

DETERMINATION OF OPTIMUM  
PROPORTIONAL-INTEGRAL-DERIVATIVE (PID) CONTROLLER  
GAIN VALUES FOR  
AUTONOMOUS UNDERWATER VEHICLE (AUV)

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MAY 2015

**Determination of  
Optimum Proportional-Integral-Derivative (PID) Controller Gain Values for  
Autonomous Underwater Vehicle (AUV)**

by

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16877

Dissertation submitted in partial fulfillment of  
the requirements for the  
Bachelor of Engineering (Hons)  
(Mechanical)

MAY 2015

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**CERTIFICATION OF APPROVAL**

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Approved by,

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TRONOH, PERAK

May 2015

## **CERTIFICATION OF ORIGINALITY**

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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(GUNA RAMASAMY)

## ABSTRACT

In this paper, the author has developed a Simulink model for an Autonomous Underwater Vehicle (AUV) so that its displacement in underwater can be simulated. Apart from that, a Proportional-Integral-Derivative (PID) controller is also designed to ensure the model achieves the desired displacement target.

AUV is a programmable robotic vehicle that can drive, glide and drift in the ocean. This project is undertaken because the AUV model modeled by previous student is not equipped with controller. Besides, many of the AUVs in the market are based on linear equations. By using non-linear equations of motion as the one being used in this project, the motion of the AUV can be represented more accurately. The data used for the AUV simulation is based on available data and the response of the AUV is measured when it is in normal condition and environment only.

In the first phase of this project, the displacement behaviors of the AUV model when subjected to various conditions are investigated. The conditions chosen to be investigated are hydrodynamic Coriolis, added mass and damping. Initially, the author planned to design the PID controller by using MATLAB's System Identification Tool and PID Tuner. However, it is later decided that developing the model using Simulink is easier and allows the author to refine the gains better. Thus, the second phase of the project deals with the Simulink model development as well as using trial and error method to determine the optimum gain values.

The gain values obtained are increased and reduced by 5% respectively to investigate the effect of each gains towards the characteristics of the model such as rise time, settling time, steady-state error and overshoot/undershoot.

## **ACKNOWLEDGEMENTS**

Firstly, I would like to express my sincere gratitude to my supervisor Dr. Setyamartana Parman for the continuous support of my Final Year Project (FYP) and for his patience, motivation and immense knowledge. His guidance helped me in all the time of research and writing of this paper. I could not have imagined having a better supervisor for my FYP.

Besides my supervisor, I would like to thank my family: my parents and my sisters for supporting me mentally throughout completing this paper. Apart from that, I want to express my heartfelt gratitude to my friends for giving me useful inputs, which I used to improve the accuracy of the AUV model simulation

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## ABBREVIATIONS AND NOMENCLATURES

AUV	Autonomous Underwater Vehicle
FYP	Final Year Project
PID	Proportional-Integral-Derivative
CFD	Computational Fluid Dynamics
$M_{RB}$	Rigid-Body Mass Matrix
$C_{RB}$	Rigid-Body Coriolis Matrix
$M_A$	Added Mass Matrix
$C_A$	Hydrodynamic Coriolis Matrix
$D_l$	Linear Damping Matrix
$D_{nl}$	Non-linear Damping Matrix
$D_u$	Linear Damping with Forward Speed Matrix
$v$	Velocity
$\dot{v}$	Acceleration

# **CHAPTER 1**

## **INTRODUCTION**

### **1. INTRODUCTION**

In this chapter, the background, problem statement, objectives and scope of study of this project will be briefly discussed.

#### **1.1 Background**

AUVs are robotic vehicles that can move through the ocean without being controlled by human in real time. The AUVs can drive, drift or glide through the ocean based on the design of the AUV itself [1]. The AUV is also commonly known as unmanned underwater vehicles. It is used to achieve various objectives such as allowing scientists to conduct experiments from ship while the AUV collects data elsewhere on the surface or in the deep ocean. It is also used to map submerged rocks and wrecks that may pose a hazard to navigation for commercial and recreational vessels. Figure 1 in the following page shows a type of commercial AUV by Teledyne Gavia.

