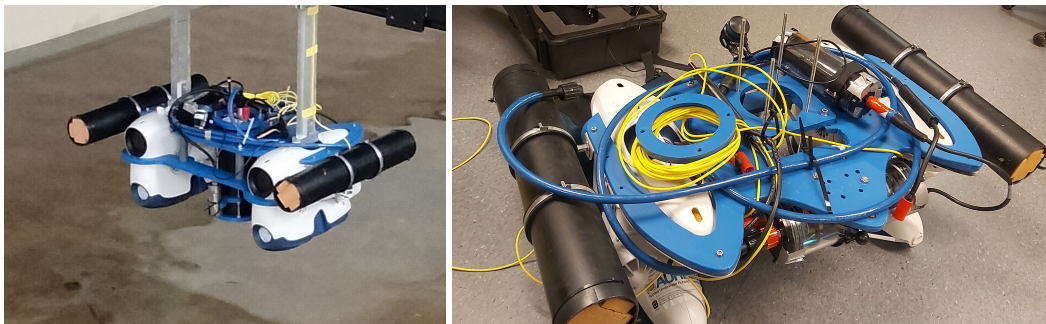


FIGURE 1.1: Overview of the Double Blueeyes Løvås, Sørensen, and Ludvigsen, 2020

To implement a GNC system, the first step is ROV system identification, but in our case it is no longer a one-time thing. To deal with different missions in the underwater world, different devices will be removed or added on the vehicle. In this situation, we will have many versions of the vehicle, which will raise a new challenge in the GNC system of Double Blueeyes. The GNC system requires different control plant models for each of them. An easy system identification algorithm is also an important component in this thesis.

Thus, this thesis will focus on three parts:

- Double Blueeyes parameters identification system
- Build up Double Blueeye simulation environment
- GNC system implementation

We will implement them both on the double Blueeyes robot and the UWsim environment with the platform of Robot operative system (ROS). Some tests and simulations will be included in this thesis.

1.2 Objective

The main goal of this project is to develop an easy system identification system and a robust GNC system for the double Blueeyes Robot, which include a navigation system, Guidance system and a robust controller. In terms of hydrodynamics, There is still no perfect way to estimate with empirical method, test and experiments are still needed. in this situation the free running test is a good choose. Thus, the easy system identification system will be developed base on free running testis going to include making a model of the drone and estimate its hydrodynamic parameters that can be used into GNC system. Also, a description about the sensor will be included.

1.3 Contribution

To achieve the objective in the previous section, The following structure and development path will be applied,

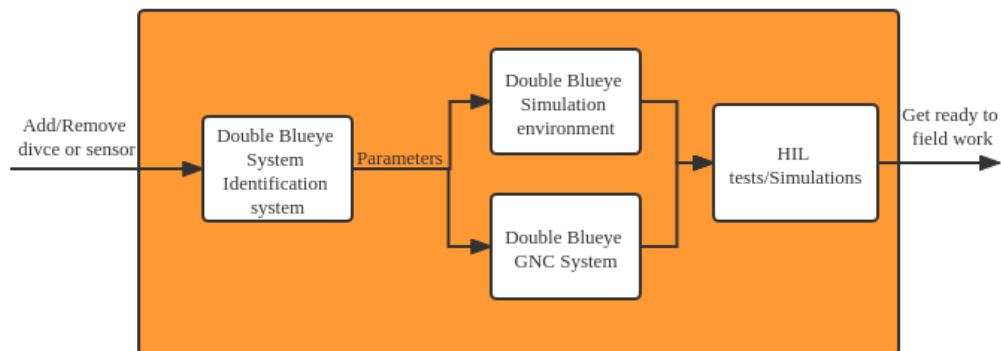


FIGURE 1.2: The Frame of the Thesis work

The contribution of each part of work is stated as following

Double Blueeye System identification system:

A test and experiment proceed and data process method is implemented for dynamic parameters identification of Double Blueeye. It is a combination of empirical method, free running test and decay test. their data will be processed properly. The initial Double Blueeye is set as an example, its result was also compared with towing test to verify the validation.

Double Blueeye Simulation environment :

With the accuracy parameters we got from previous part, the environment was built up base on ROS and UWsim, which will be useful for further develop and HIL tests for different GNC system of Double Blueeye

Double Blueeye GNC System

The contribution of this part is that I applied the GNC algorithm and tuning them for our Double Blueeye, and did the HIL tests to test their performance

1.4 Thesis Structure

The main structure of this report is outlined as following:

Chapter 2:

This chapter mainly presents some background theories and concepts such as ROV, hydrodynamic parameters estimation, ArUco SLAM, Free Running test, towing test, Thrust allocation, PID controller, Kalman Filter and line of sight guidance system.

Chapter3:

This chapter will implement the easy system identification process of ROV which is made up by Free Running test, decay test and their corresponding data process methods. For fear that the in some situation it is impossible to process the test, the Eidsvik's empirical method was also introduced here.

Chapter 4:

This chapter will record the towing test in the MC-Lab, which is used to verify the validation of free running test

Chapter 5:

This chapter mainly presents the process of building up the simulation environment, which include : 3d model of double Blueeyes, dynamic identification of the robot and how to build up the virtual sensors on the ROV to simulate the real sensor performance.

Chapter 6:

To replace the Qualisys used in the Free Running test, An ArUco positioning system will be implemented with Double Blueeye front camera and ArUco markers, which could record the position of markers and estimate the position information of the ROV. It will be tested in the simulation environment.

Chapter 7:

After the simulation environment built up, I will use this chapter to represent the process of GNC system design, which include the design of the controller, observer and guidance, tuning of these systems and their performance

Chapter 8:

In this chapter, three set test was simulated: Free Running Test with ArUco Positioning system, which will extend the test to any clam water environment. After that we will use two set of simulation to test the GNC system: the lawn motion test in clam water and in wave. I will represent the results and discuss them. **Chapter 9:**

In this chapter, I will discuss the work throughout this thesis and further works could be considered.

Chapter 2

Theories and Literature Review

2.1 ROV

ROV is a kind of underwater vehicle which has an umbilical between surface ship and the vehicle for communication and power supply. Depending on the usage, ROVs are usually equipped with camera, light and manipulators Ludvigsen and Sørensen, 2016. For the propose of monitoring and mapping of oceans, payload sensors are installed on the ROVs.

2.2 Double Blueyes

In this thesis, The double Blueyes robot will be used, which is illustrated in the following figures.

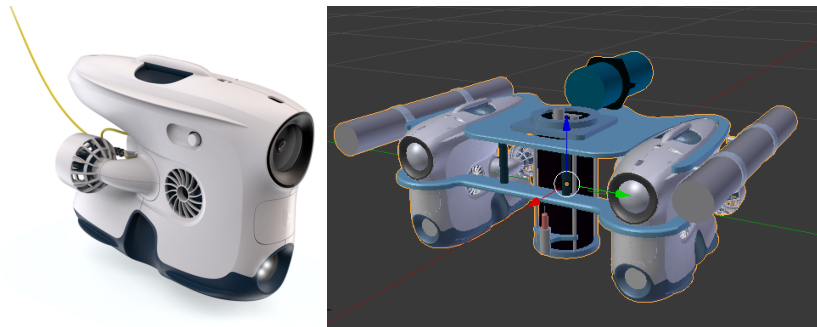


FIGURE 2.1: Blueeye Pionner LLC, 2021 and 3D model of the Double Blueyes built in chapter 5

The drone is made up by two eye ball underwater vehicles (Blueeye Pioneer). The drone is an observation class ROV, the vehicle is equipped with UHI in the middle of the vehicle. UHI: Underwater Hyperspectral Imaging is a new tool for marine archaeology, Ødegård et al., 2018 which can gather data across the entire visible colour spectrum and the near infrared (370-800 nm – with possibilities for further adjustments), which can be used to detect biological and chemical characteristics of seabed habitatsecotone, 2018. The 3D model is built in this thesis as the following plot. The detailed process is described in the section 5.



FIGURE 2.2: Underwater Hyperspectral Imaging ecotone, 2018

For the eyeball ROV- Blueye Pionner is a product of the blueye company. It is shown as the following plot, which consist four thrusters to move on the directions of surge sway heave and yaw.

2.3 Notation

In this project, the notation is adopted from SNAME (1950). For this vehicle is a kind of multi-body. Thus the notation used in this work is the same as Løvås (2020). In general, the notation is shown as following equations

2.4 Dynamic Model

In this section the dynamic model of ROV and the method of hydrodynamic estimation will be introduced. The Dynamic model of a underwater vehicle can be divided into two parts. One is kinematics, which treats only geometrical aspects of motion, the other is kinetics, which is the analysis of the forces causing the motion. Fossen, 2011 For building up the dynamic model on the platform of ROS. The parameters will be estimated with empirical methods

2.5 Kinematics

The Kinematics is a transformation between body-fixed frame and world frame for the vehicle velocity.

$$\dot{\eta} = J_{\theta}(\eta)v \quad (2.1)$$

Where:

$$\eta = [x, y, z, \phi, \theta, \psi]^{\top} \quad (2.2)$$

$$v = [u, v, w, p, q, r]^{\top} \quad (2.3)$$

η represents the position and orientations in the world frame, x, y and z are the projected distance from the world frame origin and ϕ, θ and ψ are the Euler angle between world frame and body frame. v represents the vehicle velocity in the body-fixed frame. u, v and w are the linear velocity in surge, sway and heave direction respectively. p, q and r are angular velocity in roll, pitch and yaw direction respectively. $J_{\theta}(\eta)$ is the rotation matrix for 6 DoF (Degree of Freedom), which will be explained in the section 2.5.3

2.5.1 Body-Fixed Frame

The body-fixed reference frame $\{b\} = (x_b, y_b, z_b)$ is a moving frame fixed to the vehicle. As it is shown in the Figure 2.3, The origin is located at the center of the

vehicle, which will move together with the vehicle. the body axes x_b, y_b and z_b are chosen to coincide with the principal axes of inertia, and they are usually defined as:

- x_b - longitudinal axis (surge, forward positive)
- y_b - transversal axis (sway, rightward positive)
- z_b - normal axis (heave, downward positive)

and the direction of roll, pitch and yaw are the rotational direction around the surge, sway and yaw direction respectively.

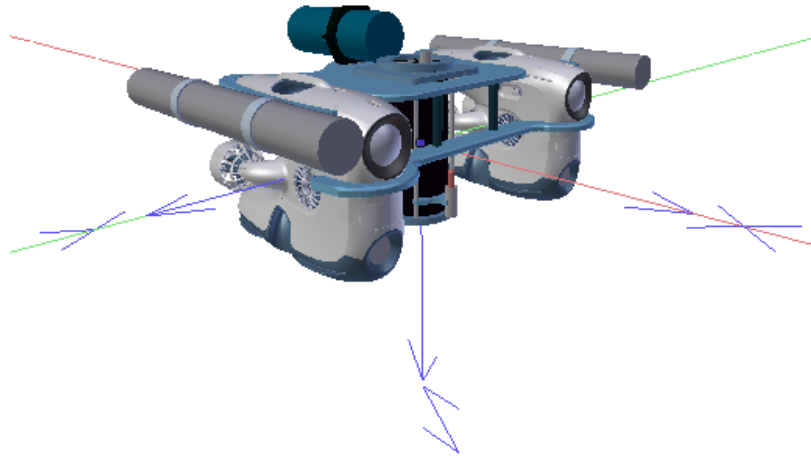


FIGURE 2.3: Body-Fixed Frame of Double Blueeyes

2.5.2 World Frame

The World frame of the underwater robots are usually set as a NED frame. NED: The North-East-Down coordinate system $n = (x_n, y_n, z_n)$ with origin o_n is defined relative to the Earth. This is the coordinate system we refer to in our everyday life. It is usually defined as the tangent plane on the surface of the Earth moving with the craft, but with axes pointing in different directions than the body-fixed axes of the craft. For this system the x axis points towards true North, the y axis points towards East while the z axis points downwards normal to the Earth's surface. The location of n relative to e is determined by using two angles l and b denoting the longitude and latitude, respectively. For marine craft operating in a local area, approximately constant longitude and latitude, an Earth-fixed tangent plane on the surface is used for navigation. This is usually referred to as flat Earth navigation and it will for simplicity be denoted by n . For flat Earth navigation one can assume that n is inertial such that Newton's laws still apply.

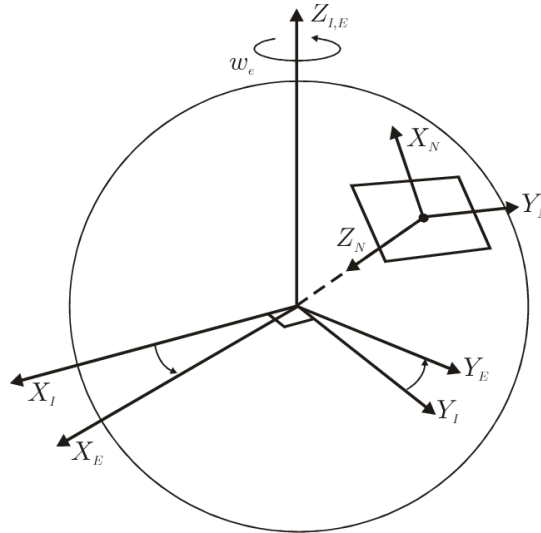


FIGURE 2.4: World Frame Breivik, 2003

2.5.3 Rotation Matrix

To transfer the location from one coordinate to another, especially, transfer vehicle velocity from body-fixed frame to NED frame for kinematic. A rotation matrix will be needed. For 6 DOF system the Euler angle rotation matrix is implemented as following equation:

$$J(\eta) = \begin{bmatrix} c\psi c\theta & -s\psi c\theta + c\psi s\theta s\phi & s\psi s\theta + c\psi c\theta s\phi & 0 & 0 & 0 \\ s\psi c\theta & c\psi c\theta + s\psi s\theta s\phi & -c\psi s\theta + s\psi s\theta c\phi & 0 & 0 & 0 \\ -s\theta & c\theta s\phi & c\theta c\phi & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & s\phi t\theta & c\phi t\theta \\ 0 & 0 & 0 & 0 & c\phi & -s\phi \\ 0 & 0 & 0 & 0 & s\phi/c\theta & c\phi/c\theta \end{bmatrix} \quad (2.4)$$

where $s(\cdot)=\sin(\cdot)$, $c(\cdot)=\cos(\cdot)$ and $t(\cdot)=\tan(\cdot)$. For tan function is not defined at ± 90 deg. So this Rotation matrix is singular when pitch angle is ± 90 deg. But most of ROVs are not designed to operate pitch motion over or nearby ± 90 deg. This limitation for pitch angle is not significant.

2.6 Kinetics

Kinetics in this system represents the vehicle dynamic, whose motion is driven by the thruster force and the environment force. According to Fossen, 2014, This process is shown as the equation

$$M_{RB}\dot{v} + C_{RB}(v)v + M_A\dot{v}_r + C_A(v_r)v_r + D(v_v)v_v + g(\eta) = \tau + \tau_{env} \quad (2.5)$$

Where:

- M_{RB} : Rigid body inertia matrix
- M_A : Added mass matrix
- C_{RB} : Rigid-body Coriolis and centripetal matrix
- C_A : Additional Coriolis and centripetal matrix
- $g(\eta)$: Restoring Force

τ : Thruster Force

τ_{env} : Environment Force

2.6.1 Rigid body

For the rigid body dynamic, the rigid body inertia matrix M_{RB} and the coriolis-centripetal matrix C_{RB} are expressed as the following equation for 6 DoF from Fos- sen, 2014:

$$\begin{aligned} M_{RB} &= \begin{bmatrix} mI_{3 \times 3} & -mS(\mathbf{r}_g^b) \\ mS(\mathbf{r}_g^b) & I_b \end{bmatrix} \\ &= \begin{bmatrix} m & 0 & 0 & 0 & mz_g & -my_g \\ 0 & m & 0 & -mz_g & 0 & mx_g \\ 0 & 0 & m & my_g & -mx_g & 0 \\ 0 & -mz_g & my_g & I_x & -I_{xy} & -I_{xz} \\ mz_g & 0 & -mx_g & -I_{yx} & I_y & -I_{yz} \\ -my_g & mx_g & 0 & -I_{zx} & -I_{zy} & I_z \end{bmatrix} \end{aligned} \quad (2.6)$$

$$C_{RB}(\mathbf{v}) = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ -m(y_g q + z_g r) & m(y_g p + w) & m(z_g p - v) \\ m(x_g q - w) & -m(z_g r + x_g p) & m(z_g q + u) \\ m(x_g r + v) & m(y_g r - u) & -m(x_g p + y_g q) \end{bmatrix} \quad (2.7)$$

$$\begin{bmatrix} m(y_g q + z_g r) & -m(x_g q - w) & -m(x_g r + v) \\ -m(y_g p + w) & m(z_g r + x_g p) & -m(y_g r - u) \\ -m(z_g p - v) & -m(z_g q + u) & m(x_g p + y_g q) \\ 0 & -I_{yz}q - I_{xz}p + I_z r & I_{yz}r + I_{xy}p - I_y q \\ I_{yz}q + I_{xz}p - I_z r & 0 & -I_{xz}r - I_{xy}q + I_x p \\ -I_{yz}r - I_{xy}p + I_y q & I_{xz}r + I_{xy}q - I_x p & 0 \end{bmatrix} \quad (2.8)$$

The parameters to be estimated for this system are :

- m : mass of ROV
- I_x : Moment of Inertia about x
- I_y : Moment of Inertia about y
- I_z : Moment of Inertia about z
- $[x_g, y_g, z_g]$: The location of gravity center of the vessel

These parameters could be measured or estimated through the real robot or 3d model.

Hydrodynamic

The hydrodynamic parameters of a ROV could be described by added mass, coriolis-centripetal matrix and damping matrix

$$\mathbf{M}_A = - \begin{bmatrix} X_{\dot{u}} & X_{\dot{v}} & X_{\dot{w}} & X_{\dot{p}} & X_{\dot{q}} & X_{\dot{r}} \\ Y_{\dot{u}} & Y_{\dot{v}} & Y_{\dot{w}} & Y_{\dot{p}} & Y_{\dot{q}} & Y_{\dot{r}} \\ Z_{\dot{u}} & Z_{\dot{v}} & Z_{\dot{w}} & Z_{\dot{p}} & Z_{\dot{q}} & Z_{\dot{r}} \\ K_{\dot{u}} & K_{\dot{v}} & K_{\dot{w}} & K_{\dot{p}} & K_{\dot{q}} & K_{\dot{r}} \\ M_{\dot{u}} & M_{\dot{v}} & M_{\dot{w}} & M_{\dot{p}} & M_{\dot{q}} & M_{\dot{r}} \\ N_{\dot{u}} & N_{\dot{v}} & N_{\dot{w}} & N_{\dot{p}} & N_{\dot{q}} & N_{\dot{r}} \end{bmatrix} \quad (2.9)$$

For the ROV these are often assumed decoupled, especially the open-frame ROV, and the added mass matrix could be simplified to a diagonal matrix. The rest of parameters are estimated as zero. With these assumption the coriolis-centripetal could be expressed as following

$$\mathbf{C}_A(\mathbf{v}_r) = -\mathbf{C}_A^\top(\mathbf{v}_r) = \begin{bmatrix} 0 & 0 & 0 & 0 & -Z_{\dot{w}}\omega_r & Y_{\dot{v}}v_r \\ 0 & 0 & 0 & Z_{\dot{w}}\omega_r & 0 & -X_{\dot{u}}u_r \\ 0 & 0 & 0 & -Y_{\dot{v}}v_r & X_{\dot{u}}u_r & 0 \\ 0 & -Z_{\dot{w}}\omega_r & Y_{\dot{v}}v_r & 0 & -N_{\dot{r}}r & M_{\dot{q}}q \\ Z_{\dot{w}}\omega_r & 0 & -X_{\dot{u}}u_r & N_{\dot{r}}r & 0 & -K_{\dot{p}}p \\ -Y_{\dot{v}}v_r & X_{\dot{u}}u_r & 0 & -M_{\dot{q}}q & K_{\dot{p}}p & 0 \end{bmatrix} \quad (2.10)$$

the damping matrix of a ROV could be divided into linear part and nonlinear part

$$\mathbf{D} = \mathbf{D}_L + \mathbf{D}_{NL} \quad (2.11)$$

Restoring Force

The restoring term $g(\eta)$ in the equation. ?? is expressed as following equation. It is dependent on the weight, buoyancy and relative placements of center of gravity and the center of buoyancy of the vehicle, for a ROV, these nodes are usually located on the axis of heave. So the restoring moment on the yaw direction is always zero and $x_g = x_b = y_g = y_b = 0$

$$\mathbf{g}(\boldsymbol{\eta}) = \begin{bmatrix} (W - B) \sin(\theta) \\ -(W - B) \cos(\theta) \sin(\phi) \\ -(W - B) \cos(\theta) \cos(\phi) \\ (z_g W - z_b B) \cos(\theta) \sin(\phi) \\ (z_g W - z_b B) \sin(\theta) \\ 0 \end{bmatrix} \quad (2.12)$$

Where: W is the total weight of ROV and B is the total buoyancy. In the most case of ROVs have a slightly positive buoyancy.

2.6.2 Wave Force

The ROV can be tested under the influence of waves. The force of wave could be expressed as the following equations

$$\boldsymbol{\tau}_{\text{wave}} = [X_{\text{wave}}, Y_{\text{wave}}, Z_{\text{wave}}, K_{\text{wave}}, M_{\text{wave}}, N_{\text{wave}}]^\top \quad (2.13)$$

$$\tau_{\text{wave}}(i) = \frac{K_w^{[i]} s}{s^2 + 2\lambda^{\{i\}} \omega_e^{\{i\}} s + (\omega_e^{\{i\}})^2} w_i + d_i \quad (2.14)$$

$$\dot{d}_i = w \quad (2.15)$$

Where: wave drift force d_i are modeled as slowly varying bias terms, w_i are Gaussian white noise processes, the gain constant K_w is calculated by $K_w = 2\lambda\omega_0\sigma$. σ is the wave intensity, λ is a damping coefficient and ω_0 is the dominating wave frequency. These parameters could be parameterized by wave spectra. Also, while the vehicle is moving forward, the wave frequency should be transfer to body-fixed frame with following equation 2.16

$$\omega_e(U, \omega_0, \beta) = \left| \omega_0 - \frac{\omega_0^2}{g} U \cos(\beta) \right| \quad (2.16)$$

2.6.3 Dynamic Parameter Estimation

In this ROV, we will have different sensor suites for different missions, every time we change the sensor, we will have different dynamic parameters. It is impossible for us to test them in the MC-Lab with towing test, which is time-consuming and unaffordable. Thus, an easier system identification method is demanded. The parameters could be divided into three categories, one is the rigid body dynamic parameters, the other is the hydrodynamic parameters, which consist added mass and damping.

The system identification system could be categorized into the following situation: When there is no way to do any experiment, the empirical method will be applied, but for the fact that the empirical method is approximate the ROV to cuboid, which is not accuracy from theory. So if we could have an experiment, a free running test will be applied. There are two kinds of positioning system could be used, one is Qualisys system Malý and Lopot, 2014, which is made up by six cameras and them could track the reflective markers in the water which is accurate. But not every lab have these set of system, in this case the ArUco SLAM system could be a good alternative. It only requires a camera and a set of ArUco markers underwater. In this thesis, we will use the empirical method at first, do the Free Running test with Qualisys in the MC-lab and simulate the free running test in the UWsim. After all these done, A towing test will be deployed in the MC-lab as the ground truth. Through comparing the different between ground truth and result of free running test and empirical method we could get the accuracy of this easier system identification system.

2.6.4 Rigid Body dynamic parameters

Rigid body dynamic parameters can be estimated through the configurations of ROV and sensors:

$$m = m_{ROV} + \sum m_{sensors,i} \quad (2.17)$$

$$CoG = \frac{m_{ROV} * CoG_{ROV} + \sum m_{sensors,i} * CoG_{sensors,i}}{m} \quad (2.18)$$

$$I_n = m_{ROV} * (CoG_{ROV} - CoG)^2 + \sum m_{sensors,i} * (CoG_{sensors,i} - CoG)^2, n = x, y, z \quad (2.19)$$

But for the hydrodynamic parameters, it is never a linear problem, The superposition theory could not be applied. So in this thesis, we would like to focus on this part of the work. For this situation two method will be tried, one is empirical method,

the other is Free Running test. their theories will be introduced in the following two sections. For the propose of verifying the validation of these two methods, a towing test will be processed in the MC-Lab as the ground truth.

2.6.5 Empirical method

When we come to the situation that it is impossible to do any test, the empirical method could be applied. In this part the parameters will be estimated with the empirical method in the work of Eidsvik, 2015. For the detailed calculation process will be introduced in the next section.

2.6.6 Free Running test

Free running test has been used in ship model basin area to validity or confirm ship's maneuvering/motion or resistance performance before the ship's building. Im and Seo, 2010. In the field of ROV it is used to verify the hydrodynamic parameters estimated from CFD in the work of Chin, Lin, and Lin, 2017. In the work of Bellingmo, 2020, A free running test is used to estimate damping parameters and had got a good performance. The main idea of the Free Running test is running the ROV in the water and grab its thruster input and position or velocity output and then estimate the parameters with known input and out put of the system

For this ROV, the following process is implemented:

- Free Running for surge, sway, heave and Yaw
- Decay test for roll and pitch
- Estimate the damping and added mass matrix

The Free Running test is a kind of inverse process of the towing test. In this test, we will have control on the heading and depth and give certain force on surge and sway, which will drive the ROV to achieve certain velocity. We repeat the process with different force and record the velocity to get the relationship between force and velocity.

For the fact that the ROV have motion limitation on the direction of roll and pitch, so the previous method is not valid. Thus the decay test could be a good alternative to test linear damping and added mass. The detail of theory is explained in the next subsection.