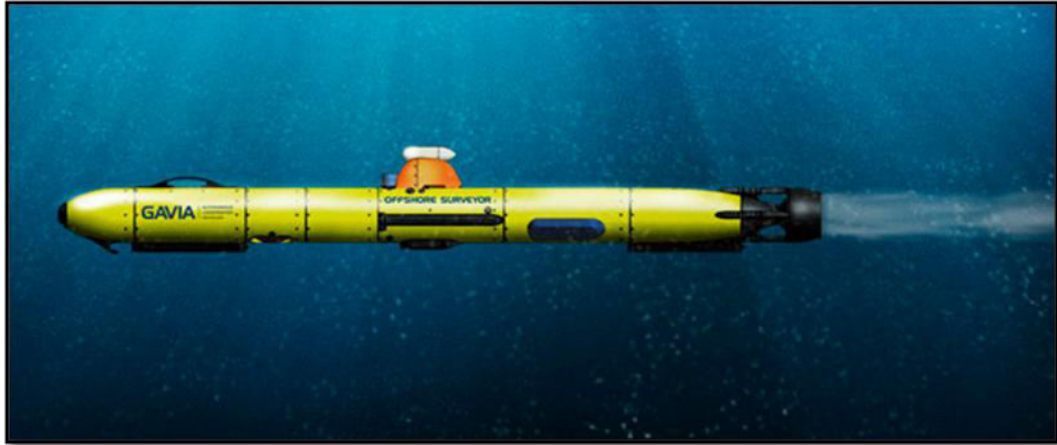


FIGURE 1. Example of an AUV

In one of the recent studies [2], it is stated that various oceanographic sensors or sonar systems such as side scan sonar, Conductivity-Temperature-Depth (CTD) sensors, GPS-aided Inertial Navigation Systems (INS) and Acoustic Doppler Current Profiler (ADCP) can be equipped for the AUV. For scientific research, AUVs can function in water depths of up to 6000 m. However, this depends mainly on the pressure resistance of the vehicle.

Since AUV operates underwater, it is subjected to various external hydrodynamic forces. These forces cause the AUV model to deviate from its intended path. To rectify this problem, the AUV will be equipped with a PID controller. PID controller is a closed loop feedback system, which constantly attempts to reduce the difference between the desired setpoint and actual setpoint. With the presence of controller, accuracy of the motion of AUV can be greatly improved.

## 1.2 Problem Statement

- AUV model in UTP is not equipped with any controller
- AUV could not get to the desired setpoint due to external hydrodynamic forces acting on the AUV model

### **1.3 Objectives**

The objectives of this project are stated explicitly in the beginning of the project itself in order for the project to stay on track and reach its intended purpose. These objectives are closely related with the problem statements of this project. The objectives of this project are as listed below:

- To ensure AUV model reaches the desired setpoint
- To compare performance of AUV model with and without PID controller

### **1.4 Scope of Study**

To ensure the project to be completed in time, certain measures have been undertaken to narrow down the scope of this study so that it only covers certain main points. This is important because the author have limited time, resources and knowledge to investigate AUV as a whole. The time allocated for the author to complete the FYP is two weeks, which comprises of 28 weeks. The project completion is necessary for the graduating students of Universiti Teknologi PETRONAS (UTP). The scope of this study is as listed below:

- AUV is assumed to be in normal condition and environment without effect of water current acting on it
- The development of AUV model is based on available data only
- This project concentrates on incorporating only non-linear equations into PID controller
- The degree of freedoms are decoupled

## **CHAPTER 2**

### **LITERATURE REVIEW**

#### **2. LITERATURE REVIEW**

For the literature review of this project, the author has divided this chapter into two subsections. The first subsection will discuss about PID controllers while the latter part will discuss about AUV.

##### **2.1 PID Controllers**

PID controller is one of the most widely used control algorithm in various industries. This controller is preferred to be used by many due to their functional simplicity as well as their capability to perform exceptionally well in a wide range of operating conditions. Three coefficients; proportional, integral and derivative makes up the PID control algorithm. By varying the values of the coefficients, optimal response can be obtained.

PID controller is used to convert an open-loop system into a closed-loop system. In a typical closed-loop system, desired setpoint (input) will be compared to the actual setpoint (output). The difference between input and output will be sent to the controller so that corrective action can be taken. In the case of PID controller, the controller read a sensor and computes the desired actuator output by calculating proportional, integral, and derivative responses.