From the Free Running test and decay test, we could estimate the damping parameters directly with curve fitting.

After the damping parameters settle down, the added mass is the only parameter estimated with an inaccuracy method. At that time we could estimate them through the optimisation methods. The object function could be expressed as

$$f = \frac{1}{N} \sum | y_{measured} - y_{estimated}(M_{add}, \tau, y_{measured}(0)) | \quad (2.20)$$

The estimated added mass from empirical method could be a good initial point. To solve this optimal problem, The NSGA-II method could be applied. NSGA-II method have been used in the work of Hoyer, 2021 to estimate the hydrodynamic parameters of a UUV, which has achieved good performance in single directions. For situations where the ROV parameters are decoupled, this method should be valid for our case. The theory will be introduced in the next section.

2.7 Theory of NSGA-II

NSGA-II is short for Non-dominated Sorting Genetic Algorithm II, which is a kind of genetic algorithm developed by the work of Deb et al., 2002. The process of the NSGA-II is shown as following Deb et al., 2002

```

for generation in 1:1:n_gen_max
    max_n_parents = size(R) / 2
    F = non_dominated_sort (f,Rt)
    P = empty_set()
    for Fi in F
        if size(P)+size(Fi)<= max_n_parents
            add(P,Fi)
        else
            crowding_distance_sort(Fi)
            add(P,Fi[1:(max_n_parents-size(P)]
            break
    Q = empty_set()
    for p1,p2 in P
        add(Q,crossover(p1,p2))
    R= union(P,mutate(Q))
pareto_frotier(f,R)

```

In the work of Hoyer, 2021, this method is used to estimate both added mass and damping for a single direction. In our case the damping parameters could be calculated directly with the free running test, So this method will be used to estimate the added mass As this thesis is not focus on the theory of NSGA-II , we focus on the application of the algorithm. In this case, we will use the package of pymoo under the python3 environment directly to solve the problem of optimal of added mass for each direction. The script is attached in the attachment.

2.8 Theory of Decay Test

From the dynamic model of the roll dimension, which is expressed in the following equation when the motion on other directions are zero. The dynamic model on roll could be expressed as:

$$(I_y + I_{y-added})\ddot{\phi} + D_p\dot{\phi} + WB\bar{G}_z\phi = \tau_4 + \tau_{wind4} + \tau_{wave4} \quad (2.21)$$

For we do not apply force on the Roll direction and working on the clam water , Thus The equation could be simplified as :

$$(I_y + I_{y-added})\ddot{\phi} + D_p\dot{\phi} + WB\bar{G}_z\sin(\phi) = 0 \quad (2.22)$$

$$\phi''(t) + \frac{D_p}{(I_y + I_{y-added})}\phi'(t) + \frac{WB\bar{G}_z}{(I_y + I_{y-added})}\phi(t) = 0 \quad (2.23)$$

With the Laplace transformation:

$$\lambda^2 + b\lambda + c = 0 \quad (2.24)$$

where:

$$b = \frac{D_p}{(I_y + I_{y-added})}; c = \frac{WB\bar{G}_z}{(I_y + I_{y-added})} \quad (2.25)$$

For the fact that the vehicle is stable for the roll and pitch direction, the eigenvalue will have negative real part, in the following form:

$$\lambda_1 = -\frac{b}{2} + i\omega; \lambda_2 = -\frac{b}{2} - i\omega; \omega = \sqrt{\frac{4c - b^2}{4}} \quad (2.26)$$

After the inverse Laplace transformation we could get the system performance in the time domain, which is expressed as following equation:

$$\phi(t) = \phi_0 e^{-\frac{b}{2}t} \cos(\omega t - \varepsilon) \quad (2.27)$$

Where ϕ_0 is the initial angel of the vehicle and ε is the initial phase angle of the decay curve. So the decay test is implemented as following proceed

- Put the vehicle in the clam water
- Incline the vehicle to an initial angel ϕ_0 and then is released
- Record the Roll or Pitch angle during this process
- Fitting the recorded curve with the equation 2.27 and calculate the linear damping with following equation

For the added mass on roll or pitch direction is unknown, we could estimate through curve fitting.

$$I_{y-added} = \frac{WBG_z}{\omega^2 + \frac{b^2}{4}} - I_y \quad (2.28)$$

For W, BG and I_y are known parameters of the system

$$D_L = b * (I_y + I_{y-added}) \quad (2.29)$$

Thus, In this way, we could find the linear damping and added mass on the direction of roll and pitch.

2.8.1 Theory of Towing test

Towing test play an important role on the damping force measurement for marine structures, whose result is usually taken as the ground truth. For it is accuracy in the work of Mogleiv, 2017. this test is used to measure the damping of Blueeye ROV in the MC-lab with a complex set of experiment device. In the work of Lack, Rentzow, and Jeinsch, 2019 towing test result was used to compare with the result of open water self-propelled test on the heave direction of BlueROV 2 to verify the open water self-propelled test. In our work this kind of comparison with be extended to surge, sway and heave for Double Blueeye.

When we tow the ROV in constant velocity, from the control plant model we could find that at this time the damping force is the only resistance left for the ROV. We could get the relationship between damping force and velocity through towing the ROV with different velocity and measure the resistance force.

For the damping force could be divided into linear force and nonlinear force

$$D = D_L + D_{NL} \quad (2.30)$$

For the 6 DOF model we then have

$$\begin{aligned} D_L &= \text{diag}[X_u u, Y_v v, Z_w w, K_p p, M_q q, N_r r] \\ D_{NL} &= \text{diag}[X_{uu} u^2, Y_{vv} v^2, Z_{ww} w^2, K_{pp} p^2, M_{qq} q^2, N_{rr} r^2] \end{aligned} \quad (2.31)$$

The non-linear least squares is applied to fit a curve data to a function, which could be formalized as following equation

$$\min \sum (F_{data} - (D_L * V_{data} + D_{NL} * V_{data}^2))^2 \quad (2.32)$$

To calculate this optimisation problem, the function of `scipy.optimize.curve_fit` is used here. The scripts could be found out in the attachment.

After the damping parameters settle down, we would find the added mass is the only inaccuracy parameter left in the dynamic model. This could be formalized as another optimal problem. We treat the added mass as the variable of the dynamic model and minimize the error between measured data and predicted states.

The object function is defined as

$$f = \frac{1}{N} \sum | y_{measured} - y_{estimated}(M_{add}, \tau, y_{measured}(0)) | \quad (2.33)$$

where N is the step number of the dynamic model. For the ROV decoupled system, the added mass could be calculated for each direction, which will be presented in the next section.

2.9 Sensors

Sensors on the ROV are important parts of the navigation system. They will help the GNC system know about the local position information of the ROV. For in this project we will focus on the IMU, APS and Pressure Sensor

2.9.1 IMU

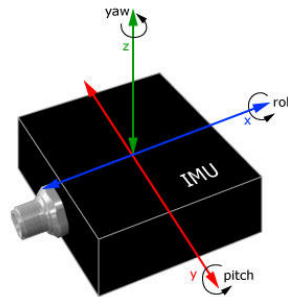


FIGURE 2.5: IMU *Inertial Measurement Unit (IMU) n.d.*

In a IMU-Inertial Measurement Unit, an inertial measurement unit works by detecting linear acceleration using one or more accelerometers and rotational rate using one or more gyroscopes. Some also include a magnetometer which is commonly used as a heading reference. Typical configurations contain one accelerometer, gyro, and magnetometer per axis for each of the three principal axes: pitch, roll and yaw. Iosa et al., 2016 The IMU will return orientation signal for ROV, angular velocity and

linear acceleration in body frame. For the propose of simulation, a virtual IMU will be implemented

2.9.2 APS

APS - Acoustic Positioning Systems is an acoustic system connected to the ship. In the work of Bellingmo, 2020, the positioning system from Water Linked named "Underwater GPS" is used as the APS. It is based on the short baseline acoustic technology.

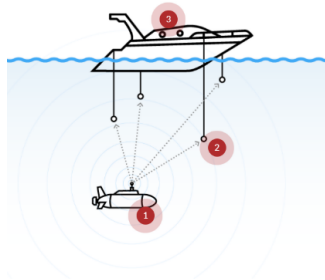


FIGURE 2.6: Acoustic Positioning Systems operating principle. Bellingmo, 2020

This system is designed with the purpose of tracking the ROV from a surface ship. There is a clear connection between the two systems, which is a reliable acoustic communications link can be established between the surface and the unit on the ROV. Alcocer, Oliveira, and Pascoal, 2006

Thus, the APS will return position signals for the ROV, x and y in the global frame (the ship frame), which often give signals once every second. It is usually used to estimate the position of ROV in the water.

2.9.3 Pressure Sensor

The ROV depth information could be estimated through the use of pressure sensor. When the ROV deep into water, the water pressure or hydraulic pressure is exerted on the diaphragm of the pressure sensor. ROV / AUV / UUV PRESSURE TRANSDUCERS 2019 The deeper ROV goes, the higher pressure. In this way we could estimate the depth information in the global frame. This sensor will be used as the feedback sensor for depth controller.

2.9.4 Camera

For observation of the underwater world, most ROVs are equipped with a camera. For the double blueeyes robot, the ROV is equipped with two front camera sensors, which could be used to take pictures and video of the underwater environment. In this thesis, it will be used to build up the ArUco position system.

2.9.5 Qualisys

Qualisys is a camera system designed initially for 3D record of body motion that is firmly marked with special points called markers. Malý and Lopot, 2014 The system is an important component of The Marine Cybernetic Lab (MC-Lab) marine cybernetics laboratory (mc-lab) 2021. It is used to track a model vessel's motions. In the work of

Arnesen, 2016, This set of system is used as the measurement of extended Kalman filter of VideoRay to estimate the position in the MC-lab. In our case we will use the measure of position directly for free running test.

2.10 GNC system

After the parameters settle down, we will start to implement the GNC system of the ROV, which consists of the following parts. For it is mainly adopted from the GNC system of ship. Dukan, 2014

- Thruster Allocation
- Controller
- Observer
- Guidance system

and they will be discussed in the following subsections

2.11 Thruster allocation

The first part we will implement is thruster allocation, when we have the demanding force or moment on the generalized directions of ROV body-frame. We will need to calculate the force for each thruster. In this thesis, The pseudo inverse method will be applied.

$$F_{general} = T * K * u \quad (2.34)$$

where $F_{general}$ is the applied force along the body frame axis in these case is $[surge_{force}, sway_{force}, heave_{force}, roll_{moment}, pitch_{moment}, yaw_{moment}]$. In the GNC system these values are given out by the controller, which will be talk about later. The vector u represents the rotation velocity of each thruster. The K matrix represents the map from rotation velocity to the force.

$$u = K^{-1} * T^{-1} * F_{general} \quad (2.35)$$

2.12 Controller

The controller is an important part of GNC, which could provide the desired force on each axis by minimize the error between the measured or estimated current state and the desired state. In this thesis, the controller will be implemented base on the dynamic positioning system, which utilized three decoupled PID controllers to control the horizontal motion of a ship in surge, sway and yaw directions. Fossen, 2011 So 5 decoupled PID controller will be applied here.

2.12.1 PID controller for each direction

$$u(t) = K_p e(t) + K_i(t) dt + K_p \frac{de}{dt}$$

$u(t)$ =PID control variable

K_p =proportional gain

$e(t)$ =error value

K_i =integral gain

d e=change in error value

The theory of PID controller is introduced here, and its application on the double Blueeyes will be introduced in the next section.

2.13 Observer

The observer system in this thesis is chosen as extended Kalman filter. The control plant model of the ROV is nonlinear. The theory of extended Kalman filter is shown as following.

2.13.1 Extend Kalman Filter

The control plant model of this ROV with 6 dimension of freedom is shown as follows

$$\begin{aligned} \dot{\eta} &= \mathbf{J}_b^n(\theta, \omega, \psi)\mathbf{v} \\ \mathbf{M}\dot{\mathbf{v}} + \mathbf{C}(\mathbf{v})\mathbf{v} + \mathbf{D}(\mathbf{v})\mathbf{v} + \mathbf{g}(\eta) &= \boldsymbol{\tau} + \mathbf{J}_n^b(\theta, \omega, \psi)\mathbf{b} \\ \dot{\mathbf{b}} &= -\mathbf{T}_b^{-1}\mathbf{b} + \mathbf{E}_b\omega_b \end{aligned} \quad (2.36)$$

set $\mathbf{x} = [\eta, \mathbf{v}, \mathbf{b}]^T$ and rewrite the functions into state space function

$$\begin{aligned} \dot{\mathbf{x}} &= \mathbf{f}(\mathbf{x}) + \mathbf{B}\mathbf{u} + \mathbf{E}\mathbf{w} \\ \mathbf{y} &= \mathbf{H}\mathbf{x} + \mathbf{v} \end{aligned} \quad (2.37)$$

where $\mathbf{f}(\mathbf{x})$, \mathbf{B} , \mathbf{E} and \mathbf{H} are given by

$$\begin{aligned} \mathbf{f}(\mathbf{x}) &= \begin{bmatrix} \mathbf{J}(\theta, \phi, \psi)\mathbf{v} \\ -\mathbf{M}^{-1}\mathbf{D}\mathbf{v} - \mathbf{M}^{-1}\mathbf{R}^T(\psi)\mathbf{G}\eta + \mathbf{M}^{-1}\mathbf{R}^T(\psi)\mathbf{b} \\ -\mathbf{T}_b^{-1}\mathbf{b} \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} \mathbf{0}_{6 \times 6} \\ \mathbf{M}^{-1} \\ \mathbf{0}_{6 \times 6} \end{bmatrix} \\ \mathbf{E} &= \begin{bmatrix} \mathbf{0}_{6 \times 6} \\ \mathbf{E}_b \\ \mathbf{0}_{6 \times 6} \end{bmatrix}, \quad \mathbf{H} = [\mathbf{I}_{12 \times 12} \quad \mathbf{0}_{12 \times 6}] \end{aligned} \quad (2.38)$$

So the extend Kalman filter is written as following

Initial values:

$$\begin{aligned} \bar{\mathbf{x}}_{k=0} &= \mathbf{x}_0 \\ \bar{\mathbf{P}}_{k=0} &= \mathbf{E} [(\mathbf{x}(0) - \hat{\mathbf{x}}(0)) (\mathbf{x}(0) - \hat{\mathbf{x}}(0))^T] = \mathbf{P}_0 \end{aligned} \quad (2.39)$$

Corrector:

$$\begin{aligned} \mathbf{K}_k &= \bar{\mathbf{P}}_k \mathbf{H}^T [\mathbf{H} \bar{\mathbf{P}}_k \mathbf{H}^T + \mathbf{R}]^{-1} \\ \hat{\mathbf{P}}_k &= (\mathbf{I} - \mathbf{K}_k \mathbf{H}) \bar{\mathbf{P}}_k (\mathbf{I} - \mathbf{K}_k \mathbf{H})^T + \mathbf{K}_k \mathbf{R} \mathbf{K}_k^T \\ \hat{\mathbf{x}}_k &= \bar{\mathbf{x}}_k + \mathbf{K}_k (\mathbf{y}_k - \mathbf{H} \bar{\mathbf{x}}_k) \end{aligned} \quad (2.40)$$

Predictor:

$$\begin{aligned} \bar{\mathbf{P}}_{k+1} &= \boldsymbol{\Phi}_k \hat{\mathbf{P}}_k \boldsymbol{\Phi}_k^T + \boldsymbol{\Gamma}_k \mathbf{Q} \boldsymbol{\Gamma}_k^T \\ \bar{\mathbf{x}}_{k+1} &= \mathbf{f}_k(\hat{\mathbf{x}}_k, \mathbf{u}_k) \end{aligned} \quad (2.41)$$

Where:

$$\begin{aligned} \mathbf{f}_k(\hat{\mathbf{x}}_k, \mathbf{u}_k) &= \hat{\mathbf{x}}_k + T [\mathbf{f}(\hat{\mathbf{x}}_k) + \mathbf{B}\mathbf{u}_k] \\ \Phi_k &= \mathbf{I}_{n \times n} + T \left. \frac{\partial \mathbf{f}_k(\mathbf{x}_k, \mathbf{u}_k)}{\partial \mathbf{x}_k} \right|_{\mathbf{x}_k = \hat{\mathbf{x}}_k} \\ \Gamma_k &= T\mathbf{E} \end{aligned} \quad (2.42)$$

2.14 Guidance system for an ROV

The guidance system of an ROV contents 3 level of nodes: the first one is ROVGUI in this node we could set the 3d way-points of the ROV as a way-points list and transfer the message into the second node: Line of Sight system. in this node we will calculate the 6 DOF setpoints and publish them to the reference model system, which will generate a path from the start point to the set points. This information will be transported to the controller. The theory of Line-of-Sight guidance system is shown as following

2.14.1 Line of Sight

An ROV navigating between way points P_k and P_{k+1} with Los is shown as following figure

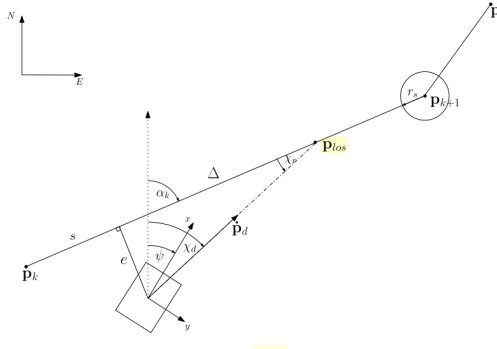


FIGURE 2.7: 2-D LOS parameters Lauritzsen, 2014

From the figure we could find that the bearing between way points α_k

$$\alpha_k = \text{atan2}(y_{k+1} - y_k, x_{k+1} - x_k) \quad (2.43)$$

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

$$\begin{aligned} s(t) &= [x(t) - x_k] \cos(\alpha_k) + [y(t) - y_k] \sin(\alpha_k) \\ e(t) &= -[x(t) - x_k] \sin(\alpha_k) + [y(t) - y_k] \cos(\alpha_k) \end{aligned} \quad (2.44)$$

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

$$\begin{aligned} \chi_r &= \arctan\left(-\frac{e(t)}{\Delta}\right) \\ \chi_d &= \alpha_k + \chi_r \end{aligned} \quad (2.45)$$

where Δ is the look ahead distance, which is a constant.

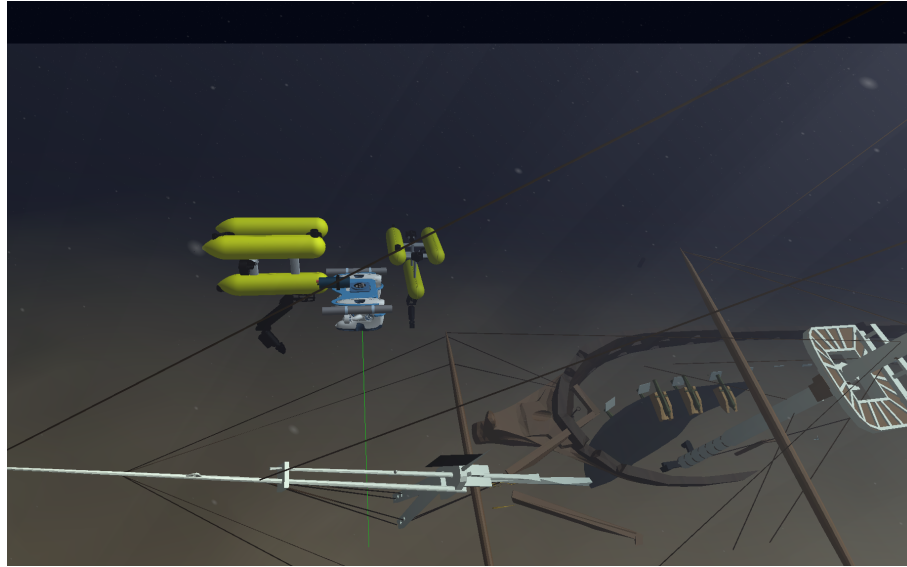


FIGURE 2.9: UWSiM scene

2.17 ArUco SLAM

SLAM is short for Simultaneous Localization And Mapping, which is a kind of visual position method using ArUco markers as landmark. This kind of visual navigation system have been well-developed and implemented on the platform of drone and many other different robots. In the work of Bačík et al., 2017, they applied ArUco SLAM on a quadcopter for indoor navigation and their result show that the position of drone can be estimated within an average error of 10 cm. Thus, we could assume this method can be accurate for the underwater environment in the MC-Lab. For the water in the is clam and clear, which does not have much difference with air environment. However - the refraction properties for underwater cameras need to be taken into consideration by proper camera calibration. The ArUco Slam system consists of three parts :

- ArUco Marker Detection
- ArUco Marker Pose estimation
- SLAM

2.17.1 ArUco Marker

ArUco stands for Augmented Reality University of Cordoba, which is a Spanish University developing this marker. It is developed in 2014 by Garrido-Jurado et al., 2014. It is a kind of fiducial marker, which could be used to estimate the position of the markers through images. They proposed a square based graph.



FIGURE 2.10: Example of the ArUco Marker

2.17.2 ArUco Detection and Position estimation with Camera

When the ArUco marker comes out, it is developed together with a detection algorithm, which is included in the OpenCV package. We work under the python3 environment, and the following function will be used

```
cv.aruco.detectMarkers( image, dictionary[, corners[, ids[,
parameters[, rejectedImgPoints[, cameraMatrix[, distCoeff]]]]]]
) ->corners, ids, rejectedImgPointsd
```

It is a well-developed function which could return the ID and pose of the ArUco markers.

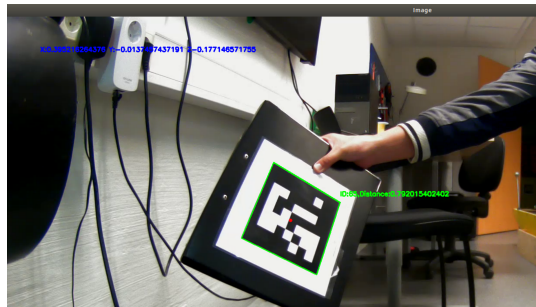


FIGURE 2.11: Performance of ArUco detection

Thus the markers could be considered as the landmarks, and the camera could be considered as position sensor which provide the position and ID of landmarks. Base on these set of system, A SLAM positioning system for ROV could be implemented.

2.17.3 SLAM

SLAM is focusing on the problem that when a vehicle or robot start in an unknown location in an unknown environment, how to learn about the surroundings and locating itself. Dissanayake et al., 2001 This is also the problem we may need to solve in the free running test, For we will put the ArUco markers and Double Blueye randomly at the beginning of the test. Thus SLAM could be a good solution. the structure of the SLAM could be expressed as following the next steps

- set initial states
- when the first landmark detected. Set the current position as the original of the world frame and add the landmark into the set of map. And start the loop of SLAM
- SLAM loop
 - predict the states with dynamic model
 - match the detected markers with existing landmarks in map, if the marker is not within map set, add it to map set
 - correct the states with measurements

Chapter 3

Double Blueeyes System Identification

In this section the system identification for double Blueeye robot is implemented as shown in the following figure

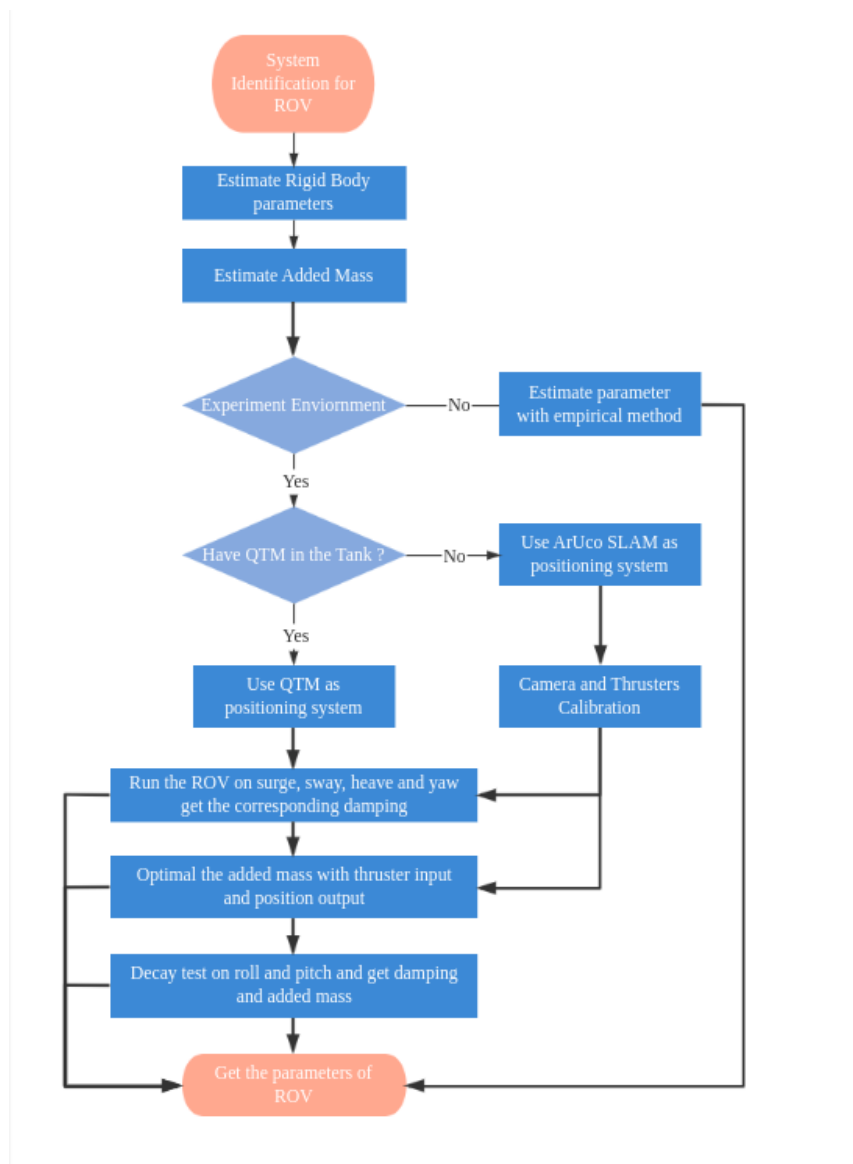


FIGURE 3.1: The work flow of Double Blueeyes System Identification

The dynamic model of ROV have been introduced in detail in the previous section. To build up specifically model for Double Blueeyes, we need to estimate the following parameters

- M_{RB} : Rigid body Mass Matrix
- M_A : Added Mass Matrix
- C_{RB} : Rigid body coriolis-centripetal matrix
- C_A : Added coriolis-centripetal matrix
- D : Damping Matrix

For the C_{RB}, C_A share the same parameters with M_{RB} and M_A . So in this section they will not be discussed.

3.1 Rigid Body Mass Matrix

For the origin of the double Blueeyes is set at COG so $x_g = y_g = z_g = 0$. The matrix could be simplified to the following format

$$M_{RB} = \text{Diag}([m, m, m, I_x, I_y, I_z]) \quad (3.1)$$

m is the weight of the ROV, which is 30 kg for the double Blueeyes. With the help of SolidWorks model, the interital mass for each axis is estimated.

$$M_{RB} = \text{Diag}([30, 30, 30, 2.69, 3.88, 2.99]) \quad (3.2)$$

3.2 Hydrodynamic Parameters

For the double Blueeyes case, three methods will be applied to estimate the parameters and the results will be compared with each other to prove the validation of free running test.

- Empirical Method
- Towing Test
- Free Running Test

3.3 Estimate Parameters with Eidsvik's Empirical Method

In the work of Eidsvik, A very great empirical method was proposed to estimate the hydrodynamic parameters for ROV.

3.3.1 Added Mass

In this section, the added mass matrix is estimated with the method in the work of Eidsvik Eidsvik, 2015, which follow the same procedure as following

- to find added mass for translational DOFs using empirical 3D data
- to find added mass for translational DOFs using 2D data and strip theory.

- Calculate the difference in the two methods.(scaling factor)
- Find added mass for rotational DOFs using 2D data and strip theory.

The ROV is approximated to the shape of rectangular prism, which have 2 of edges have the same length. This shape is more similar to the sway direction motion. The process have been well introduced in the work of Eidsvik, 2015, which got a good result and compared with towing test and CFD. So I will insert the parameters of Double Blueeyes into the his system and got the following results

In this way the added mass matrix is being estimated to:

$$M_A = \text{Diag}([21.2, 8.95, 28.6, 1.7, 3.8, 1.5]) \quad (3.3)$$

3.3.2 Damping Parameters

For most situation, we would like to estimate the damping directly with experiments. Because It is very hard to estimate damping analytically, and most of these methods are for surface vessels. Fossen, 2011 But we may face the situation that we could not do any experiment. In this situation, We will have to estimate them with the empirical method. In the work of Eidsvik, 2015, he use the rotational pressure to estimate the quadratic damping and estimate the linear damping with a scale through the result of quadratic damping, which result performance is not very well, but it is still better than nothing. So In this part, we will insert the parameters of Double Blueeye and we could got the result as following:

$$D_N = \text{diag}([90.55, 46.58, 194.05, 4.62, 1.21, 3.03]) \quad (3.4)$$

$$D_L = \text{diag}([14.48, 7.45, 31.05, 0.0928, 0.44, 0.085]) \quad (3.5)$$

3.4 Free Running Test Set Up

For we can not do the towing test every time when the ROV shape change, The free running test is a good alternative. When the thruster input is known and the system output- position or velocity is available, we could estimate the hydrodynamic parameters through free running. So some basic onboard sensors are needed in this test.

3.4.1 Sensors needed in this test

For in this test we will run the ROV will a set of constant force and measure its corresponding velocities, we could deploy the sensors which could measure the velocity directly like DVL and IMU or the sensors could measure the position and estimate the velocity through differential like APS, depth sensor and compass. All these have been introduced in the previous sections.

For the double Blueeye robot, we already have depth sensor and compass onboard, which will get the measurements on heave and angle positions. And we would like to test it in the MC-lab. The Qualisys is used to measure the position of ROV on surge and sway direction.

3.4.2 Test the thruster force

Attach the ROV on the force sensor and use the Blueyes. SDK to control force parameters($[-1,1]$) to test the corresponding force. For simplifying the process, we assume the thruster forces are the same with each other



FIGURE 3.2: Measure the thruster force of Double Blueyes Robot

Total Force parameters	
Surge	20 N
Sway	10 N
Heave	22 N

TABLE 3.1: Double Blueye Thruster Max parameters

These parameters Thus the thruster force is calculated as following way

$$F_i = i_{max} * a \quad (3.6)$$

Where i represents the motion dimension and a is the force parameter

$$\begin{aligned} i &= Surge, Sway, Heave \\ a &\in [-1, 1] \end{aligned} \quad (3.7)$$

3.4.3 Controller needed in this test

We need to run the ROV in a certain depth with a certain direction. A depth controller and a heading PID controller are implemented with the feedback from the depth sensor and the compass. To make sure the ROV can run with a constant surge force or sway force, the thruster allocation is needed. All these have been introduced in the sections of GNC system build up. The parameters of the PID controller is set according to the following table.

Direction	P	I	D	sample time	limitation
Depth	30	0	1	0.05 s	$[-22,22]$ N
Yaw	1.2	0.1	5	0.05 s	$[-5.5,5.5]$ N*m

TABLE 3.2: controller parameters

To map the force to the corresponding parameter of SDK , The output will be divided by the max force. To allocate the generalized force to each thruster, The work of thruster in section 7.1 will be used.

3.4.4 Experiment and simulation of free running test

The free running test was be tested in the MC-lab, and the process and results from the MC-lab will be introduced in the next section.

To replace the Qualisys measurementns with the ArUco SLAM for positioning the ROV, we would like to simulate this process in the UWSim to prove that the ArUco SLAM is a good alternative of Qualisys. The process and result will be introduced in the section of simulations. If the performance of the ArUco SLAM is good, the test environment could be extended to any tank or swim pool with clam water.

3.5 Free running test with Qualisys and results in MC-lab

In this section, we will put the vehicle into the water and run the vehicle with given thruster force till it got to a constant velocity and measure the position, velocity and orientation with Qualisys sensor and onboard sensors

3.6 Surge test

For surge direction, we will dive the ROV to certain depth and run forward with a set of certain forces and measure the position on the platform using the Qualisys system.

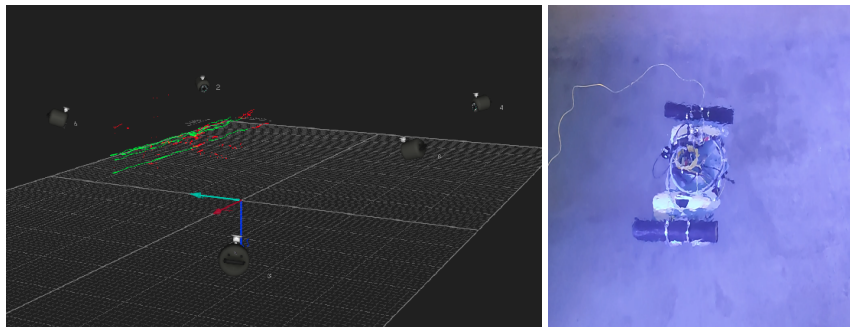


FIGURE 3.3: Experiment environment

The tests results are shown as following plots

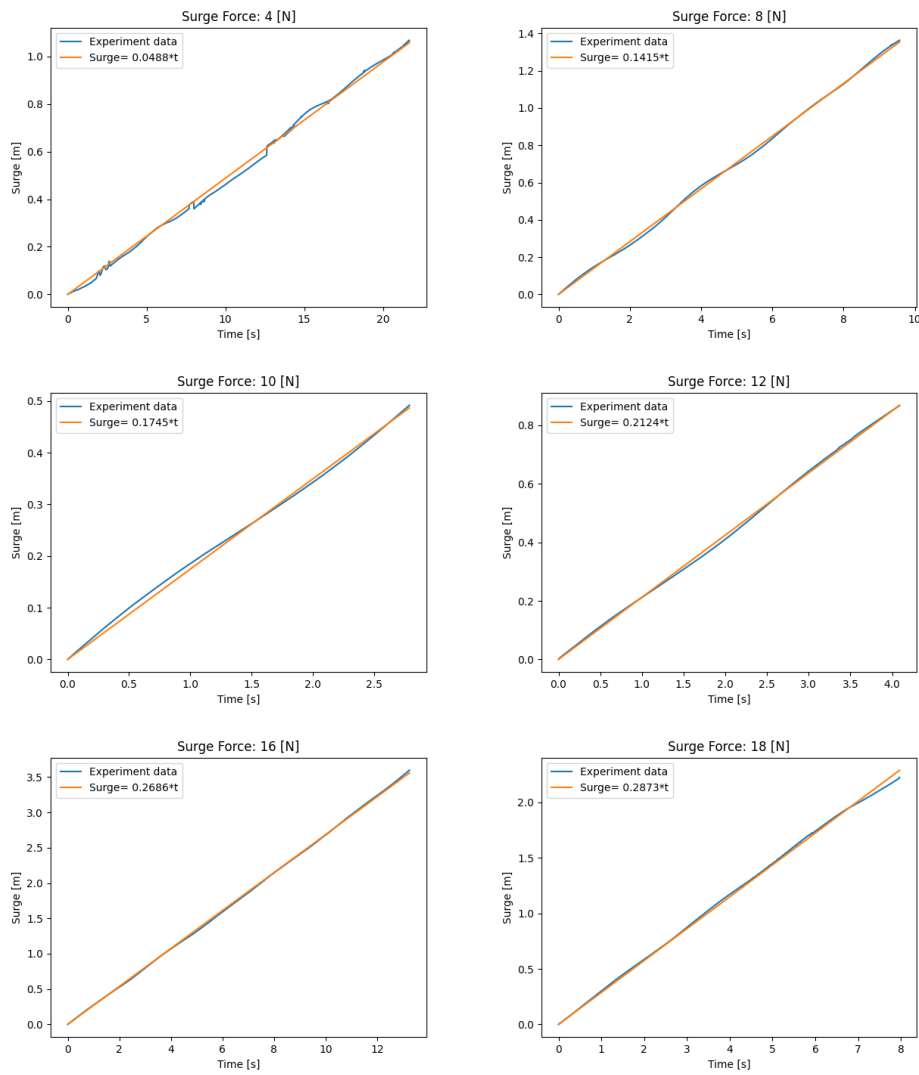


FIGURE 3.4: The Qualisys measurement in tests with different Surge thruster force

Right ROV parameter	Left ROV parameter	Force [N]	Velocity [m/s]
0.2	0.2	4	0.048
0.4	0.4	8	0.1415
0.5	0.5	10	0.1745
0.6	0.6	12	0.2124
0.8	0.8	16	0.2685
0.9	0.9	18	0.2872

TABLE 3.3: Experiment Data of Surge

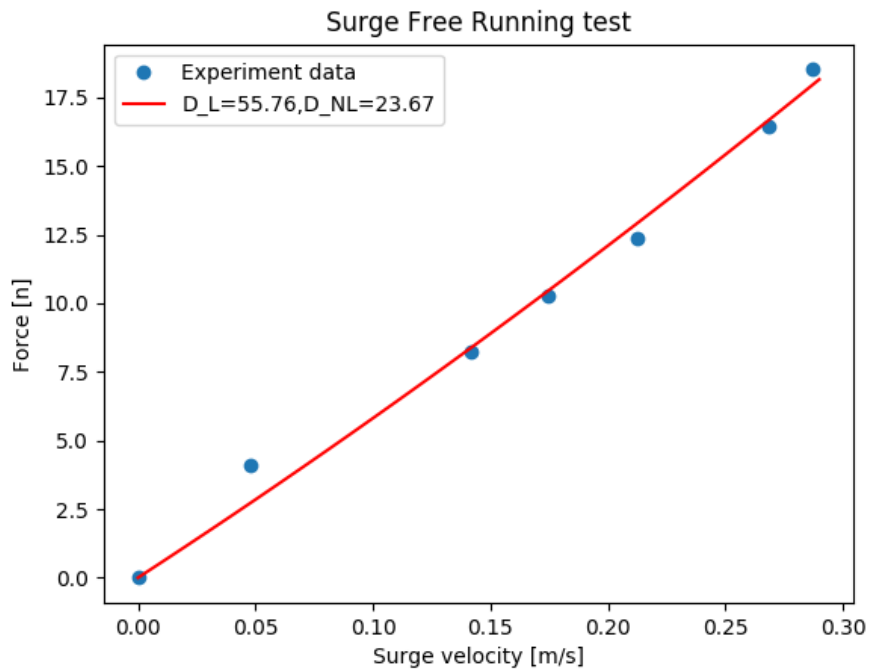


FIGURE 3.5: Damping Force vs Velocity on Surge

So the Damping parameters are:

$$D_L = 55.76, D_{NL} = 23.67 \quad (3.8)$$

From the recorded data of Qualisys, we find it is hard to record the position information from start to end for the limited measure area of Qualisys.

3.7 Sway test

For the sway direction, we did the almost same thing as the Surge tests.

Right ROV parameter	left ROV parameter	Force [N]	Velocity [m/s]
0.2	0.2	2	0.041
0.4	0.4	4	0.065
0.6	0.6	6	0.1314
0.8	0.8	8	0.1575

TABLE 3.4: Experiment Data of Sway

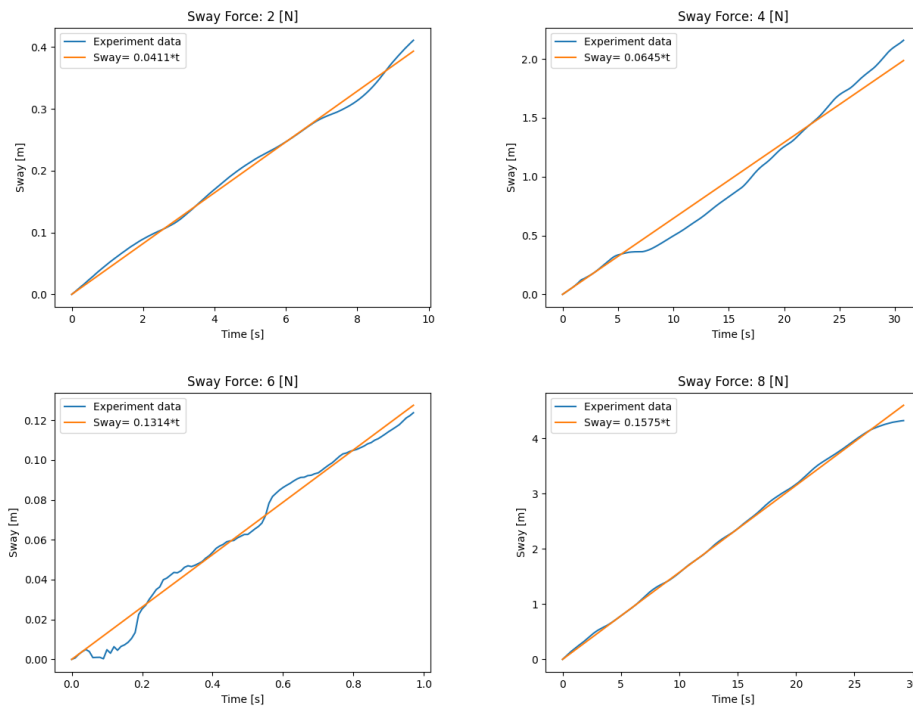


FIGURE 3.6: Free Running Result and corresponding velocity estimation

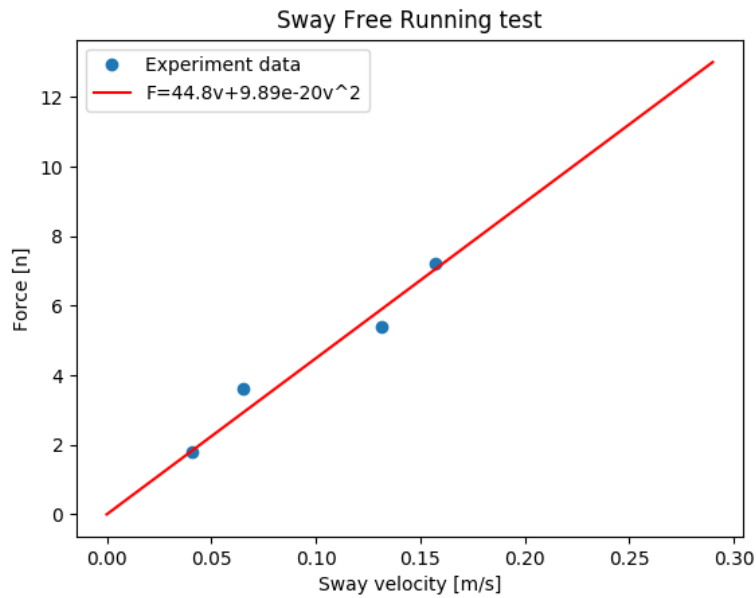


FIGURE 3.7: Damping on sway direction

So the Damping parameters are:

$$D_L = 44.8, D_{NL} = 0 \tag{3.9}$$

3.8 Heave test

3.8.1 Estimate damping

For heave test, we use different thruster parameters to dive the ROV to certain depth with certain force and measure the depth with the onboard depth sensor. From the experiment, when the heave=0.45, the ROV will not go downward. So at that time thruster force equal to the buoyancy.

Right ROV parameter	Left ROV parameter	Force [N]	Velocity [m/s]
0.5	0.5	1.10	0.028
0.55	0.55	2.20	0.034
0.6	0.6	3.30	0.041
0.7	0.7	5.5	0.0603

TABLE 3.5: Experiment Data of Heave

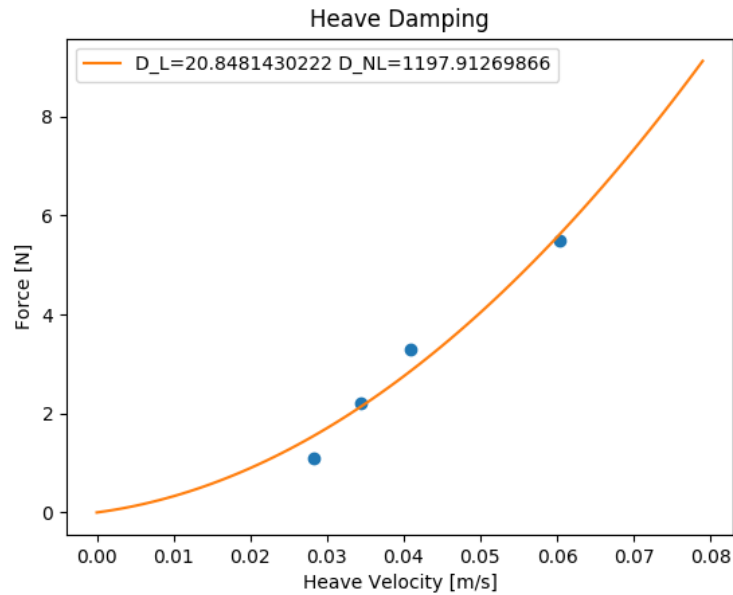


FIGURE 3.8: The Heave Damping result

So the damping of heave is

$$D_L = 20.848, D_{NL} = 1197.91 \quad (3.10)$$

3.8.2 Optimal Added mass

the heave test have recorded the ROV position from beginning to the end. Thus, in theory, we could optimal the added method through the force input and position output. For the bigger velocity we achieve, the speed-up process will be longer. So choose the test which gives 5.5 N as the thruster force, the position is shown as following plot.

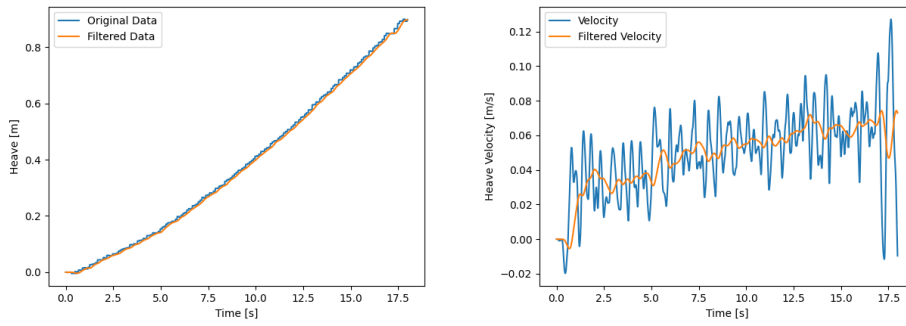


FIGURE 3.9: The original heave motion data and processed data

From the data we could find it is noisy, and it is the state of velocity. In the model we have integrated twice to get the position. The error will aggregate over time to become a big error. If the added mass is optimal with position will come up will overfit problem. So we differential the position measurement and filter it to a smooth curve as the following picture. For the optimal problem, we have two variables one is the added mass, the other is the thruster force for the way we calculate the thruster force is inaccuracy. And they should be within the bound of following equation

$$Heave_{addedmass} \in [0, \text{inf}], Thruster \in [5.2, 5.8] \quad (3.11)$$

With the optimization of NSGA method, the cost function is designed as previous section. And we got the result as following The simulated heave and real heave are shown as following

$$Heave_{addedmass} = 291.7945\text{kg}, Thruster = 5.2[N] \quad (3.12)$$

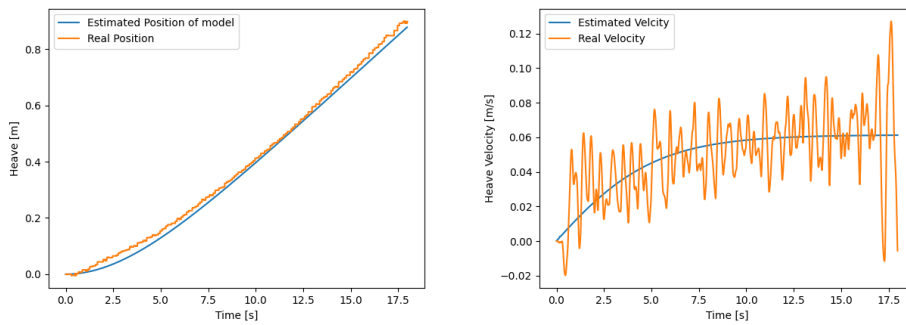


FIGURE 3.10: The original heave motion data and estimated motion from heave model

3.9 Roll decay test

For the motion limitation of Roll and pitch, the decay test will be applied to estimate the hydrodynamic model of roll and pitch

3.10 Roll Decay test in MC-Lab

In the MC-Lab, the Roll damping parameter is estimated with decay test. The double Blueyes is placed in the tank of MC-Lab as the Figure 3.12 left figure. After the water surface become clam, we would like to incline the vehicle to 30 deg with a stick and release it latter. Recording the roll angle during this process with compass sensor. The python scripts of recording roll angel is attached in the attachment

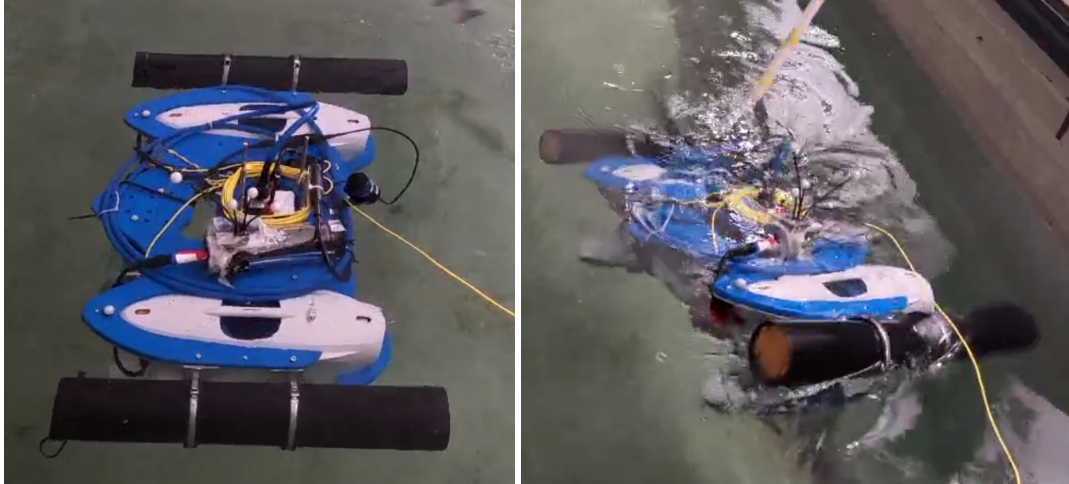


FIGURE 3.11: Roll Decay Test in MC-LAB

3.11 Pitch Decay test in MC-Lab

After the Decay test roll direction, we would like to repeat the same process on the pitch direction to test its linear damping parameter. The python script is also attached in the attachment.