### **2.1.1 Proportional Control ( $K_P$ )**

Proportional control is determined by multiplying the coefficient with the current error in order to produce an actuation [3]. Thus, if the error produced is large, the actuation applied will be large as well. This is unfavorable due to the oscillations that will be produced. Besides, the large value of actuation may also result in permanent error. This permanent error is known as steady-state error.

### **2.1.2 Integral Control ( $K_I$ )**

Integral control takes into account of the error history. The value of the error will be added which will eventually result in elimination of steady-state error near its final state.

### **2.1.3 Derivative Control ( $K_D$ )**

Derivative control focuses on the rate of change of the error. It predicts the error that might occur in the future. This enables the system to respond quickly to changes. At the same time, presence of derivative control also makes it unstable. Apart from that, derivative control is sensitive to noises and slightest amount of noise can affect the output in a significant way.

### **2.1.4 Application of PID Controller in Various Systems**

In the paper published by Kada and Ghazzawi [4], an Unmanned Aerial Vehicle (UAV) is controlled using a combination of PID feedback and feedforward

controllers. Combination of these two controllers is needed in order to control conventional control surfaces and engine throttle. According to the authors of the paper, in order to obtain optimum performances such as zero steady-state error, minimum overshoot/undershoot and fast response, tuning is vital. Tuning the parameters is a time-consuming process since it must satisfy specified criteria while still under the constraint of some system actuators. When the UAV is in autopilot mode, the method of cascading controllers is used whereby multiple PID controllers are combined into one input/output loop. The term cascading controller is also used when an output from one PID unit is used as input for another PID unit. This method is advantageous when the UAV is required to make more complex missions and maneuvers.

In another paper published in 2011 [5], the authors have discussed about the PID controller design for a quadrotor unmanned air vehicle. From this paper, quadrotor is defined as an under actuated aircraft having four rotors at a fixed pitch angle.

According to the authors, method of controlling the UAV is one of the criteria for the controller selection. For this study, few assumptions have been undertaken:

- a) UAV structure is symmetrical and rigid.
- b) Inertia of the vehicle is very small and negligible.
- c) The propellers used are rigid.
- d) Thrust and drag are proportional to the square of the propellers speed.

There are two methods; mode-based or non-mode based. Mode-based controller requires independent controllers for each state, which will then allow another higher-level controller to decide on how the independent controllers interact. For non-mode based controller, a single controller controls all the states. For the UAV, the control system has been divided into two subsystems with the first one relates to the position control and another subsystem controls attitude.



## 2.2 AUV

Sanitwong et al. [6] discussed about the AUV used for coastal surveys. In their paper, the designed AUV are simulated to observe its hydrodynamic behavior. Torpedo-shaped AUV is opted due to its high speed characteristic and also because of its ease of maneuverability. The vehicle's motion system is made of three servos and one thruster. A microcontroller will be used as a control center while three accelerometers will be used as motion sensors to supply feedback signal for maneuverability and accurate stability. Navigation system is done by using global positioning system (GPS).

In his paper [7], Elnashar explained the control system adopted for his AUV. To measure the AUV state, a combination of trajectory generator and sensors are used. Trajectory generator and tracking controller receives feedback on current position and velocity values from the sensor suite. Trajectory generator calculates desired velocities and accelerations for the tracking controller. Based on the values received, tracking controller produces a thrust value for the motors. Elnashar proposes a combination of PID, low pass filter and saturation to control AUV. He discusses that by having this combination, the useful properties of each one can be used to improve the performance and stability of the overall controller.

## **CHAPTER 3**

### **METHODOLOGY**

#### **3. METHODOLOGY**

For this project, the author has divided the flow of the project into two with the first part describing the flow of the project itself while the second section is about the MATLAB/Simulink simulation process for this project.