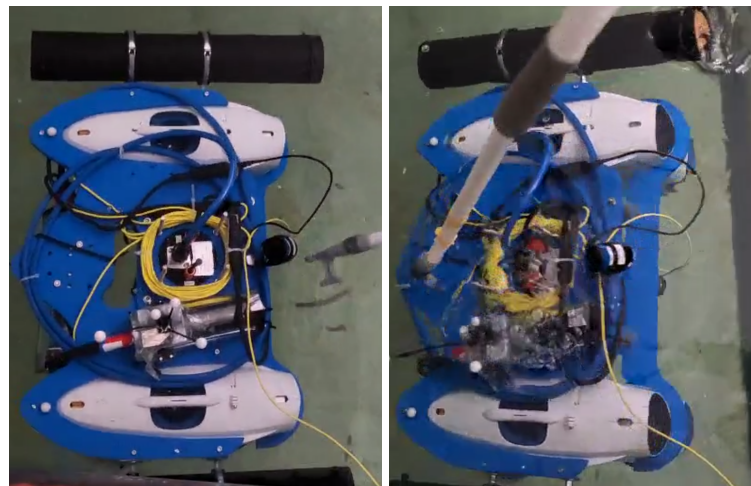


FIGURE 3.12: Pitch Decay Test in MC-LAB

The results of decay test will be presented in the next section. After the Roll decay test in the MC-lab, the recorded compass data is shown as the following plot. The initial roll angle is -33.42 deg and then is released. With the least squared method,

the curve is fitted as the following equation:

$$\phi(t) = -33.42e^{-0.39t} \cos(0.95t + 0) \quad (3.13)$$

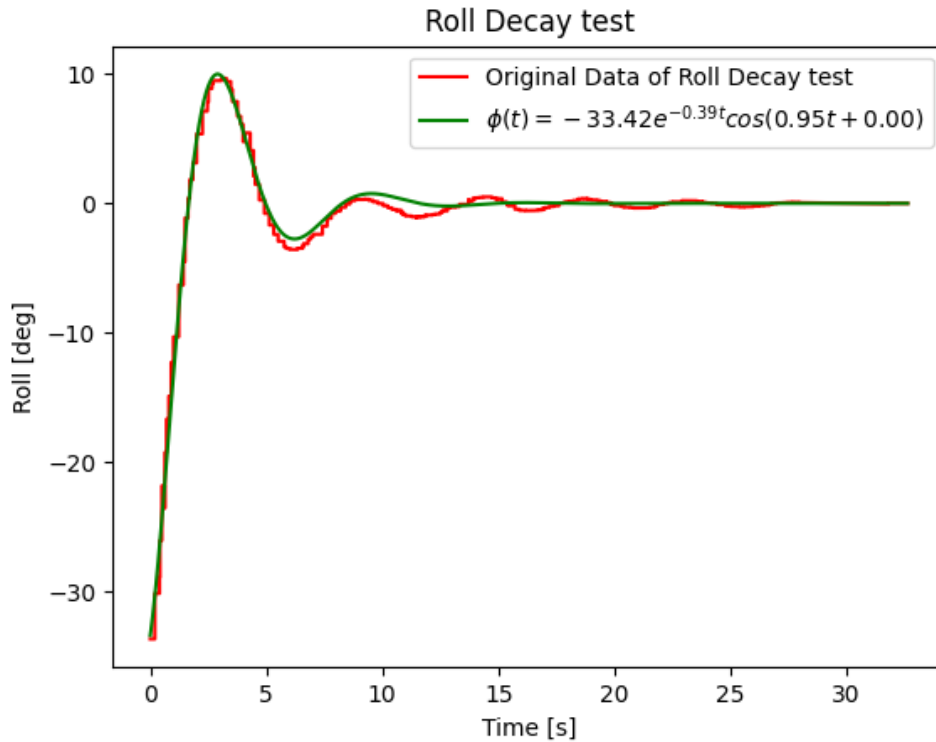


FIGURE 3.13: Roll Decay Test Result

From the result, we could get parameters of b and ω . From the configuration of ROV, we could get the rest parameters needed in the equation 2.28 :

$$\frac{b}{2} = 0.39; \omega = 0.95; W = 30[\text{kg}]; BG_z = 0.17[\text{m}]; I_x = 0.82[\text{kg} * \text{m}^2] \quad (3.14)$$

Insert these parameters into the equation 2.29 and 2.28:

$$I_{x-added} = \frac{30 * 0.17}{0.95^2 + \frac{0.78^2}{4}} - 2.69 = 2.16[\text{kg} * \text{m}^2] \quad (3.15)$$

$$D_L = 2 * 0.39 * (2.69 + 2.16) = 3.78 \quad (3.16)$$

The Data of pitch decay test is recorded as the following plot. These data is fitted with following equation:

$$\phi(t) = -39.95e^{-0.50t} \cos(1.87t + 0) \quad (3.17)$$

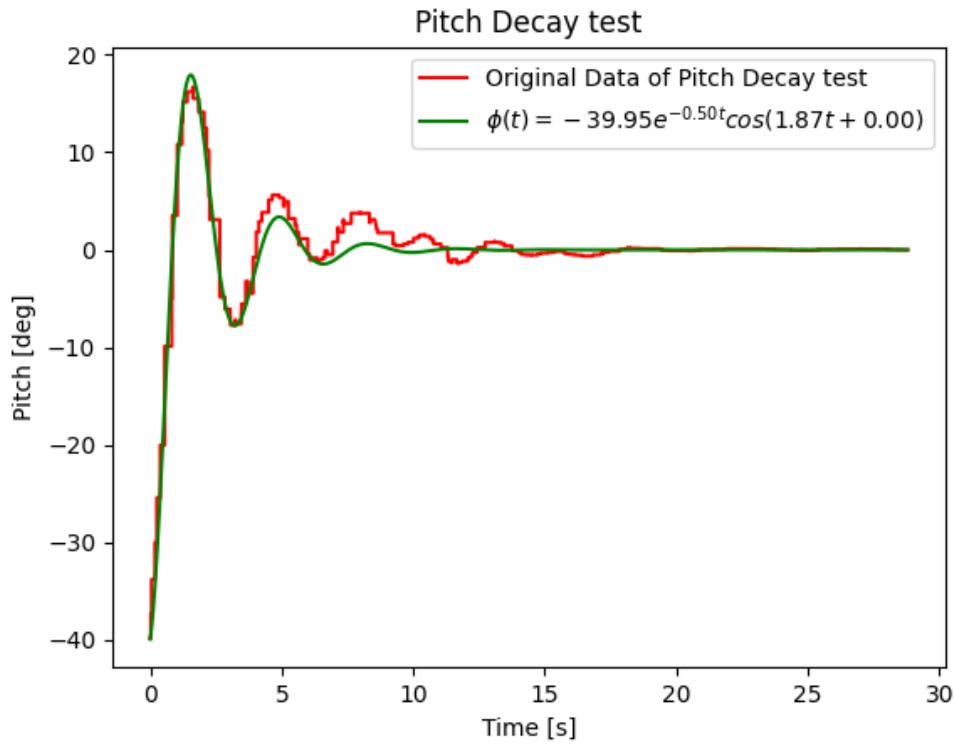


FIGURE 3.14: Pitch Decay Test Result

Thus we could get parameters of b and ω and ROV configuration as following:

$$\frac{b}{2} = 0.50; \omega = 1.87; W = 30[\text{kg}]; BG_z = 0.17[\text{m}]; I_x = 0.82[\text{kg} * \text{m}^2] \quad (3.18)$$

Insert these parameters into the equation 2.29 and 2.28:

$$I_{y-added} = \frac{30 * 0.17}{1.87^2 + \frac{1.0^2}{4}} - 0.82 = 0.54[\text{kg} * \text{m}^2] \quad (3.19)$$

$$D_L = 2 * 0.5 * (0.82 + 0.54) = 1.35 \quad (3.20)$$

3.12 Yaw free running test result

For the yaw direction, It is hard to test hydrodynamic parameters with towing test or get accuracy result from empirical method, thus free running test could be applied. The following process is applied:

- Apply constant moment on the vehicle with thrusters
- Record the data from compass
- Change moment and repeat the previous steps
- Process the data and calculate the corresponding velocity

In the MC-Lab, The ROV is placed in the tank and apply different thruster force on right and left Blueeye robot with the blueeye SDK. The script of test and record are attached in the attachment.

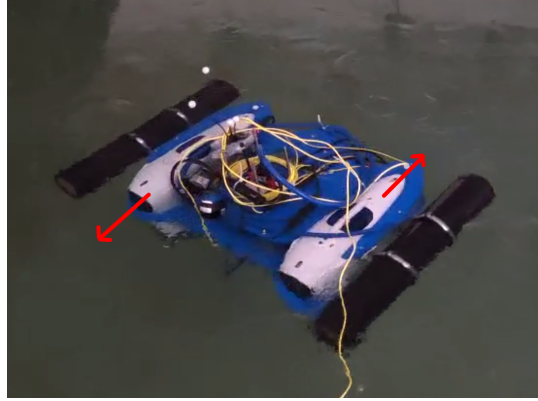


FIGURE 3.15: Free Running Test on Yaw direction

3.12.1 Estimate Damping

The results processed from yaw angle record of onboard compass, the moment and rotational velocity are calculated as following.

Right ROV parameter	Left ROV parameter	Moment [N*m]	Rotational Velocity [rad/s]
0	0	0	0
0.2	-0.2	1.1	0.437
0.4	-0.4	2.2	0.442
0.6	-0.6	3.3	0.586
0.8	-0.8	4.4	0.731
1	-1	5.5	0.785

TABLE 3.6: Experiment Data of Yaw Free Running Test

The relationship between moment and velocity are plotted as following. With these data and least square method, it could be expressed as following function:

$$M = 0.178 * v + 8.5 * v^2 \quad (3.21)$$

Thus the damping parameter of yaw direction is :

$$D_L = 0.178; D_{NL} = 8.5 \quad (3.22)$$

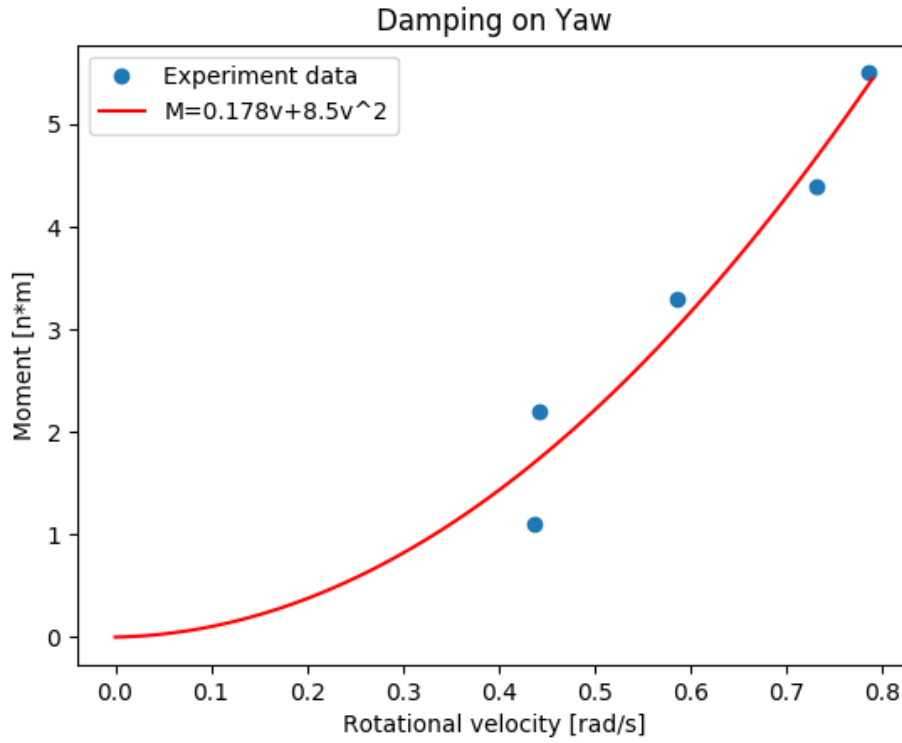


FIGURE 3.16: The experiment data of yaw free running test

3.12.2 Optimal Added mass

To optimal the added mass on the direction of yaw, the data of the last test is used, which give constant moment 5.5 [n*m] on the yaw direction. The position data is shown as following plot, to calculate the velocity, we need to filter the position. The velocity could be calculated as following figure.

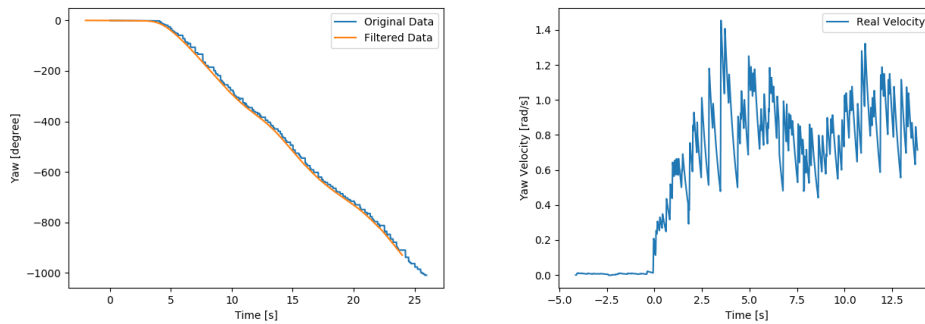


FIGURE 3.17: The data of test 6, filtered position and velocity

After the optimization with NSGA method as stated in the theory, The result is shown as following.

$$I_{yawaddedmass} = 3.845 - 2.99 = 0.855[kg * m^2] \quad (3.23)$$

Insert the result into the ROV model, the result is shown as following figure.

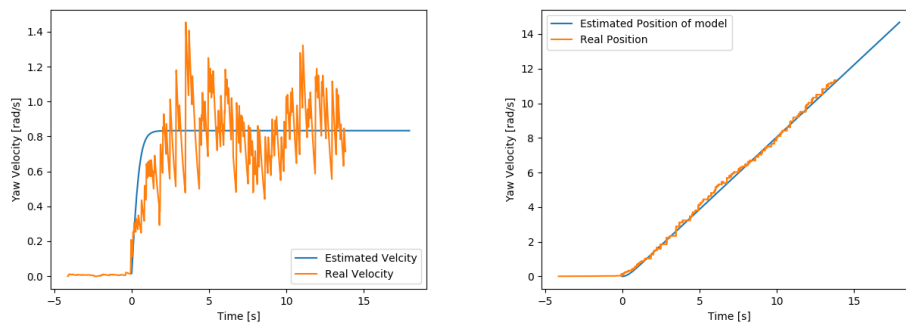


FIGURE 3.18: Comparison between model and the experiment data

3.13 Conclusion of Free Running test

The free running test result is shown as following table

Direction	Surge	Sway	Heave	Roll	Pitch	Yaw
Added Mass	NA	NA	291.8	2.16	0.54	0.855
Linear Damping	55.76	44.8	20.848	3.78	1.35	0.178
Nonlinear Damping	23.67	0	1197.91	0	0	8.5

TABLE 3.7: Free Running Test Result

From the result we could find that. We could not estimate the added mass on the direction of surge and sway for the fact that, In the MC-Lab, it is hard to record the speed-up process with Qualisys. This part of work will be done in the free running test with ArUco positioning system in the simulation part. To verify the validation of the free running test, a towing test will be applied in the MC-Lab. The result will be shown and discussed in the next section.

Chapter 4

Towing Test and Validation of System Identification

For verify the validation of the free running test, we would like to test the double Blueyes with the towing test and compare the results.

4.1 Theory of Towing test

When we tow the ROV in constant velocity, from the control plant model we could find that at this time the damping force is the only resistance left for the ROV. So We could get the relationship between damping force and velocity through towing the ROV with different velocity and measure the resistance force.

For the damping force could be divided into linear force and nonlinear force

$$D = D_L + D_{NL} \quad (4.1)$$

For the 6 DOF model we then have

$$\begin{aligned} D_L &= \text{diag}[X_u u, Y_v v, Z_w w, K_p p, M_q q, N_r r] \\ D_{NL} &= \text{diag}[X_{uu} u^2, Y_{vv} v^2, Z_{ww} w^2, K_{pp} p^2, M_{qq} q^2, N_{rr} r^2] \end{aligned} \quad (4.2)$$

For the fact that the rig did not support rotation, so another method is used to test the rotational hydrodynamic parameters, which is covered in the free running test.

4.2 Experimental setup and process of Towing test

The towing test is processed in the MC-lab by using the towing carriage. For attaching the ROV to the carriage, A rig is designed by engineers in the MC-lab. Thanks to their great work, The rig is implemented as 4.1, which is made up with a beam and two poles. The beam is attached with the carriage. Six force sensors were used as the connection between the rigs and beam, which could provide the force information on xyz direction for each rig. the rigs are connected to each Blueye handle. The rigs' cross-section was designed as blade shape to minimize the influence of surface affect.

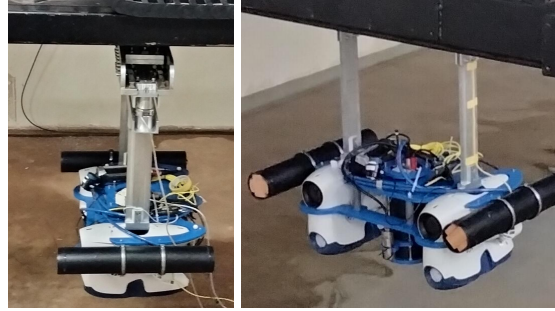


FIGURE 4.1: The rig for towing test

After setting up the experiment, The towing test is processed in the following way, The carriage will tow the ROV in different constant velocities, After the transient accelerations, The drag force of ROV will become constant, In this way we could grab the relationship between drag force and velocity. To find the linear and nonlinear damping parameters, we will fit the curve in the form of $ax^2 + bx$ with least-squared estimation, where a is the nonlinear term and b is the linear term.

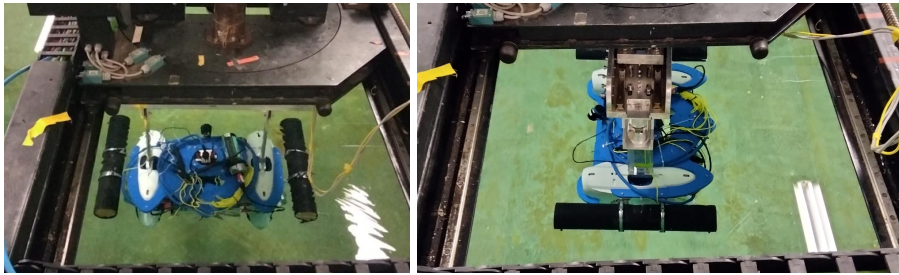


FIGURE 4.2: Towing test

4.3 Result of the Surge Towing test

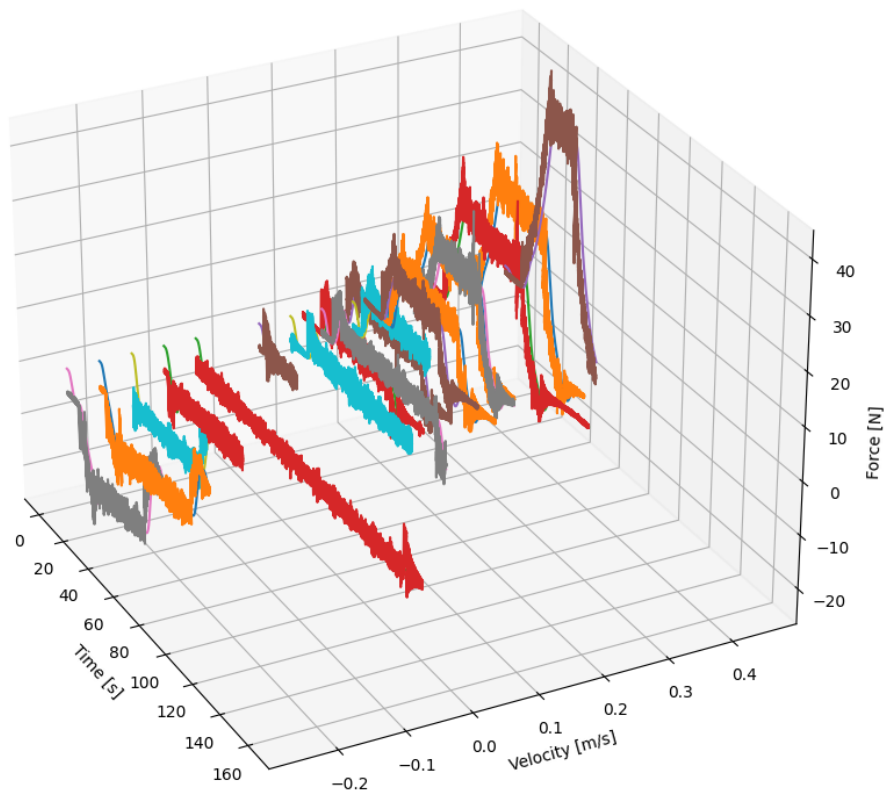


FIGURE 4.3: Surge towing test result original data

From the original data of the towing test, we could find the data is noisy. For processing the data, a low pass filter is used here, which will filter out the data changes higher than 500 hz, the result is shown as following

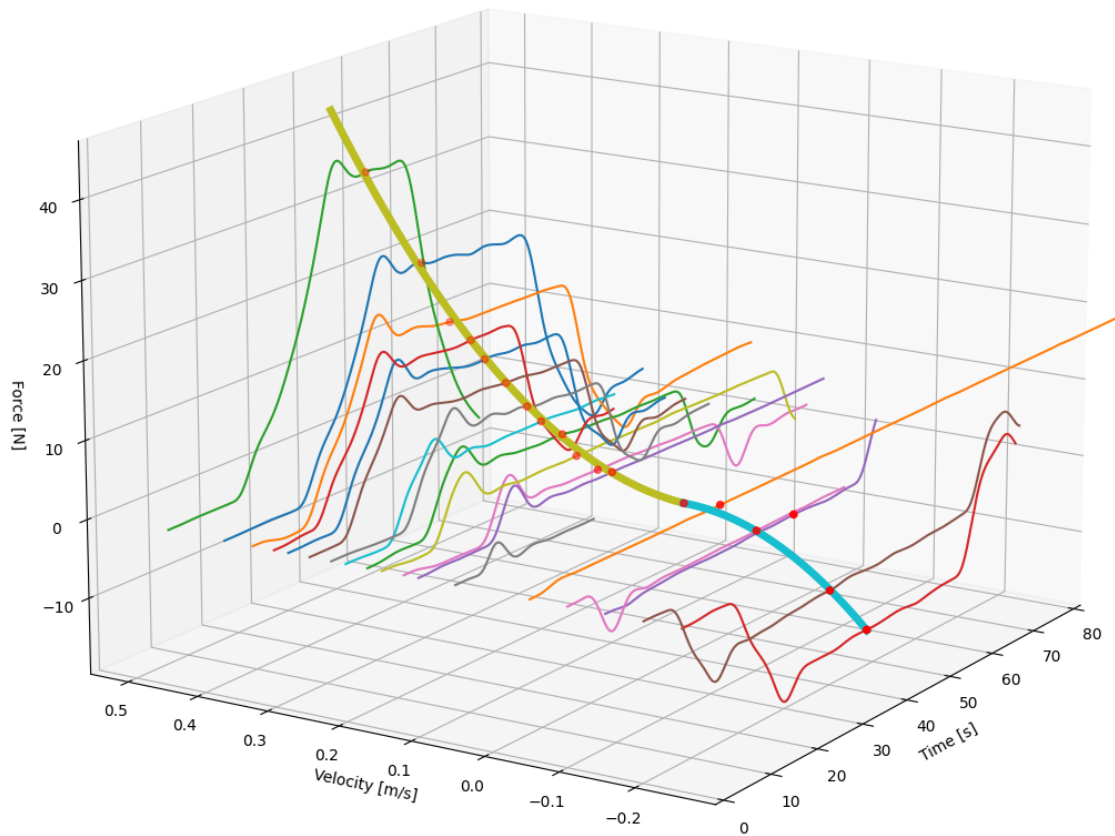


FIGURE 4.4: Surge towing test result processed data

After processing the data we could find that the drag force increase first during the acceleration process and get to constant after the velocity become constant, So we select the average force as the drag force during the constant velocity process. The processed data are calculated as following table.

And we could get the surge damping hydrodynamic parameter:

$$\begin{aligned} \text{ForwardDamping} : D_L &= 6.48, D_{NL} = 158.86 \\ \text{BackwardDamping} : D_L &= 0.07, D_{NL} = 189.75 \end{aligned} \quad (4.3)$$

For the ROV have different configuration for forward and backward on surge. we have different parameters.

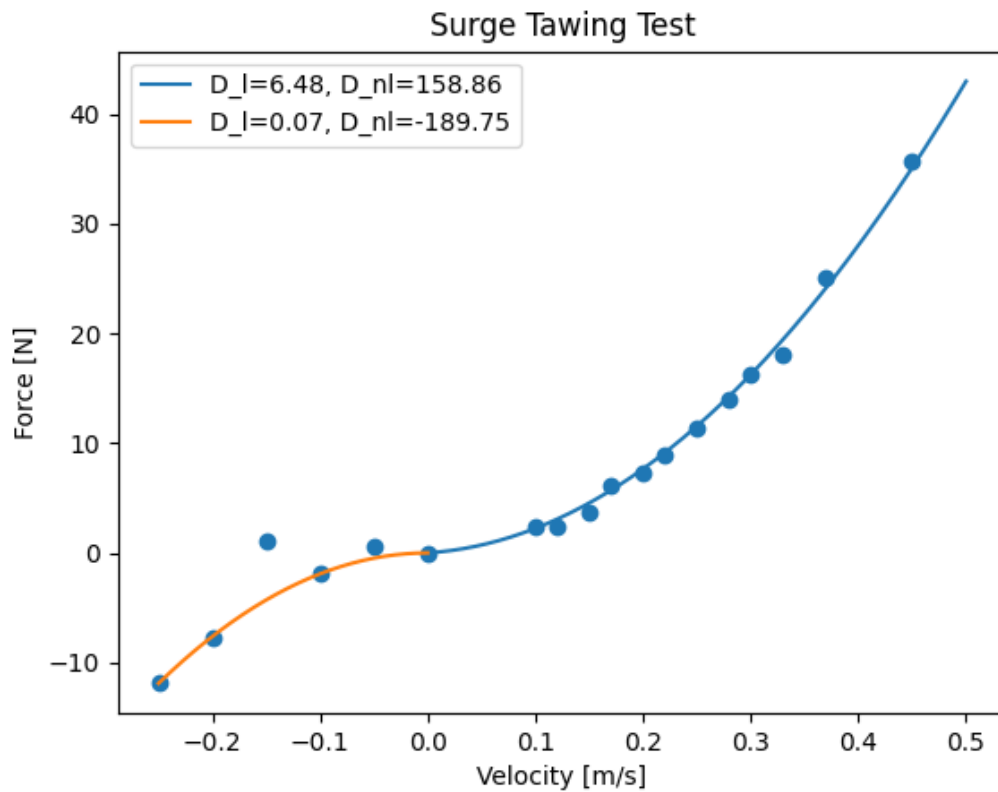


FIGURE 4.5: Surge towing test result : Velocity vs Damping Force

4.4 Result of the Sway Towing test

After the surge towing test, we rotate the rig for 90 degree so that we could test the sway hydrodynamic parameters with moving carriage forward as shown in the figure 4.2. For the fact that the ROV is symmetry on the sway direction, thus we only move the towing carriage forward in different velocity. Its result is shown as figure 4.9. The original data is processed with low pass filter and repeat the process of the previous section 4.3. We could get the sway hydrodynamic parameter:

$$D_L = 3.12, D_{NL} = 146.38 \quad (4.4)$$

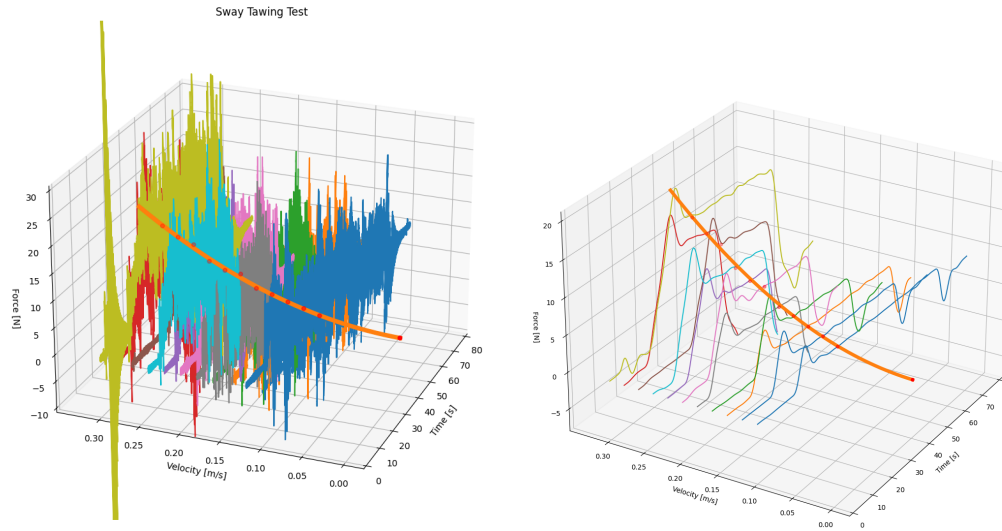


FIGURE 4.6: Sway towing test result and processed data

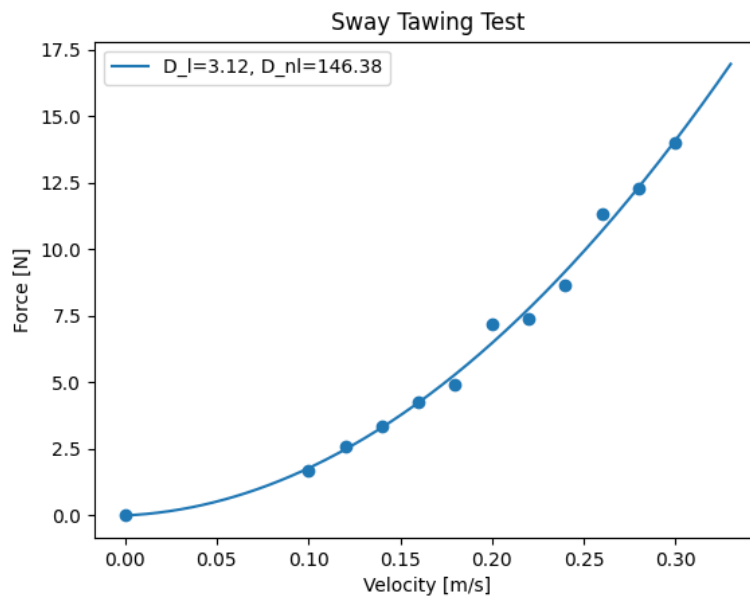


FIGURE 4.7: Sway towing test result processed data

4.5 Result of the Heave Towing test

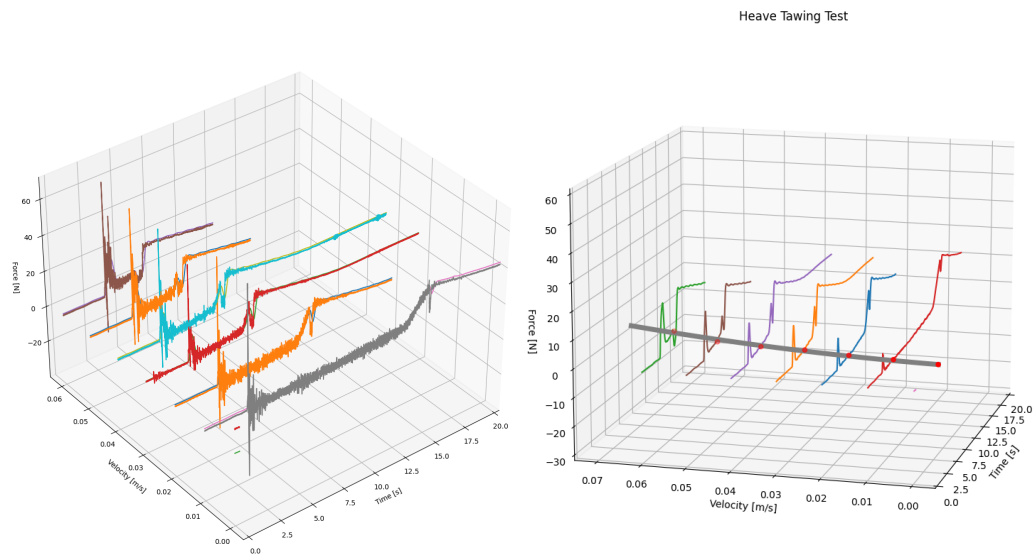


FIGURE 4.8: Sway towing test result and processed data

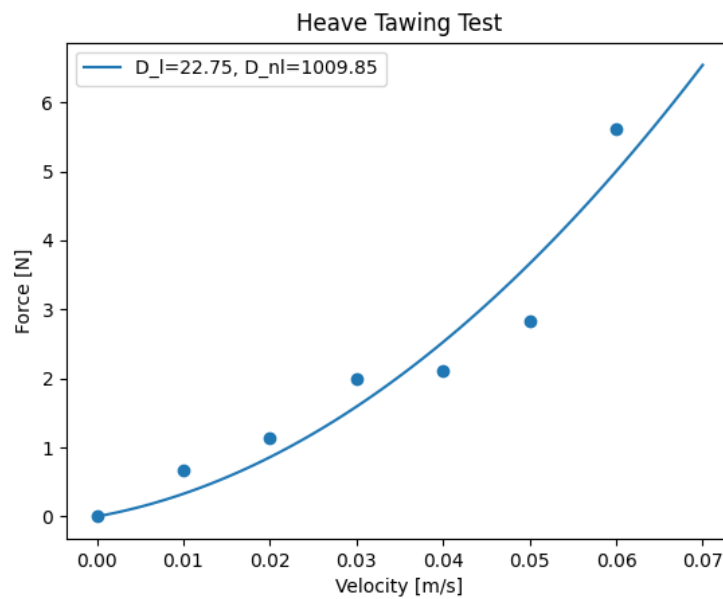


FIGURE 4.9: Sway towing test result processed data

After the sway test, we will work on the heave test. For the carriage has movement limitation, which could only move within 0.15 meter. Thus, The movement time is decreasing with higher velocity. So the highest velocity we could test is 0.06 m/s. So we could get the heave hydrodynamic parameters as :

$$D_L = 22.75, D_{NL} = 1009.85 \quad (4.5)$$

4.6 Comparison between three methods

4.6.1 Added Mass

Direction	Surge	Sway	Heave	Roll	Pitch	Yaw
Free Running Test	NA	NA	291.8	2.16	0.54	0.855
Empirical Method	21.2	8.95	28.6	1.7	3.8	1.5

TABLE 4.1: Free Running Test Result

From the experiment in the MC-lab, It is hard to record the position Completely from initial position to the end, In Figure 3.3, the data have many break points. So we could not use the data from Qualisys to optimal the added mass. From the results, we could find on the direction of roll, pitch and yaw the added mass results almost at the same magnitude. The Heave added mass from free running test is almost ten times of the empirical result. which will be discussed later together with the damping result.

4.6.2 Damping

Direction	Empirical Method	Free Running Test	Towing Test
Surge	$D_L = 14.48D_{NL} = 90.55$	$D_L = 55.76D_{NL} = 23.67$	$D_L = 6.48D_{NL} = 158.86$
Sway	$D_L = 7.45D_{NL} = 46.58$	$D_L = 44.8D_{NL} = 0$	$D_L = 3.12D_{NL} = 146.38$
Heave	$D_L = 31.05D_{NL} = 194.05$	$D_L = 20.84D_{NL} = 1197.91$	$D_L = 22.75D_{NL} = 1009.85$
Roll	$D_L = 0.09D_{NL} = 4.6$	$D_L = 1.74D_{NL} = 4.15$	NA
Pitch	$D_L = 0.44D_{NL} = 1.2$	$D_L = 3.32D_{NL} = 0$	NA
Yaw	$D_L = 0.0085D_{NL} = 3$	$D_L = 0.389D_{NL} = 18.5$	NA

TABLE 4.2: Empirical Method and Free Running Test vs Towing Test

we take the result of Towing test as the ground truth of the hydrodynamic parameters. Thus, through the comparison between the Free running test and towing test, we could verify the validation of free running method.

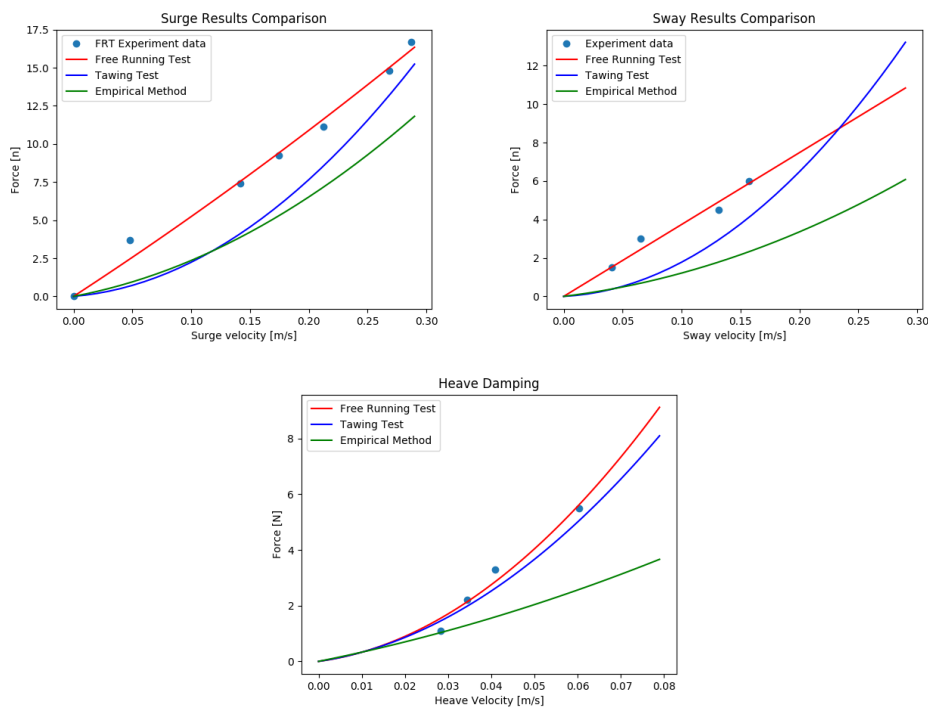


FIGURE 4.10: Empirical Method vs Free Running Test vs Towing test

We could find the results from Free Running Test is more linear than others, A guess of this kind of phenomenon is we assume the thruster force changes linearly with the sdk parameters, which have corresponding relationship in the embedded system of Blueeye vehicle. This is an open loop system, which will cause an inaccuracy problem between the real thruster force output and the one we set. This problem reflected in the results as the data nodes gets more accuracy when it is closer to the Maximum and minimum thrust. For the most of open-frame ROV move in a low speed. So the max error of damping force is at the level of 2 or 3 N, which is good enough control plant model for closed-loop system: controller and observer. We also could find that the experiment result of heave damping is almost ten times bigger than the one estimated from empirical method, which relationship is also existed in the result of heave added mass.

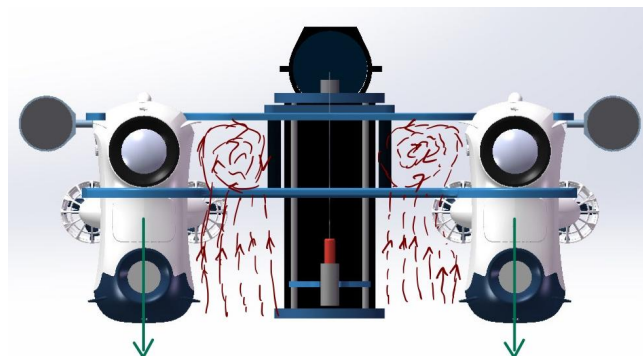


FIGURE 4.11: Guess water flow of the heave motion

The water flow during the heave motion is guessed as the Figure 4.11. The structure may generate the vortex between two blueeyes and UHI, which will take away a lot of energy from the ROV. This kind of problem is not included in the process

of the empirical method. Thus, the added mass and damping of heave is bigger than the estimated one. This situation also prove the necessity of experiment and the inaccuracy of the empirical method.

Chapter 5

Simulation Environment Build Up

For the simulation environment have been well-built in my work of master project TMR4510 during spring 2021. This section builds on the results from this project work by adding a virtual camera and new scene of MC-lab.

In this section, a simulation environment will be built up on the platform of ROS. So the following contents will focus on how the theories and equations applied to built up a virtual the Double Blueyes Robot.

5.1 3D Model

Not only for the proposal of visualization but also for the proposal of hydrodynamic parameters' estimation, A 3d model is needed for this thesis. Thanks to the 3d model of Blueye provided by the Blueye company. It is much easier to implement the Double Blueyes ROV model with SolidWorks. the 3D model is shown as the following plots. And its configuration information is shown in the following table. The file of the model is attached in the attachment with name as 'Double_blueye1.osgt'.

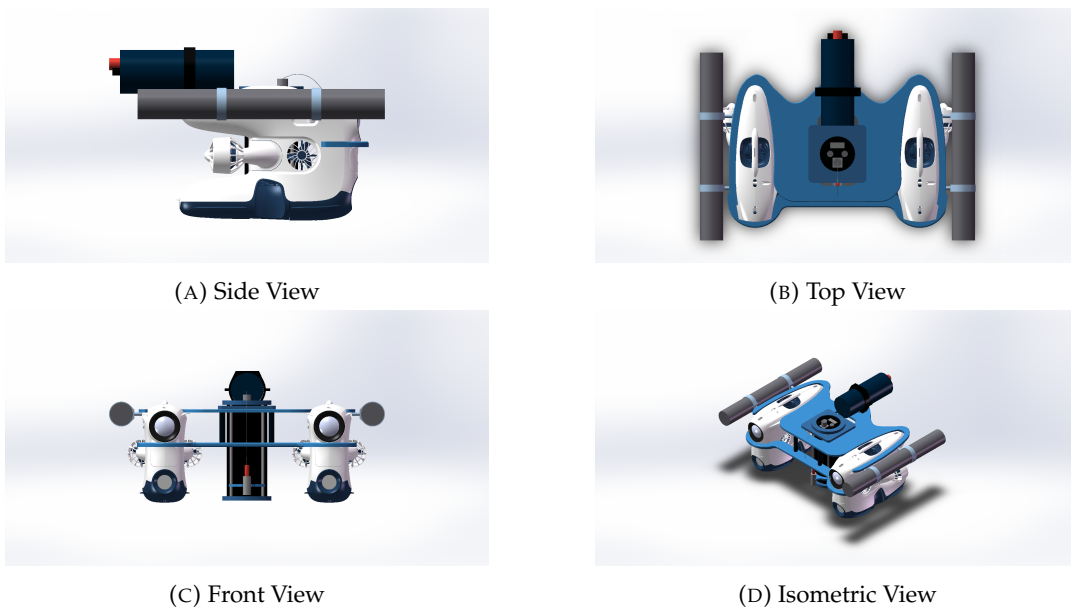


FIGURE 5.1: 3D model of ROV

ROV Configuration		
Parameter	Value	Unit
L	640	mm
W	950	mm
H	354	mm
m	30	kg
$A_{proj,front}$	173964	mm^2
$A_{proj,side}$	140366	mm^2
$A_{proj,top}$	301998	mm^2
I_x	2.69	$kg \cdot m^2$
I_y	3.88	$kg \cdot m^2$
I_z	2.99	$kg \cdot m^2$

TABLE 5.1: ROV Configuration of Double Blueyes Robot

For the propose of import the model into the platform of UWSIM.A urdf file is implemented here, which will import the model and set the frames. The body frame is set as following figure 5.2, COG is located at the centre of the vehicle named as 'Double_Blueyes', x axis is along the surge direction, y axis is along the sway direction and z axis is along the heave direction downward positive.

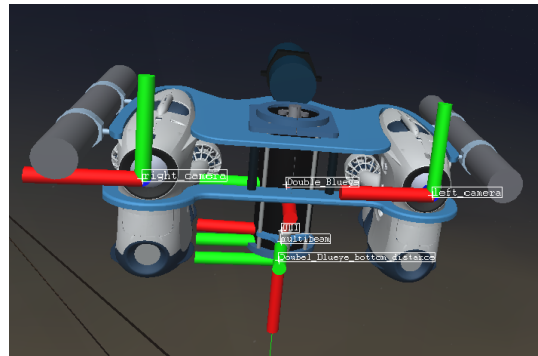


FIGURE 5.2: Body Frame of Simulation Environment

To simulate the GNC system of robot, the sence environment of is set as the Figure 5.3, with a sand seabed and a shipwreck, which is provided in the UWsim environment.



FIGURE 5.3: Simulation Sence

The world is set as Figure 5.4, which is located at the centre of map.



FIGURE 5.4: World Frame of Simulation Environment

5.2 Dynamic System

In order to simulate the ROV on the platform of UWSIM, A dynamic engine is needed as the process plant of the ROV. It will simulate the real process of the system. These systems are mainly built up on the Fossen's equation mentioned in the section 2, So in the following sections I will focus on how to build up the dynamic model of Thruster and the dynamic model of a vehicle with python code as ROS nodes

5.3 Thruster Dynamic Model

For simulate the robot dynamic within the uwsim environment, A thruster dynamic model is needed here. This part of model could be divided into two parts. One is the parameters of a single thruster, the other is the mount position of thrusters which associate with the thruster allocation

5.3.1 T200 Thruster and Pseudo-Thrusters

The current thruster-solution used by Blueye Robotics is the T200 manufactured by Blue Robotics, which has been tested and shipped since the end of 2014 [Huynh, 2016](#). The T200 Thruster is the world's most popular underwater thruster for ROVs, AUVs, surface vessels. It is designed with patented flooded motor, which is powerful, efficient, compact, and affordable.

FIGURE 5.5: T200 Thruster *T200 Thruster for ROVs 2021*

T200 Configuration		
Parameters	Value	Unit
Length	113	mm
Diameter	100	mm
Propeller Diameter	76	mm
Operating Voltage	7-20	volts
Weight	156	g

TABLE 5.2: T200 Configuration *T200 Thruster for ROVs 2021*

From the test of thruster force, we could find the relationship between total thruster force and the SDK parameters, We assume that the thruster force is equal to each other for each Blueye Pioneer. There are four thrusters in total on each Blueye Robot, two longitudinal (surge)thrusters, one transversal (sway) thruster and one vertical (heave) thruster. Løvås, Sørensen, and Ludvigsen, 2020 From the SDK of Blueye robot, An embedded thrust allocation have already been implemented on the vehicle. It allows sending the generalized thrust force in surge, sway and heave instead of individual thrusters. So I would like to describe that the thruster system of blueye in made up by three pseudo-thrusters. It is also assumed that the pseudo-thruster has its line of action through the center of origin of Blueye Robot. So the max thruster force could be expressed as following table

Thruster	Right/Left surge	Right/Left sway	Right/Left heave
Force[N]	10	5	11

TABLE 5.3: Pseudo-Thrusters

When The SDK signal changes, the thruster force could not change immediately. To simulate this phenomenon in the ROS, A discrete time Low pass filter is introduced here

$$\tau_{sim}(i) = \overbrace{\tau_{single} \left(\frac{\Delta_T}{RC + \Delta_T} \right)}^{\text{Input contribution}} + \overbrace{\tau_{sim}(i-1) \left(\frac{RC}{RC + \Delta_T} \right)}^{\text{Inertia from previous output}} \quad (5.1)$$

In this case I choose $\Delta_T = 0.001$, $RC = 0.2$ and the performance of the thruster is shown as following, when the total surge force changes from 20N to -20N

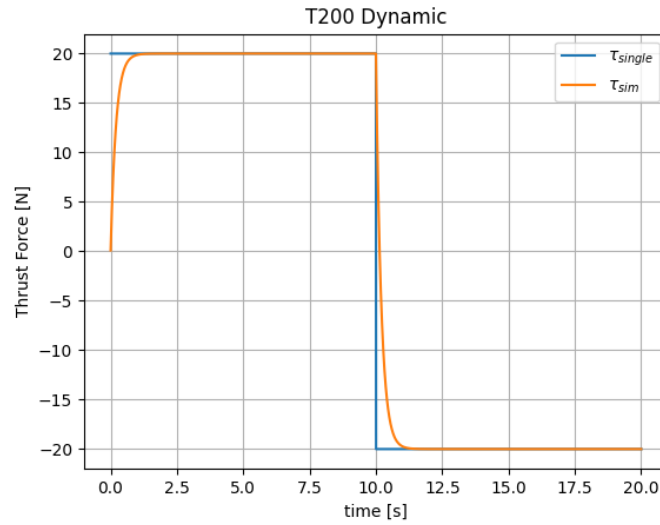


FIGURE 5.6: Total Surge Force Dynamic

5.3.2 Thruster configuration

Then we consider the thrusters in the body-fixed frame of Double Blueyes Robot. the pseudo-thrusters are located as following Table 5.4

Thruster	Position	Unit
$\tau_{1,surge}, \tau_{1,sway}, \tau_{1,heave}$	$[0,0,0.28]$	m
$\tau_{2,surge}, \tau_{2,sway}, \tau_{2,heave}$	$[0,0,-0.28]$	m

TABLE 5.4: Thruster Configuration

With these information the Thruster Configuration Matrix could be expressed as below equation, Where $d=0.28$ m.

$$\tau = \begin{bmatrix} \tau_X \\ \tau_Y \\ \tau_Z \\ \tau_K \\ \tau_M \\ \tau_N \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & -d & 0 & 0 & d \\ 0 & 0 & 0 & 0 & 0 & 0 \\ d & 0 & 0 & -d & 0 & 0 \end{bmatrix} \begin{bmatrix} \tau_{1,surge} \\ \tau_{1,sway} \\ \tau_{1,heave} \\ \tau_{2,surge} \\ \tau_{2,sway} \\ \tau_{2,heave} \end{bmatrix} \quad (5.2)$$

τ_X, τ_Y and τ_Z denote the surge, sway and heave forces while τ_K, τ_M and τ_N denote the roll, pitch and yaw moments, respectively. Obviously from the matrix we could find that the robot is not controllable on the pitch dimension. It has 5 ranks, with coupled control of surge and yaw, heave and roll, and uncoupled sway

5.4 Wave Dynamic

For simulate the wave excite force to test the GNC system of robot, The Modified Pierson–Moskowitz (MPM) wave spectrum is chosen. Pierson and Moskowitz have

developed a two-parameter wave spectral formulation from analyses of wave spectra in the North Atlantic Ocean Fossen, 2011.

$$S(\omega) = A\omega^{-5} \exp(-B\omega^{-4}) \quad (5.3)$$

$$A = \frac{4\pi^3 H_s^2}{T_z^4}, \quad B = \frac{16\pi^3}{T_z^4} \quad (5.4)$$

Thus, the MPM spectrum, System is parameterized by two parameters: H_s : Significant wave height and T_z : Average zero-cross wave period. With these two parameters, the parameters for Equation 2.14 could be calculated.

$$\omega_0 = \frac{2\pi}{T_z} \quad (5.5)$$

$$\sigma = \sqrt{\frac{A}{\omega_0^5} \exp\left(-\frac{B}{\omega_0^4}\right)} \quad (5.6)$$

Also a table for the relationship between λ : damping ratio and ω_0 : wave frequency is used from Fossen, 2011 page 217.

λ	ω_0	λ	ω_0
0.2565	0.5	0.2573	0.8
0.2588	1.1	0.2606	1.4

TABLE 5.5: Wave Damping Ratio

We could find the damping ratio is almost the same as each other, So the damping ratio λ is chosen as 0.26. The following 3 set of parameters are chosen

Set	H_s	T_z
Set 1	0.27 m	3.0 sec
Set 2	1.5 m	5.7 sec
Set 3	4.1 m	8.7 sec

TABLE 5.6: Wave Force Parameters

The Wave force on one dimension is simulated as following figures. We could easily find that with these parameters the wave force varies from -2 N to 2 N.