### 3.1 Project Process Flow

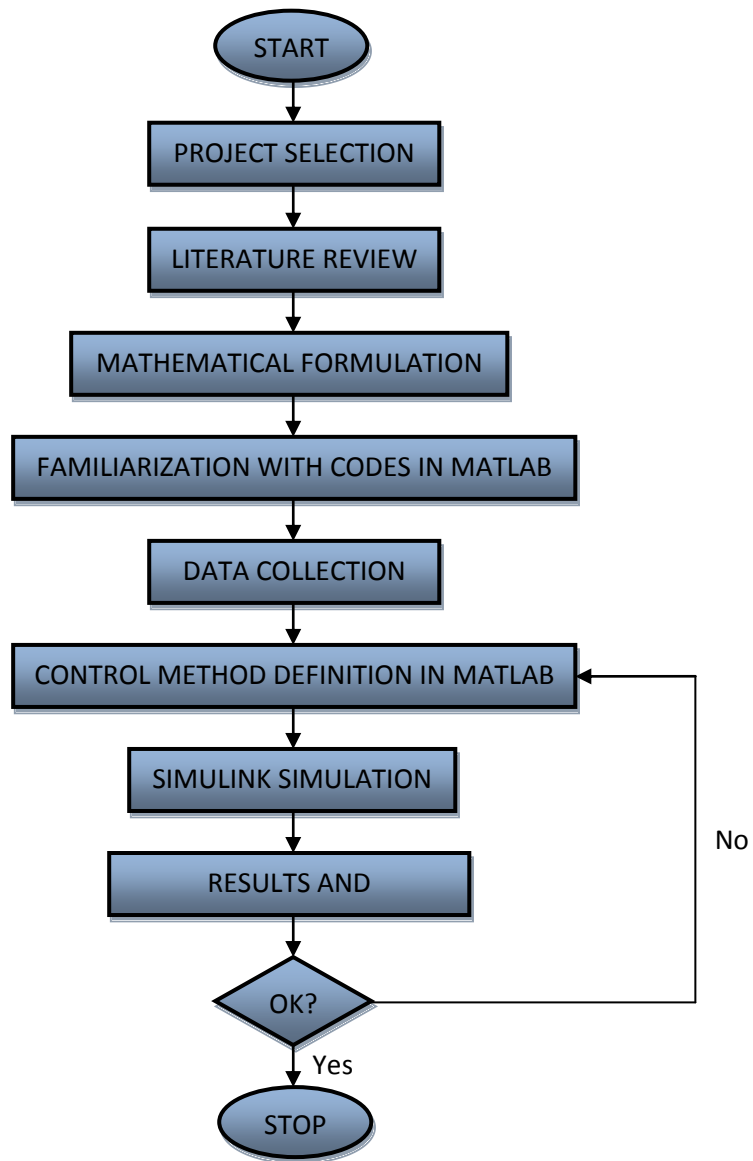


FIGURE 2. Project Process Flowchart

#### *Project Selection*

This project is suggested by the supervisor and chosen by the author followed by the verification of the course coordinator.

### *Consultation with Supervisor*

Consultation with supervisor is vital so that the author can get a better understanding of this project. Every week, author meets the supervisor to update him on the progress of this project and to get his opinion on the problems that arise.

### *Problem Identification*

The step of identifying problem is quite important since identifying the incorrect problem to be solved can lead to unexpected and unwanted outcome from the project.

### *Project Objectives and Scope of Study*

From the problems identified, listing of objectives is done as well as setting the scope of study. Scope of study should not be too extensive as it may cause the project not to be completed within the period specified.

### *Literature Review on PID Controller and AUV*

A study is conducted on the PID controllers used in other applications and the way it is integrated to the applications. Apart from that, another study is done on AUV to know more about the technical details of AUV such as the system it uses to move.

### *Data Collection*

The data obtained from the study on the PID controller and AUV is then collected to be used as guidance for this project's simulation phase.

### *Computer Code Development and Simulation*

After supervisor approved the design of PID controller, code is developed for MATLAB and simulation is done. The graphs produced by MATLAB are the results of this project.

### *Results and Validation*

The graphs are then analyzed and the performance of AUV after equipped with PID controller is compared with the AUV without PID controller.

### *Documentation*

The findings are analyzed before documented in a report for future reference. A presentation is done with the slides having information about this project. The author presents the presentation to the supervisor and external examiners.

## **3.2 Tools Used**

- *MATLAB/Simulink*

MATLAB/Simulink software is used to design the PID controller and to simulate the motion of AUV with and without the PID controller. It is also used to generate graphs from the simulation.