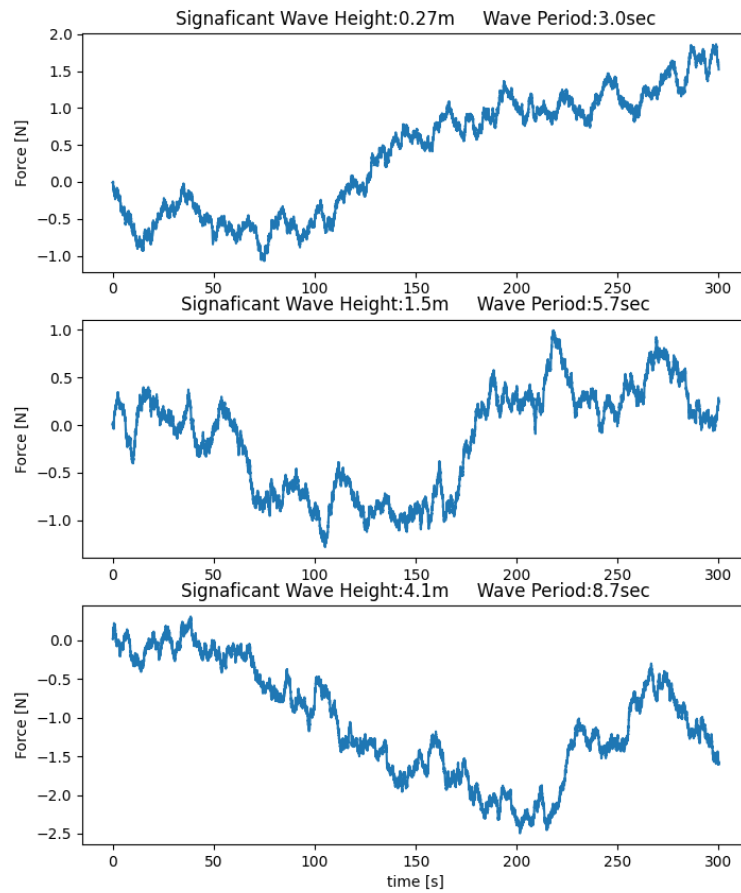


FIGURE 5.7: Wave Force

5.5 Virtual Sensors

To simulate the measurement of the sensors, The virtual sensors will be implemented.

Sensor	Noise std	Update rate	Bias
APS	0.5	1 Hz	0
Accelerometer (IMU)	$0.0308 \text{ m} / \text{s}^2$	100 Hz	$6.8 \times 10^{-6} \text{ m/s}^2$
Gyroscope (IMU)	$3.08 \times 10^{-5} \text{ rad/s}$	100 Hz	0.017 rad / s
Magnetometer (IMU)	$1 \times 10^{-3} \text{ rad}$	100 Hz	-
Pressure sensor	$1 \times 10^{-3} \text{ m}$	42 Hz	-
Camera	-	-	-

TABLE 5.7: Sensors Configuration

5.5.1 APS-Acoustic Positioning System

The APS sensor will return the x,y position for ROV in world frame. For easier implementing, The mount position of Transponder is assumed to attaching with the

body-fixed frame origin. So the measurement of APS could be express as following equation:

$$\begin{aligned} x_{APS} &= x + w, w \sim \mathcal{N}(\mu, \sigma^2) \\ y_{APS} &= y + v, v \sim \mathcal{N}(\mu, \sigma^2) \end{aligned} \quad (5.7)$$

Where the x and y is representing the ground truth position returned from ROS topic '/DBS/pose'. the simulated performance is shown as following plots when the ROV move on the surge and sway.

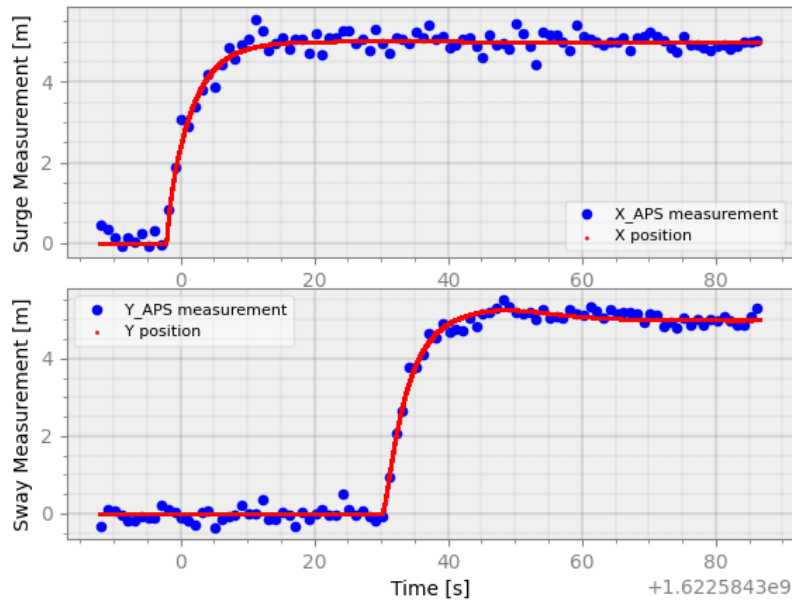


FIGURE 5.8: Virtual APS Measurement

5.5.2 Pressure Sensor

The Pressure Sensor will return the depth of the ROV (z position), which is also assumed to be attached to the body-fixed frame.

$$z_{pressure} = z + w, w \sim \mathcal{N}(\mu, \sigma^2) \quad (5.8)$$

where z is the ground truth of depth from ROS topic '/DBS/pose'. The virtual pressure sensor performance is shown in the following figure when the ROV moves downward.

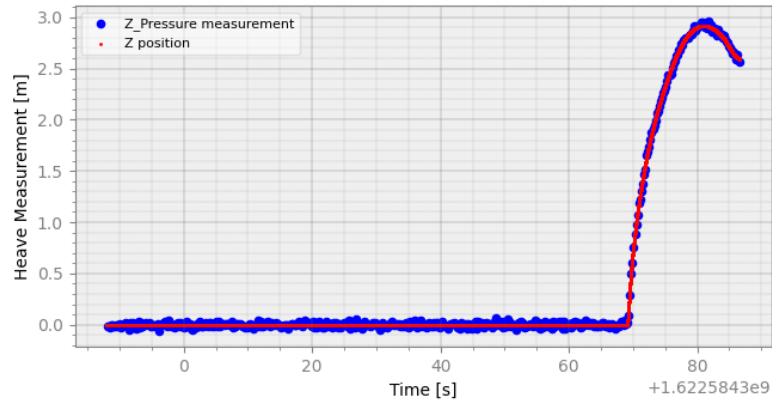


FIGURE 5.9: Virtual Pressure Sensor

5.5.3 IMU

The IMU signal is usually struct with three parts: magnetometer, Gyroscope and Accelerometer. Thus, it is simulated as following way. the position of the imu is attached to the body frame. The script is attached in the attachment.

Magnetometer:

The Magnetometer will return the orientation of the ROV between the body-fixed frame and world frame for roll, pitch and yaw. The virtual Magnetometer result is shown as following plots

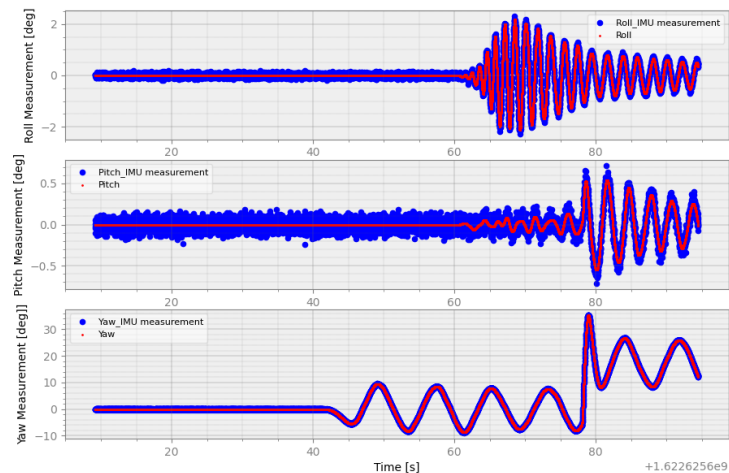


FIGURE 5.10: Virtual Magnetometer

Gyroscope:

The gyroscope will return the angular velocity of the ROV for roll_dot, pitch_dot and yaw_dot. The virtual gyroscope performance is shown in the following plots.

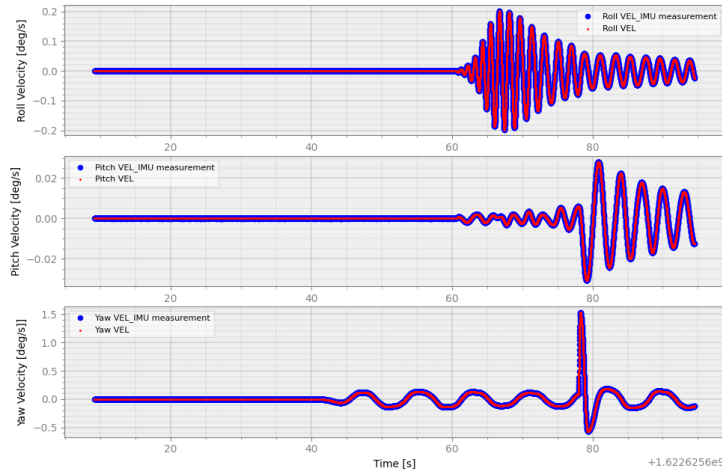


FIGURE 5.11: Virtual Gyroscope

Accelerometer

The Accelerometer will return the linear acceleration of the ROV in body-fixed frame for surge, sway and heave. The virtual accelerometer performance is shown in the following plots.

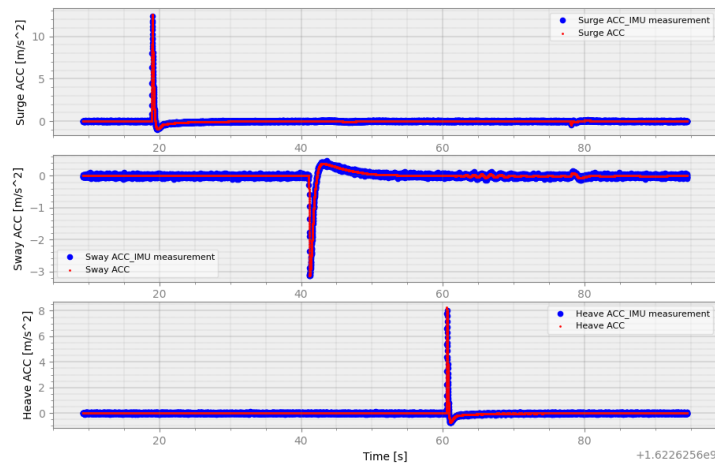


FIGURE 5.12: Virtual Accelerometer

5.5.4 virtual camera

In this thesis, the front cameras of Double Blueyes Robot is used in the ArUco positioning system. So in the simulation environment a virtual camera will be implemented. From the camera calibration of the ROV front cameras, the camera parameters are calculated in the following format as described in the OpenCV library. Bradski, 2000

$$\text{camera matrix} = \begin{bmatrix} f_x & 0 & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix}; \quad (5.9)$$

Distortion coefficients = $(k_1, k_2, p_1, p_2, k_3)$

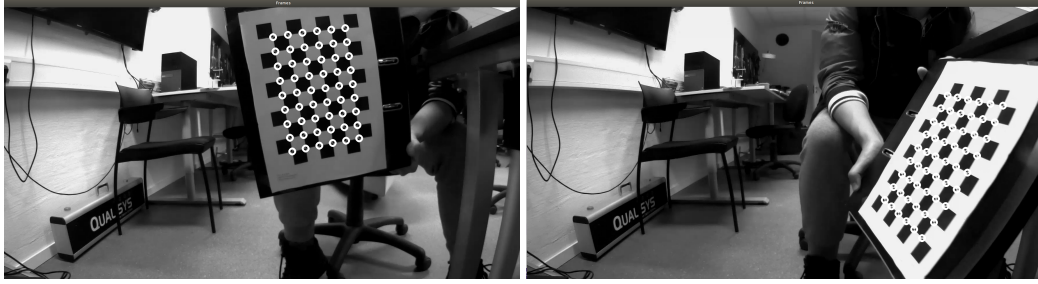


FIGURE 5.13: Camera Calibration of the Double Blueeyes Robot

	f_x	f_y	c_x	c_y	k_1	k_2	p_1	p_2	k_3
Left Camera	1025	1027	987	552	0.31	0.08	0.00	0.00	0.03
Right Camera	1014	1011	999	517	0.32	0.12	0.00	0.00	0.03

TABLE 5.8: Camera Parameters of two cameras for Double Blueeyes Robot

The cameras' coordinates are located in the front of the ROV, with the following relative position with the ROV body frame as shown in the Figure 39

	x	y	z	r	p	y
left camera	0.25 [m]	-0.29 [m]	-0.09 [m]	-1.507 [rad]	0 [rad]	1.507 [rad]
Right Camera	0.25 [m]	0.29 [m]	-0.09 [m]	-1.507 [rad]	0 [rad]	1.507 [rad]

TABLE 5.9: Relative position and orientation between camera frame and body frame

With these parameters, the cameras in the uwsim simulation performance as the following figures

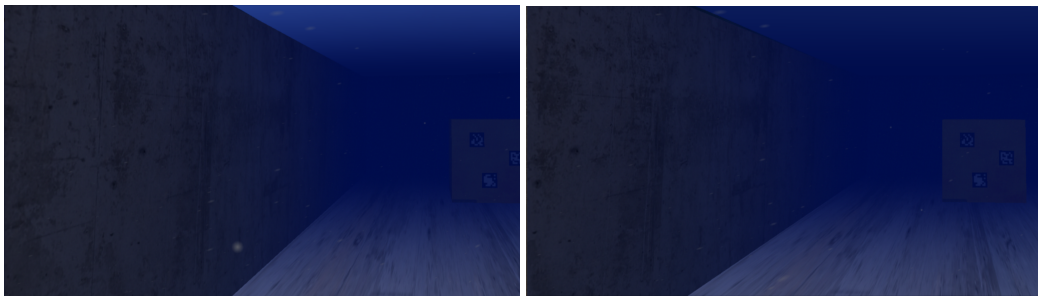


FIGURE 5.14: Camera Calibration of the Double Blueeyes Robot

5.6 Free Running Simulation scene

To simulate the test environment of MC-lab, The scene of uwsim is implemented as the following figure.

Length	Width	Depth
40[m]	6.5[m]	1.5 [m]

TABLE 5.10: Tank dimensions of MC-lab

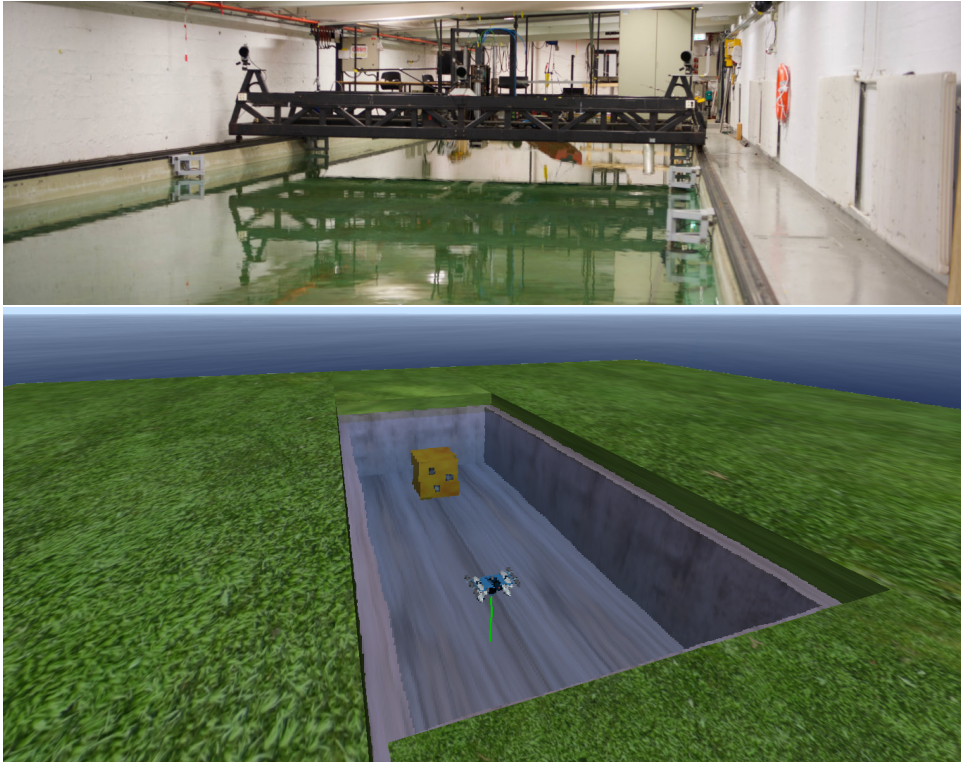


FIGURE 5.15: The MC-lab *marine cybernetics laboratory(mc-lab) 2021* in the real world and the virtual MC-lab scene

For we would like to put ArUco markers in the MC-lab. The big yellow box in the lab could be used and place it into the water. To simulate it in the uwsim the following model is built with blender, a cube with a side length of 1.5 m. Three ArUco markers with 0.15 m side length are attached on one side of cube.



FIGURE 5.16: The Yellow Box and markers in the real world and simulation

With these models built up, The scene of uwsim is implemented as following figure. The squares located at the bottom corners are the video out put of the virtual cameras on the ROV, which have been introduced in the previous section.

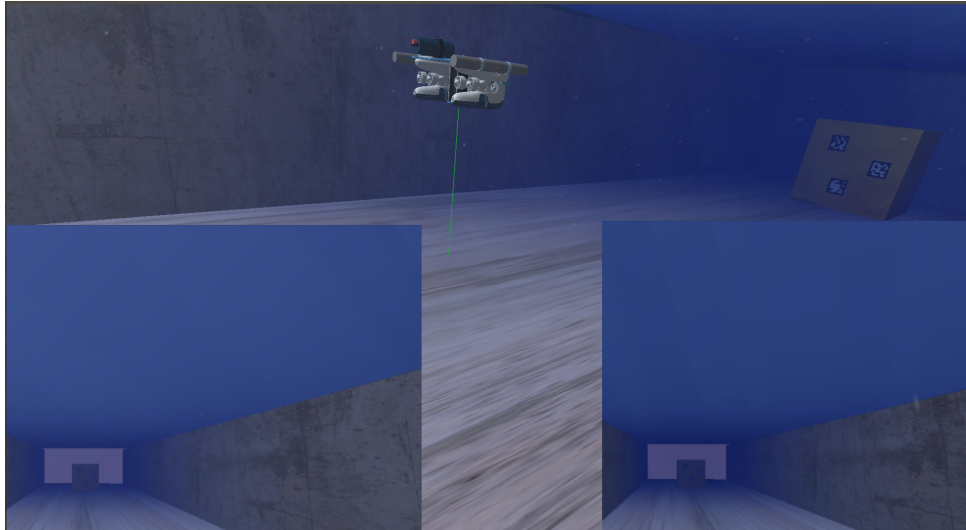


FIGURE 5.17: The simulation environment of Free Running test with ArUco SLAM

When the ROV get closer to the box, the camera could detect the ArUco markers on the box as following picture, just like what it did in the MC-lab. The camera parameters have been introduced in the camera calibration section.

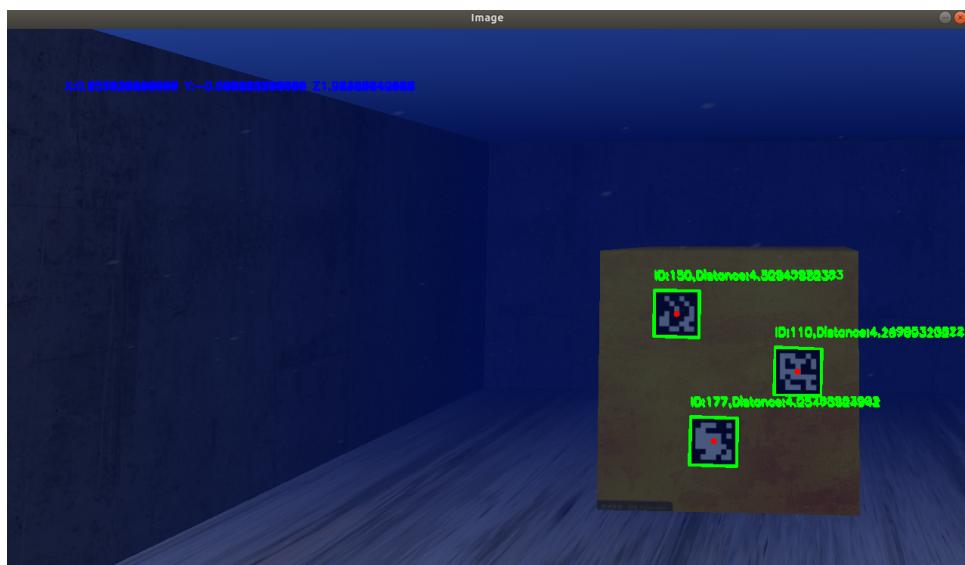


FIGURE 5.18: Front Camera detect the ArUco Markers

Chapter 6

ArUco Position System design

For our proposal is to find a generalized method of hydrodynamic parameter. Qualisys is not a common sensor for labs, but the every ROV has a camera. Thus, a visual positioning system could be applied to replace the Qualisys system in the Free Running test. Also, ArUco Slam could solve the problem that Qualisys could not record the whole process with limitation of the detection area. For time limitation, This system is tested under uwsim environment.

For the Qualisys system mainly provide the x and y position in the world frame during the free running test, So the ArUco Position system will also focus on these two directions.

For we have several ArUco markers, which are placed randomly on the yellow box, So the SLAM could be applied to find out where the markers are, and through the known markers to estimate the x,y position of ROV. The system is designed as with two parts in the frame of Luenberger observer.

- predict the states of ROV position, velocity and landmarks
- correct the states with ArUco markers distance measurement

6.1 Predict States

The states are made up by the position, velocity and landmarks. The states of position and velocity could be predicted through constant velocity model. the states of landmarks could be associate with the corresponding measurement through unique ID of ArUco marker.

6.1.1 Constant Velocity model predict position and velocity

For this system is designed to estimate the ROV model, which is unknown. So the constant velocity model could be a good alternative, which is not accuracy, But from the process of free running test, the ROV moves in constant velocity for most of the time. So that through the constant velocity model we could filter out the noisy and dead reckoning when there is no marker detected.

In this case the constant velocity model have six states, which are the position and velocity of surge, sway and heave. For we have controllers on depth and yaw, the heave and yaw are almost constant, roll and pitch is zero for most of the time. So the yaw is the only angle may change during the test, in this case we will set the yaw as the input instead of a state. With this information the discrete state space function of

constant velocity is written as the following equation.

$$\underbrace{\begin{bmatrix} x_k \\ y_k \\ z_k \\ \dot{x}_k \\ \dot{y}_k \\ \dot{z}_k \end{bmatrix}}_{X_k} = \underbrace{\begin{bmatrix} 1 & 0 & 0 & \Delta T \cos(\theta) & -\Delta T \sin(\theta) & 0 \\ 0 & 1 & 0 & \Delta T \sin(\theta) & \Delta T \cos(\theta) & 0 \\ 0 & 0 & 1 & 0 & 0 & \Delta T \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}}_{F_{k-1}} \underbrace{\begin{bmatrix} x_{k-1} \\ y_{k-1} \\ z_{k-1} \\ \dot{x}_{k-1} \\ \dot{y}_{k-1} \\ \dot{z}_{k-1} \end{bmatrix}}_{X_{k-1}} + \underbrace{\begin{bmatrix} \Delta T w_{x,k-1} \\ \Delta T w_{y,k-1} \\ \Delta T w_{z,k-1} \\ w_{x,k-1} \\ w_{y,k-1} \\ w_{z,k-1} \end{bmatrix}}_{W_{k-1}} \quad (6.1)$$

Where: ΔT is the time step between two iterations, θ is the yaw angle position of the ROV and $w_{i,K-1}$ is the white noise of the velocity states.

6.1.2 Predict state of landmarks

In the problem of SLAM, we will also put landmarks into states. For the states of landmarks in this case, It contains fours states for each: ID, position of x, y and z in the world frame. So the state space function is expressed as following equation.

$$\underbrace{\begin{bmatrix} ID_{k,1} \\ x_{k,1} \\ y_{k,1} \\ z_{k,1} \\ \vdots \\ ID_{k,i} \\ x_{k,i} \\ y_{k,i} \\ z_{k,i} \end{bmatrix}}_{X_k} = I \underbrace{\begin{bmatrix} ID_{k-1,1} \\ x_{k-1,1} \\ y_{k-1,1} \\ z_{k-1,1} \\ \vdots \\ ID_{k-1,i} \\ x_{k-1,i} \\ y_{k-1,i} \\ z_{k-1,i} \end{bmatrix}}_{X_{k-1}} + \underbrace{\begin{bmatrix} 0 \\ w_{x,k-1} \\ w_{y,k-1} \\ w_{z,k-1} \\ \vdots \\ 0 \\ w_{x,k-1} \\ w_{y,k-1} \\ w_{z,k-1} \end{bmatrix}}_{W_{k-1}} \quad (6.2)$$

6.2 Update the position with measurement

For each iteration, we may get two or three measurements from different landmarks. The first step is to compare the measurement ID with the landmark states, If the measurement is a new landmark, we will add it into the states:

$$\underbrace{\begin{bmatrix} ID_{k,new} \\ x_{k,new} \\ y_{k,new} \\ z_{k,new} \end{bmatrix}}_{X_k} = \underbrace{\begin{bmatrix} ID_{k,measure} \\ x_{k,measure} \\ y_{k,measure} \\ z_{k,measure} \end{bmatrix}}_{Measurement} + \underbrace{\begin{bmatrix} 0 \\ x_k \\ y_k \\ z_k \end{bmatrix}}_{states} \quad (6.3)$$

If the measurement ID is exist in the landmark states, they will be used to update the states. With the number of measurement, The H matrix is constructed as following

equation

$$\underbrace{\begin{bmatrix} ID_{k,1} \\ x_{k,1} \\ y_{k,1} \\ z_{k,1} \\ \vdots \\ ID_{k,i} \\ x_{k,i} \\ y_{k,i} \\ z_{k,i} \end{bmatrix}}_{Z_k} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 \end{bmatrix} \underbrace{I_{4n \times 4n}}_{H_k} \underbrace{\begin{bmatrix} x_{k-1} \\ y_{k-1} \\ z_{k-1} \\ \dot{x}_{k-1} \\ \dot{y}_{k-1} \\ \dot{z}_{k-1} \\ ID_{k,1} \\ x_{k,1} \\ y_{k,1} \\ z_{k,1} \\ \vdots \\ ID_{k,i} \\ x_{k,i} \\ y_{k,i} \\ z_{k,i} \end{bmatrix}}_{X_k} \quad (6.4)$$

In this equation we could predict the measurement of landmarks, which is the output of the state space function. So in the frame of Luenberger observer, the states could be updated with the following equations.

$$\bar{X}_k = X_k + L(Z_k - Z_{measure}) \quad (6.5)$$

Where L is designed as the following equation:

$$L = \underbrace{\begin{bmatrix} 0 & L_1 & 0 & 0 & \cdots & 0 & L_1 & 0 & 0 \\ 0 & 0 & L_1 & 0 & \cdots & 0 & 0 & L_1 & 0 \\ 0 & 0 & 0 & L_1 & \cdots & 0 & 0 & 0 & L_1 \\ 0 & L_2 & 0 & 0 & \cdots & 0 & L_2 & 0 & 0 \\ 0 & 0 & L_2 & 0 & \cdots & 0 & 0 & L_2 & 0 \\ 0 & 0 & 0 & L_2 & \cdots & 0 & 0 & 0 & L_2 \end{bmatrix}}_{\substack{I_{4n \times 4n} * L_3 \\ 6+4*n, 4*n}} \quad (6.6)$$

Where the parameters are set as the following table

L_1	L_2	L_3
$0.3/n$	0.001	0.1

TABLE 6.1: The parameters of L matrix

This system is implemented will python2 on the platform of ROS. And its script is attached in the attachment.

6.3 Performance of ArUco Position System

To test the performance of the ArUco Position System, we would like to run it in the shape of square, which will show the performance on the direction of surge and sway.

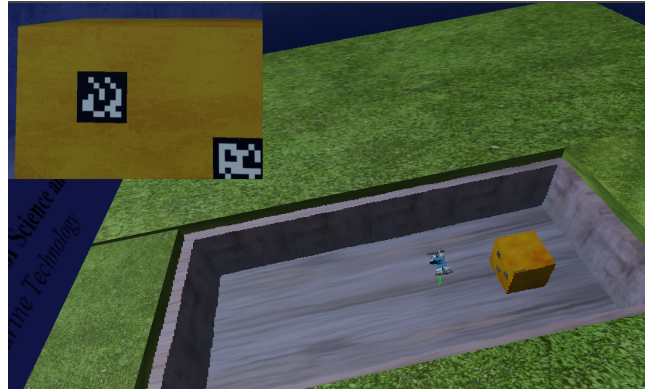


FIGURE 6.1: Square test with ArUco position system in the UWsim with camera stream in the top left corner

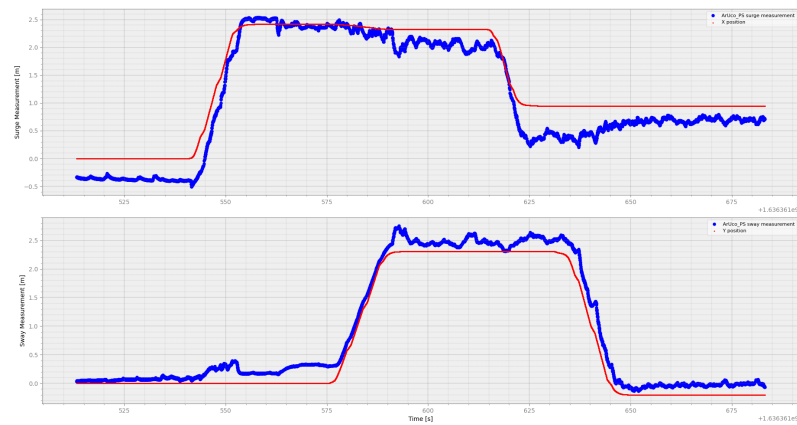


FIGURE 6.2: The estimated position on surge and sway compared with ground truth position

The recorded data is attached in the attachment with the file name of 'ArUcoPS_square'. From the result of the square test, we could find that estimated position have some bias and noisy on both direction, but we could find that the result follows the position while moving on surge and sway. And we use this system for Free Running test. So this system is good enough for the test. The Free Running test simulation on surge and sway will be shown in the section of simulation.

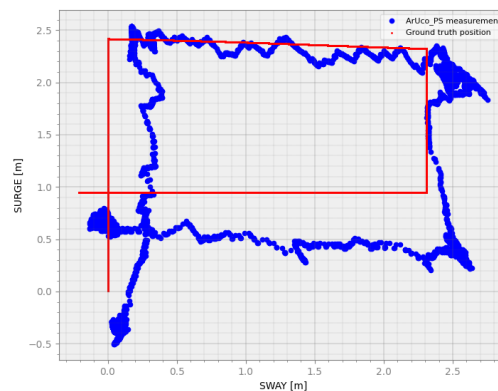


FIGURE 6.3: Estimated position with ArUco position system vs Ground truth position

Chapter 7

GNC System Design

The GNC system of ROV motion control is mainly adopted from the Dynamic Positioning system of a ship. It is mainly divided into 3 parts : Guidance system ,Navigation system and Control system. The blocks and connections of the system are shown as Figure 7.1.

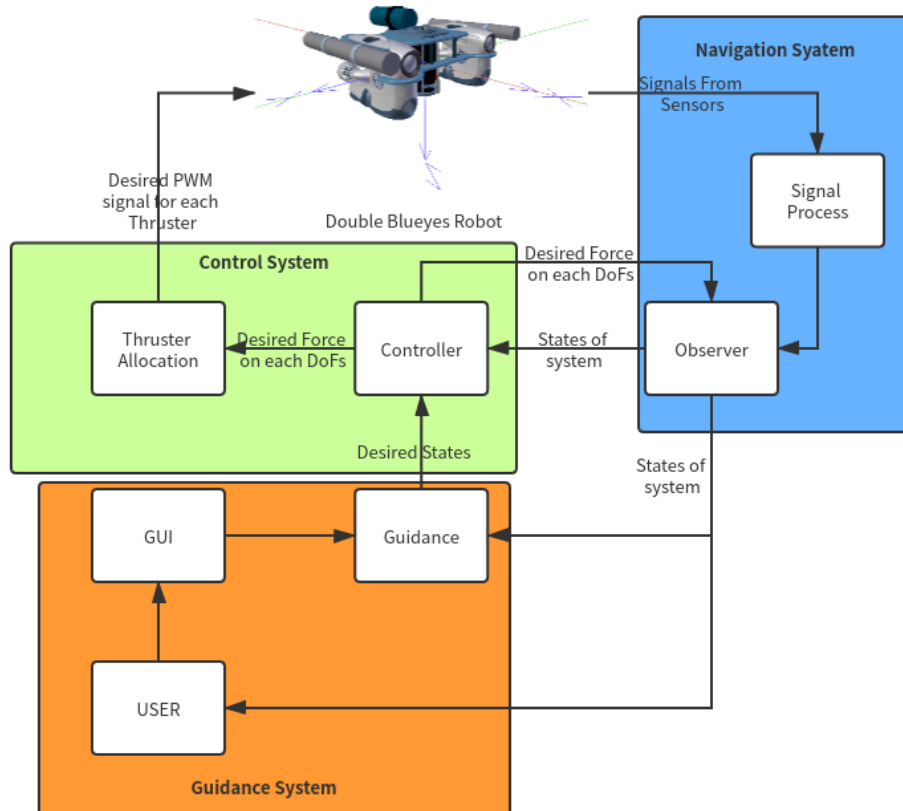


FIGURE 7.1: GNC system of Double Blueyes Robot

Control System

The Control system is made up by Controller and Thruster allocation. The controller could calculate the desired force on each DoFs with the current states and desired states, The thruster allocation will allocate the desired force for each thruster and give out corresponding PWM signals.

Navigation System

The Navigation system is made up by the signal process block and observer. The signal process block will receive the raw signals from sensors, transform them from

mounted frame into the body-fixed frame of ROV, and send these signals to the observer. The observer will process the signals and the desired force to estimate the current state of the ROV.

Guidance System

The Guidance system could be divided in three parts: GUI, Guidance and User. User will set the way points of the ROV on the GUI windows. with the desired way points and the current states, the guidance system will give out the route of ROV for better motion performance.

In this section the GNC system will be built up. Thus in the next contexts each of these nodes will be built up both in theory and in programming.

7.1 Thruster Allocation

Thruster allocation is a inverse process of the thruster dynamic. So the same matrix of K and T in the section 5.3 will be used here

$$\mathbf{u}_d = \mathbf{K}^{-1} \mathbf{T}^\dagger \mathbf{F}_{general} \quad (7.1)$$

Where:

$$\mathbf{u}_d = [\mathbf{u}_1, \mathbf{u}_2, \mathbf{u}_3, \mathbf{u}_4, \mathbf{u}_5, \mathbf{u}_6]^T \quad (7.2)$$

\mathbf{u}_d is a vector of PWM signal for each thruster

$$\mathbf{F}_{general} = [\text{surge}_{force}, \text{sway}_{force}, \text{heave}_{force}, \text{roll}_{moment}, \text{pitch}_{moment}, \text{yaw}_{moment}]^T \quad (7.3)$$

$\mathbf{F}_{general}$ is the desired force on each DoFs, which is given out by the controller. For T matrix is not invertible in this case, The pseudo inverse of T matrix: \mathbf{T}^\dagger is applied here.

7.2 Controller

with the feedback from the navigation system, A PID controller is implemented here. The inputs of 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 :

$$e_{NED} = P_{desired} - P_{obs} \quad (7.4)$$

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:

$$e_{body} = J(\eta)^{-1} * e_{NED} \quad (7.5)$$

where $J(\eta)$ is the six-DoFs rotation matrix which have been introduce in the Section 2.5. In this way the controller is designed as following equation:

$$\mathbf{F}_{general} = K_p e_{body} + K_i \int e_{body} dt + K_d \frac{de_{body}}{dt}$$

(7.6)

$F_{general}$:Desird Force on each DoFs
 e_{body} :error value in body-fixed frame
 K_p :proportional gain
 K_i :integral gain
 K_d :derivative gain

After tuning the parameters are chosen as following

DoF	K_p	K_i	K_d
Surge	1.5	0.0	1.0
Sway	1.0	0.0	1.0
Heave	1.0	0.0	1.0
Roll	3.0	2.0	0.0
Yaw	0.6	0.0	1.0

TABLE 7.1: Controller Parameters

For test the performance of the PID controller, the pose from dynamic model will be used as feedback directly. The result is shown as following

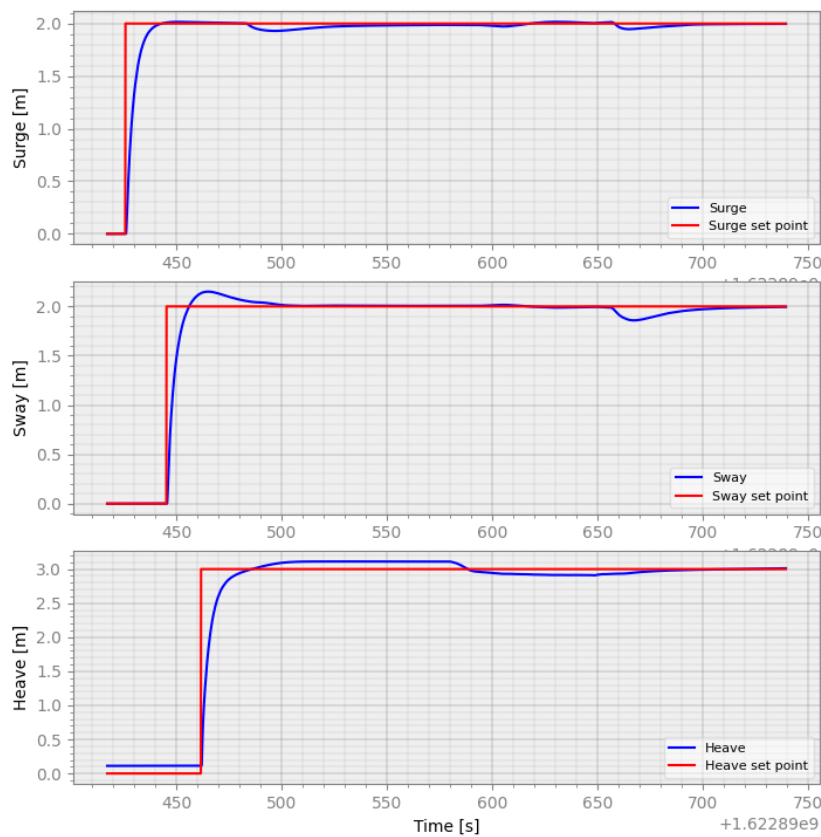


FIGURE 7.2: Controller performance for position

From the performance of the PID controller =, we could find that with these set of parameters, the Sway have a little bit overshooting and some steady error on heave. For it is not controllable on pitch direction, the restoring force will help the vehicle keep pitch at zero degree. So the figure will only include the performance on roll and yaw direction.

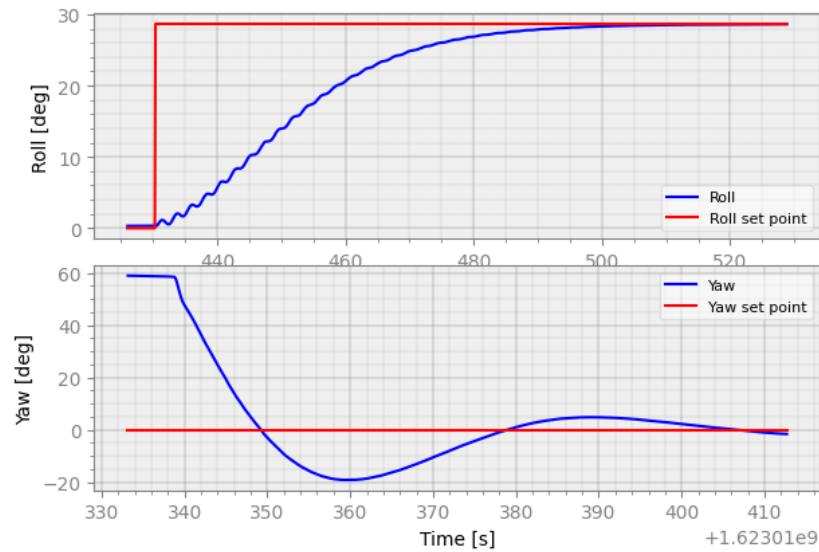


FIGURE 7.3: Controller Performance for orientation

The roll direction is tuned more stable but react slowly . For the roll direction is coupled with heave, there are still a little oscillation at beginning. For the Yaw direction it react fast with some overshooting. The reference model will applied later, which will cancel overshoot on some extend.

7.3 Navigation

The Observer is the most important For the GNC system,which will provide the current state for the ROV. Thus an accurate observer will provide better performance for not only the navigation system, but also Control system and Guidance system. For this ROV the sensor of APS, IMU and Pressure sensor is being used.For the IMU could provide accelerates on surge,sway and heave, Thus we could find the linear velocity in the following way:

$$V_n^{measured} = V_{n-1}^{estimated} + a_n^{imu} * h \quad (7.7)$$

where: the dynamic model of ROV have been implemented,An Model-based Extended kalman filter is applied as equations in the section 2.

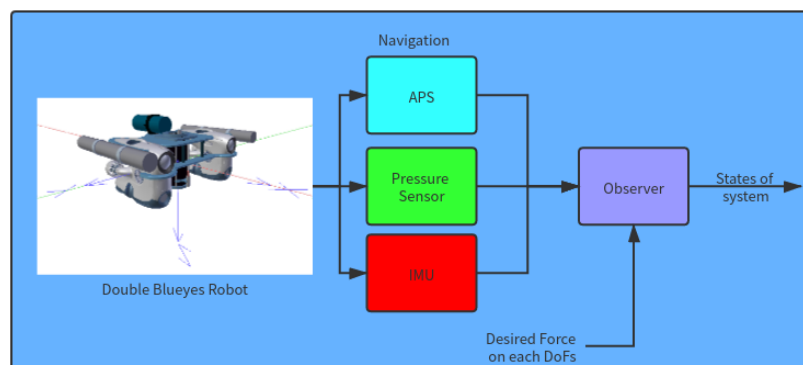


FIGURE 7.4: Signal Flow of Navigation system

For realization the Observer. Following parameters are chosen as following.

States	Measurement Source	R	Q
Surge,Sway	APS	0.5	1e-8
Heave	Pressure	0.017	1e-10
Roll,Pitch,Yaw	IMU	1e-3	1e-6
linear velocity	IMU	0.308	1e-10
Angular Velocity	IMU	3.08e-5	1e-10
Bias	N/A	N/A	1e-10

TABLE 7.2: Parameters For Extended Kalman Filter

With these set of the parameters, The observer performance is shown as following plots

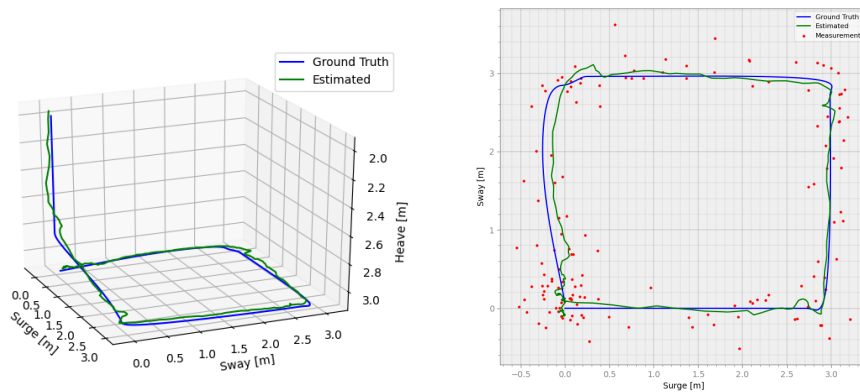


FIGURE 7.5: Observer Performance Overview

e

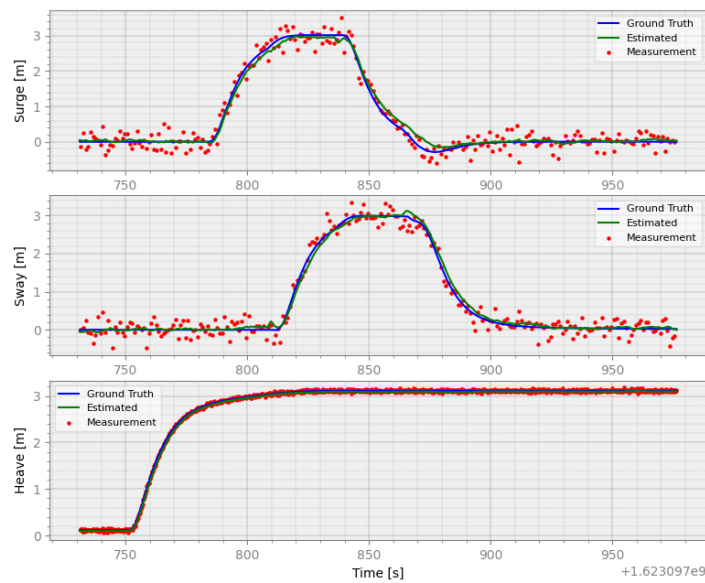


FIGURE 7.6: Observer performance on positions

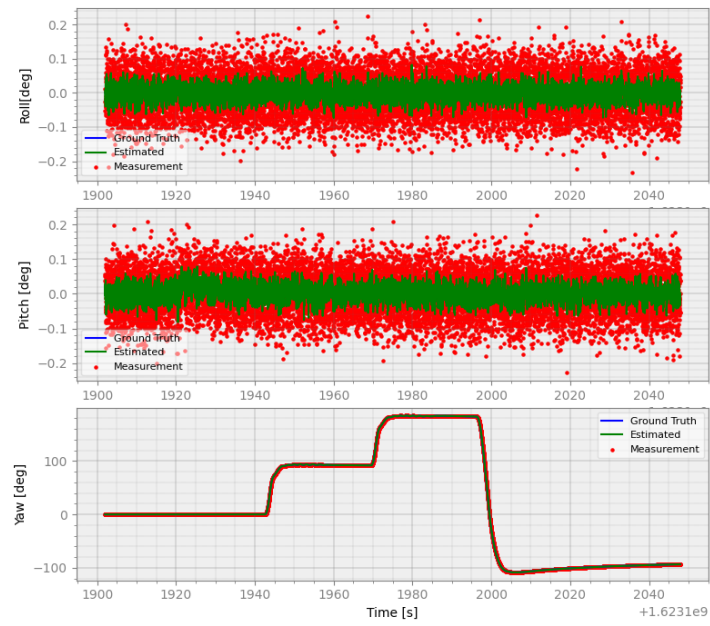


FIGURE 7.7: Observer performance on orientation

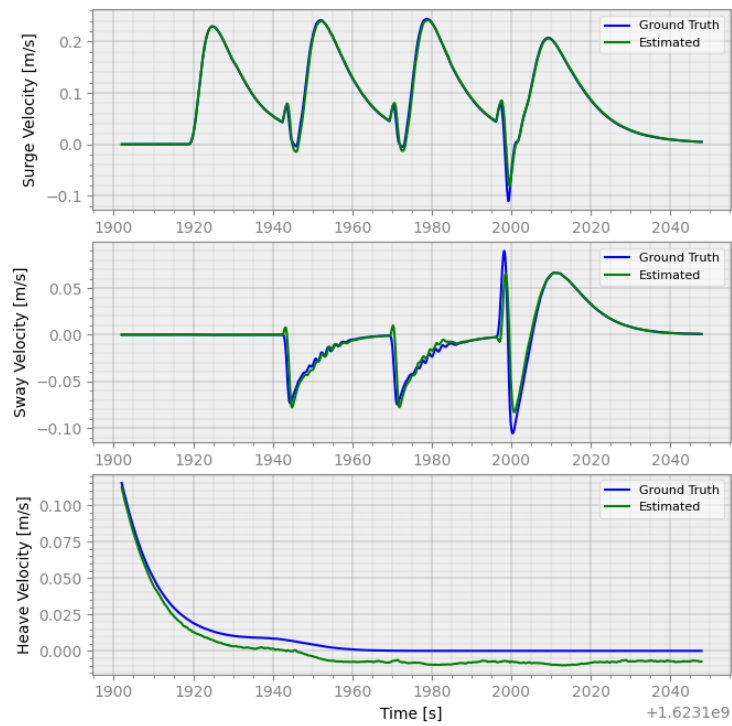


FIGURE 7.8: Observer performance on Linear velocity

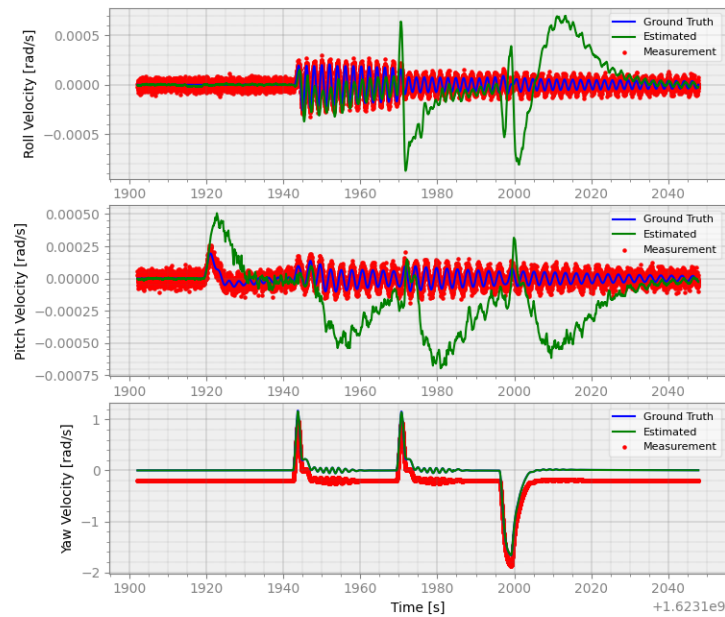


FIGURE 7.9: Observer performance on Rotational velocity

From the performance of the observer we could find that the Kalman filter works very good with this set of parameter, which could not only filter out the noise of the measurements but also could track the ground truth very well. For the angular velocities on the roll and pitch directions could not track very well, but its error is not big. On the other hand, the ROV usually don't have much motions on roll and pitch, so it will not influence much for the GNC system.

7.4 Guidance System

In this thesis, the guidance system is made up by three parts: GUI, Filter-Based reference model, and LOS. The signal flow is shown as following

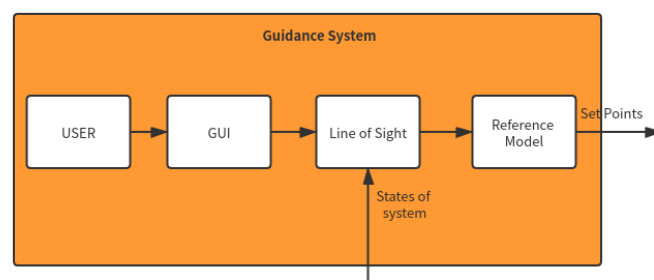


FIGURE 7.10: Signal Flow of Guidance system

7.4.1 GUI

For better operation for users a front end GUI is implemented here. The interface window is designed as following figure.

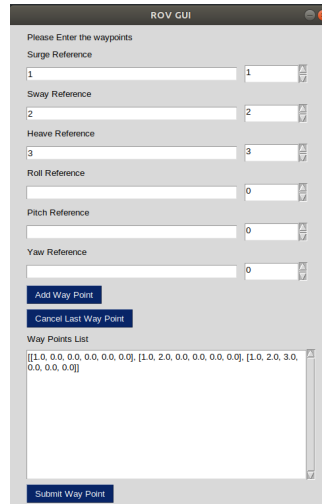


FIGURE 7.11: GUI of GNC system

The user could set the Way points in for different DoFs of ROV, and click 'Add Way Point' button, The point will show up in the list area. If the user want to change the point ,He could click 'Cancel last way point' button to change it. When way point list settle down,please click 'Submit Way Point', the ROV will start the mission. When the vehicle finish the mission, The terminal will print 'Finish the mission'

7.4.2 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.

$$\frac{P_{ref}(s)}{P_{desired}(s)} = \frac{\omega^2}{s^2 + 2\delta\omega s + \omega^2} \quad (7.8)$$

For this thesis the parameters are chosen as: $\delta = 1, \omega = 1.5$ Its performance is shown as following figure

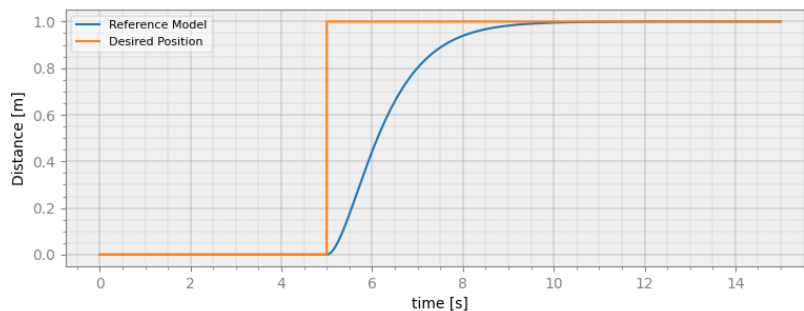


FIGURE 7.12: Filter Based Reference Model

7.4.3 2D-LOS

For the Double Blueyes ROV is not controllable on pitch direction. Thus the 2D LOS(Line of Sight) method is chosen to track lines between way points. The scheme is divided into horizontal motion and depth motion.they will be controlled separately. The theory of LOS have been introduced in the previous section. Thus when

there is a way point $[x_i, y_i, z_i]$. The system will dive to the desired depth z_i . Then the apply 2D-LOS at the plant of $z = z_i$. For in some case there may be a big error between the initial heading and the heading generated by LOS, which will cause big oscillation of heading. So the ROV will turn to the desired heading before move forward. The produce is shown as following.

1. Dive to desired depth
2. Turn to desired heading at initial point.
3. Start LOS, move to the way point.
4. When the vehicle achieve the way point within the error area r , switch to the next way point, repeat the previous steps.

The performance of the system is shown as following plots. The way points is set as $[(3,0,3),(3,3,3),(0,3,3),(0,0,3)]$. The initial position is $(0,0,0)$. Thus the ROV will get to $(0,0,3)$ first and start to follow the squat later.

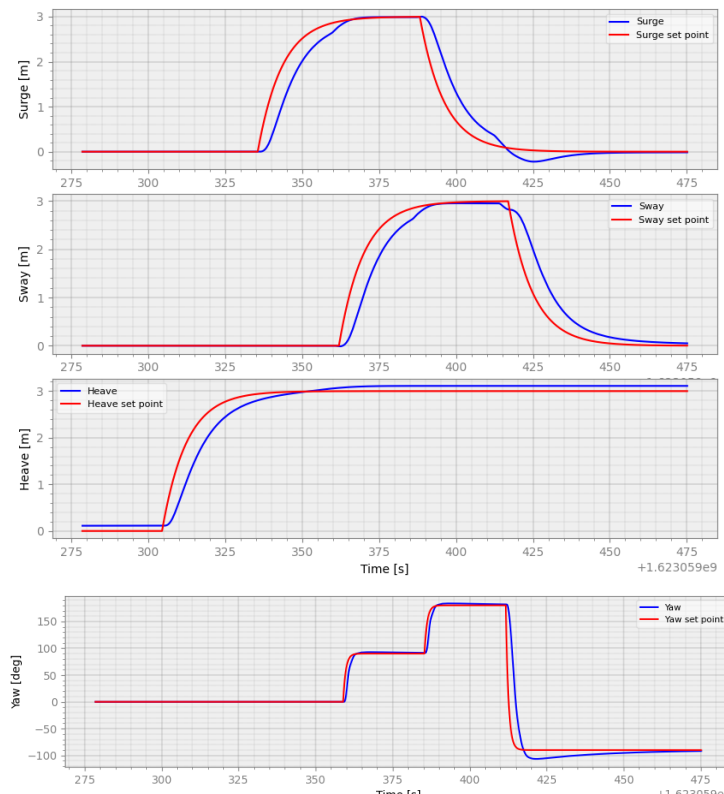


FIGURE 7.13: Guidance Performance on each directions

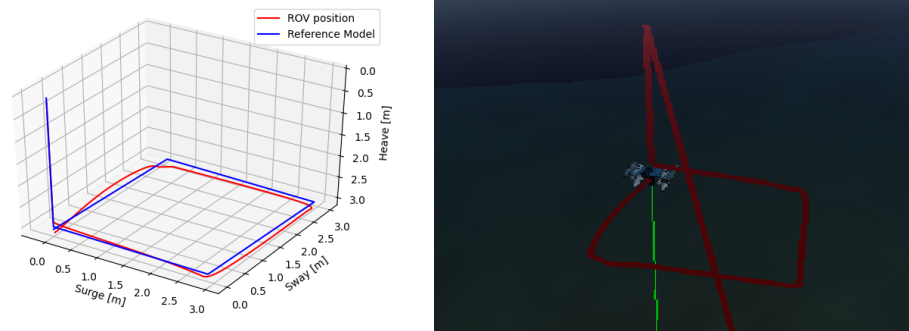


FIGURE 7.14: Overview of the Guidance Performance

with the help of reference model and the guidance system, the ROV motion performance better. After the GNC system built up in this section we will have an overall simulation test in the clam water and wave environment to achieve the lawn motion.

Chapter 8

Simulations

In this section, we will have three set of simulations.

- Free Running Test With ArUco position system
- Test GNC in the clam water
- Test GNC in the wave

For the first simulation, we will replace the Qualisys position system with ArUco positioning system I built up in the Chapter 6 to prove that it is a good alternative in the free running test. After have another two simulation to test the GNC system. In the previous chapter the Control system, navigation system and Guidance system have been test separately. To test the whole system and its stability. The last two sets of simulations will be tested.

8.1 Free Running Test With ArUco position system

For the time limitation, we have not done the Free running test with ArUco Positioning system in the MC-Lab. For the fact that we have already got the parameters of ROV, we will do the test in the simulation environment. we will use the parameters we got as the ground truth, set it to the dynamic model, and use ArUco Positioning system to estimate hydrodynamic parameters. Through the comparison between predefined parameter and estimated parameters, we could get the accuracy of this method. For the Qualisys system only provide the position on x and y , The simulation only include the surge test and sway test. For the surge test and sway test are almost the same process with each other. I will only work on the test of surge direction.

For the surge direction, we will simulate the ROV with the same set as the free running test in the MC-lab. Give the following set of force on surge direction.

Force[N]	4	8	12	16	20
Velocity [m/s] from ArUco	0.062	0.109	0.188	0.248	0.306
Velocity [m/s] ground truth	0.057	0.115	0.169	0.223	0.262

TABLE 8.1: The relationship between Thruster force and velocity

The relation between position and thruster force is shown as following plots

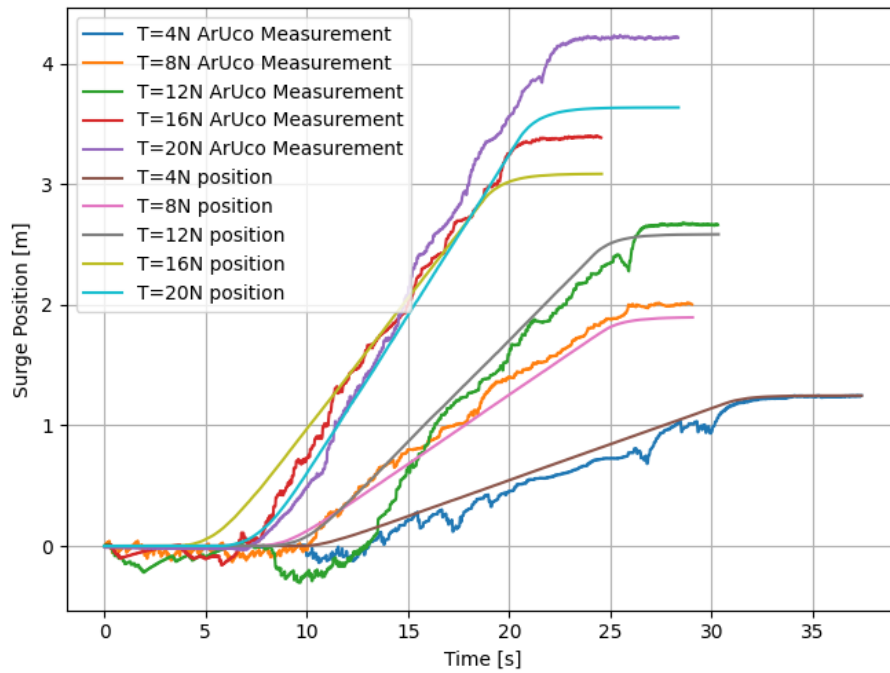


FIGURE 8.1: The surge Free Running simulation result with different thruster force

Where the noisy curve representing the position measured with ArUco positioning system and the smoothed curve representing the ground truth of the motion. From the test result, we could find that the bias of position increase with the velocity. but the Curve slope follows the ground truth and the average velocity is calculated as the Table 8.1. With these data, the damping was estimated as the following plot and compared with the predefined damping force.

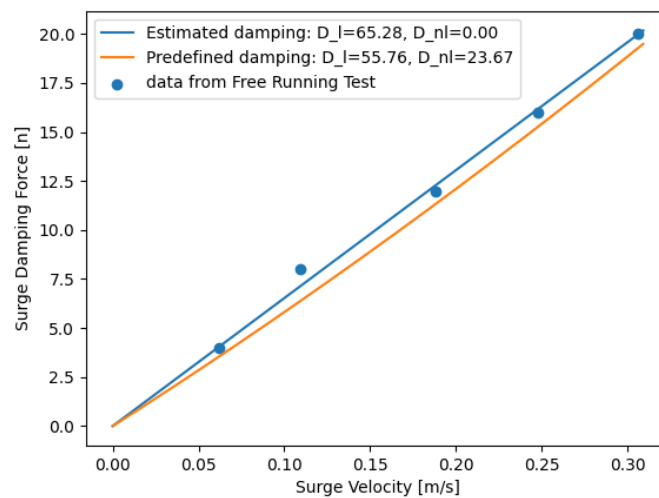


FIGURE 8.2: Surge Damping Estimation with Free Running Simulation

To estimate the added mass, the second set of simulation is used with NAGA-II algorithm. the data is selected from 8.2s to 25s, where the thruster start and end working. So the data during this period include the speed-up process and constant velocity process, it will be used to estimate the added mass. The cost function is defined as the following equation:

$$F = \text{average}(Pos_m - Pos_e(\text{added} - \text{mass}, D_l = 65.28, D_{nl} = 0, \tau = 8)) \quad (8.1)$$

Where Pos_m is the surge motion measured with ArUco positioning system and Pos_e is the position estimated by the model of surge direction. the script is attached in the attachment with name of 'Addedmassopt.py'. The result of the optimization is 53.03.

$$Surge_{\text{addedmass}} = \text{result} - \text{mass} = 53.02 - 30 = 23.03\text{kg} \quad (8.2)$$

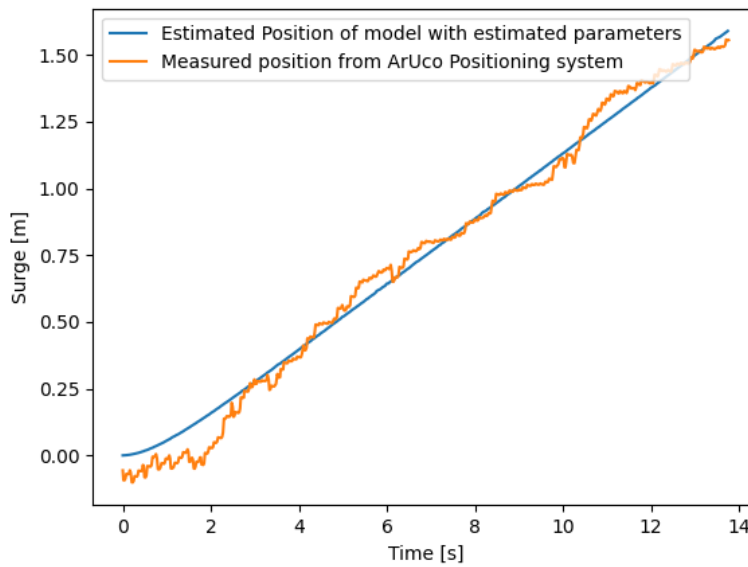


FIGURE 8.3: Caption

Parameters	Added mass	Linear Damping	Nonlinear Damping
Predefined	21.20	55.76	23.67
Estimated	23.03	65.28	0

TABLE 8.2: Comparison between predefined parameters and estimated parameters

From the result, we could find that the Free running test with ArUco positioning system could estimate the parameters with a good result

8.2 Test lawn motion in the clam water

In the previous section, The GNC system was tested separately, and all of them performance well. So in this section we will test the whole system together. In this test, the controller will use the feedback directly from the observer (EKF) and

the environment is set as clam water. To test the guidance, the following way points will be used

Way Points	Surge	Sway	Heave	Unit
1	6	0	3	m
2	6	3	3	m
3	0	3	3	m
4	0	6	3	m
5	6	6	3	m
6	6	9	3	m
7	0	9	3	m

TABLE 8.3: Way Points List

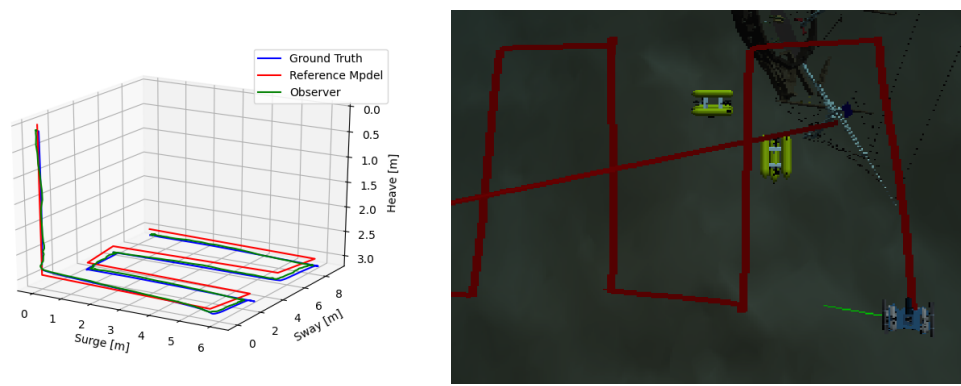


FIGURE 8.4: Overview of Lawn motion performance

From the results we could find that the GNC system works very well in the clam water situation. Also for the reference model in the plot is not straight, because the destination range was set as 0.2m , the way point will be switched while getting into the range.

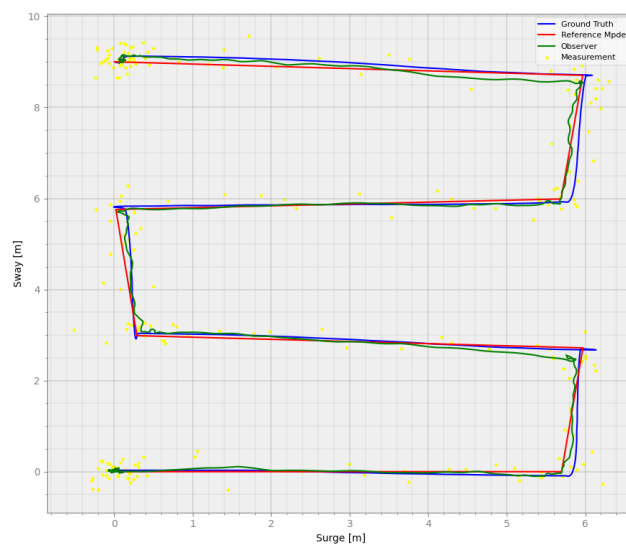


FIGURE 8.5: XY plot for lawn motion

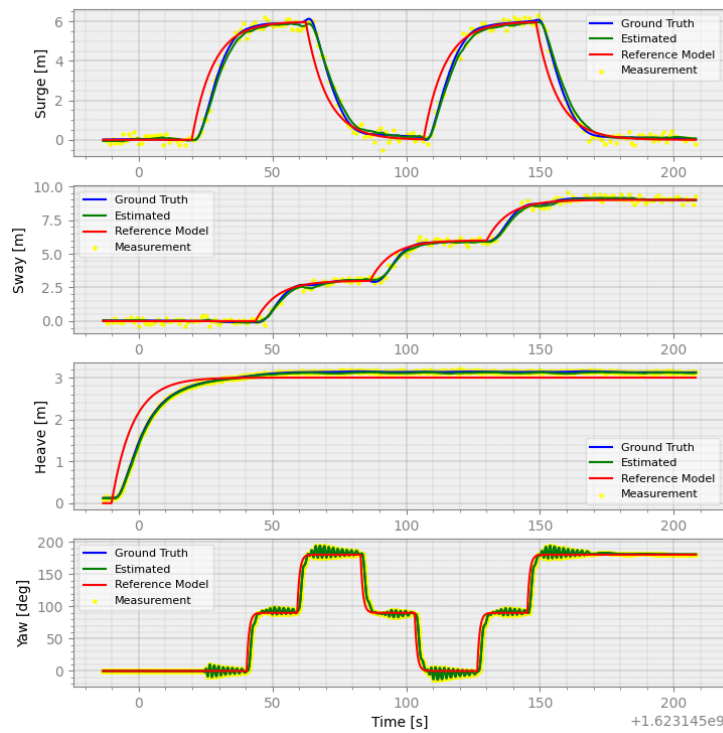


FIGURE 8.6: Lawn motion performance for each directions

8.3 Test GNC in the wave

For test the GNC system in the wave. The wave dynamic model will be included in this test. The following three set of wave parameters will be used, For comparison the way points in the last test will also be used here. The wave direction was set as Surge in the world frame.

Set	H_s	T_z
Set	4.1 m	8.7 sec

TABLE 8.4: Wave Force Parameters

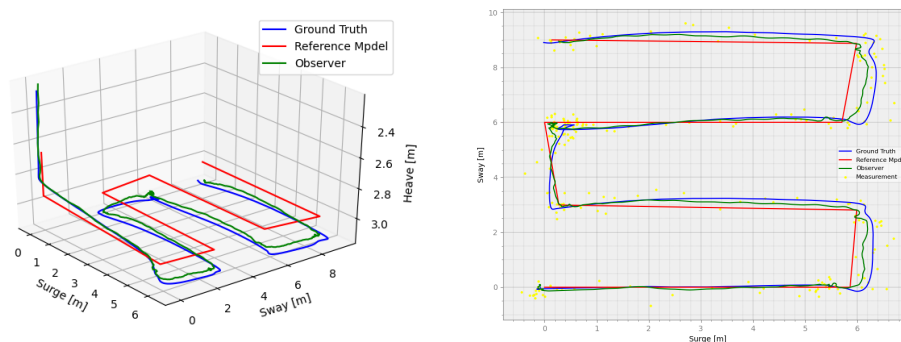


FIGURE 8.7: Overview performance in wave

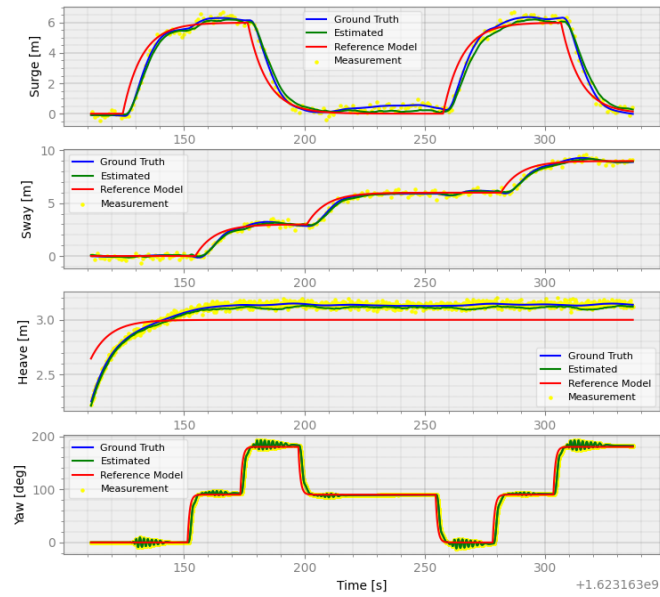


FIGURE 8.8: GNC performance in wave

From the test we could find that the controller performance worse than in clam water, which makes the ROV takes much more time to get to the way point. when the ROV moving on y direction of world frame, the wave will generate the force from side, which will cause bias on sway, with the help of sway controller, It could get to the waypoints. So the GNC system we built up could work well under 4.1 m significant height wave.

Chapter 9

Discussion and Conclusion

The work of this thesis is focus on following three parts.

- Double Blueyes System Identification
- Double Blueyes Simulation Environment
- GNC system of Double Blueyes

With these work, when we change the device in the double blueyes, we will use the Double Blueyes System Identification system to estimate the dynamic parameters. After we got the parameters, we will use them in the simulation environment and the GNC system to implement the HIL (Hardware-in-the-loop) tests, which will help us to develop the software system of Double Blueyes easier. In this thesis, we finished this develops work for initial double blueye and proved its validation. Thus, when the device change, it will be a simple and fast work to repeat the tests to estimate parameters, and insert them into the rest of two parts to get a stable GNC system and complete HIL test.

9.1 Double Blueyes System Identification

In this part of work we built up a process of easy parameter identification for double blueyes robot, which is a combination of empirical method, free running test and decay test. It is described in the Chapter 3. After the test in the MC-lab for double blueye robot and compared its result with towing test results in the chapter 4 we could find that the system performance well, we used free running test to measure parameters on surge, sway, heave and yaw, decay test for roll and pitch. The main error in this process is coming from the inaccuracy of the thruster force, So it is better to measure the force of each SDK parameters directly instead of using a linear model from max thruster force. For time limitation, this part is reserved for further work. During the experiment in the MC-lab, we could find out that the position measurement from Qualisys is not a very good solution for the following reasons

- hard to record the whole process of the test and always comes with a lot of break points
- Qualisys is not common in labs
- Qualisys is not an onboard sensor, we need another computer to record and process the data

To make the test work easier, we would like to use the ArUco positioning system to replace the Qualisys. For the hardware part, it will place the ArUco markers in

the water and detect them with front camera to estimate the position. For the software part, we will place the markers randomly, So It is designed as a combination of SLAM and Luenberger observer, which could record the position of markers as landmark and estimate the ROV position with landmarks relative positions. This system is implemented in the chapter 6 with python and OpenCV library. Comparing with Qualisys, it has the following advantages.

- Most of ROV have a camera onboard, the markers are easy to print out with paper and get it waterproofed. So the test environment could be extended to any clear clam water.
- It could record the position from start to end while the markers are visible.
- Could finish the test with one computer.

To find out whether it is a good alternative, I simulated the free running test under the scene of MC-lab I created in the chapter 5. This simulation process and result is in the chapter 8. From the result, we could find that it have a good performance in the simulation.

9.2 Double Blueeyes Simulation Environment

With the parameters of Double Blueeye Robot settled down. We built up a visualized simulation environment base on the UWsim platform in the chapter 5. To build up the environment, the following work have been done.

- Built up a 3d model of Double Blueeye, and urdf file to define the coordinates in ROS.
- Built up dynamic model of Double Blueeye based on the uwsim package code and the dynamic parameters from previous system
- built up the virtual sensors and uwsim scene and corresponding xml files to plug them into the UWsim and ROS.

With this system implemented, we could do many simulations and test for GNC system. when the device or sensors added or remove from the Double Blueeyes, It will be an easy task to replace the parameters and model.

9.3 GNC system of Double Blueeyes

After the previous two part of systems established, A GNC system was built up in the chapter 7 for Double Blueeyes the following works are finished in this thesis:

- Thruster Allocation
- Guidance system : Line of sight and filter based reference model
- Navigation system: Model based Extended Kalman Filter
- Control system: 5 Dof PID controller

In the Chapter 7 these systems are tested separately, which performance well in the simulations. To test the performance of the whole GNC system, Two set of simulations are tested. From the result, we could find the GNC system is good enough to work under both clam water and wave situation.

9.4 Further work

For the time limitation, There are still many ideas have not been implemented. They will be reserved for further work.

- Run the Free Running test with ArUco Position system in the MC-lab.
- Implement an automatic system to process the data of Free Running test.
- Implement a model based controller instead of PID controller.
- Implement an auto-tuning system for controller and observer system

With these works done, The Double Blueeyes may could automatically build up a robust GNC system when add or remove devices or sensors for itself.

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