- *Microsoft Word*

Microsoft Word is used to document the results obtained and in preparing reports.

- *Microsoft Excel*

Microsoft Excel is used to tabulate the results obtained and compare the characteristics obtained.

### 3.3 Software Process Flow

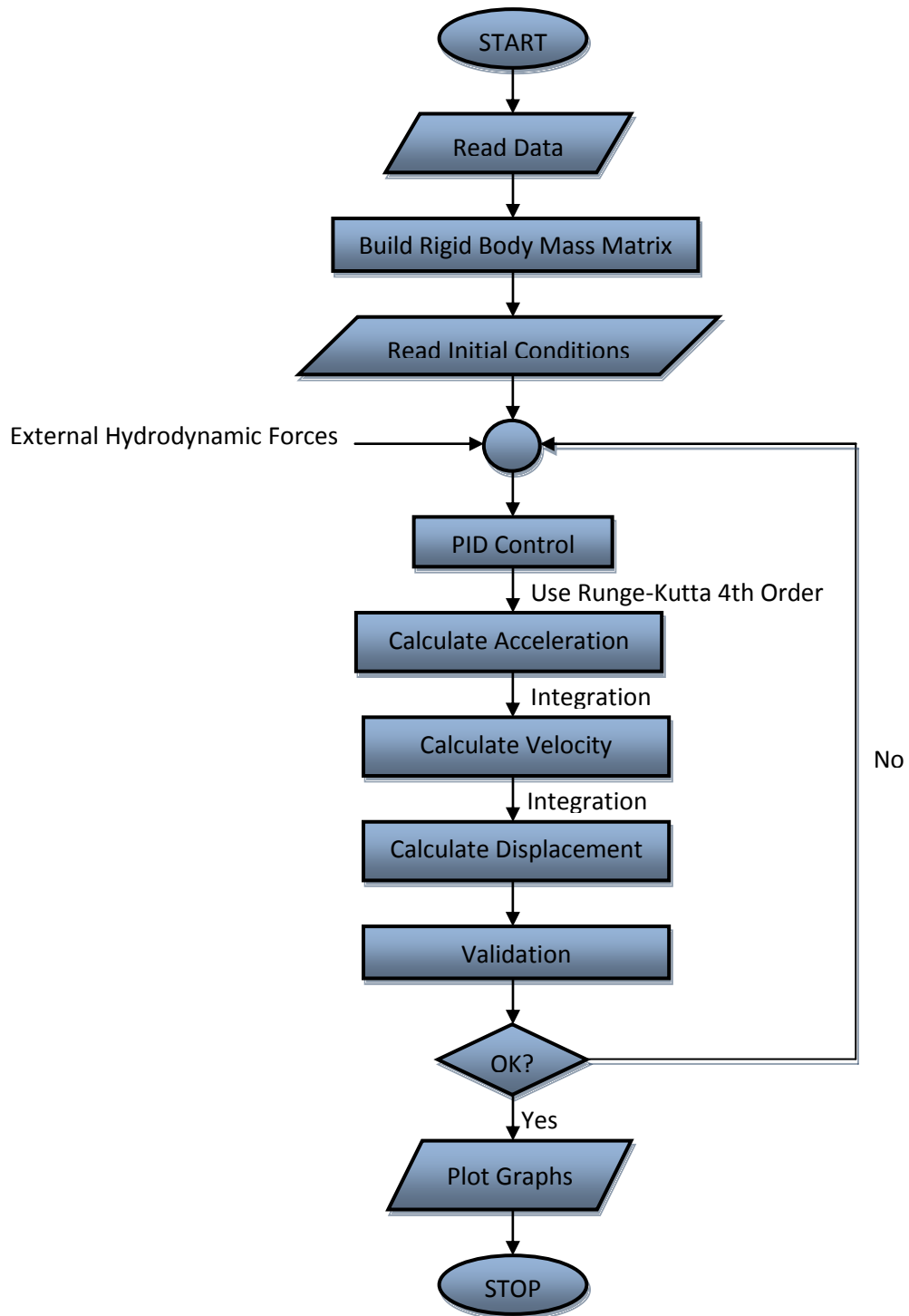


FIGURE 3. Software Process Flowchart

### 3.4 Key Project Milestones

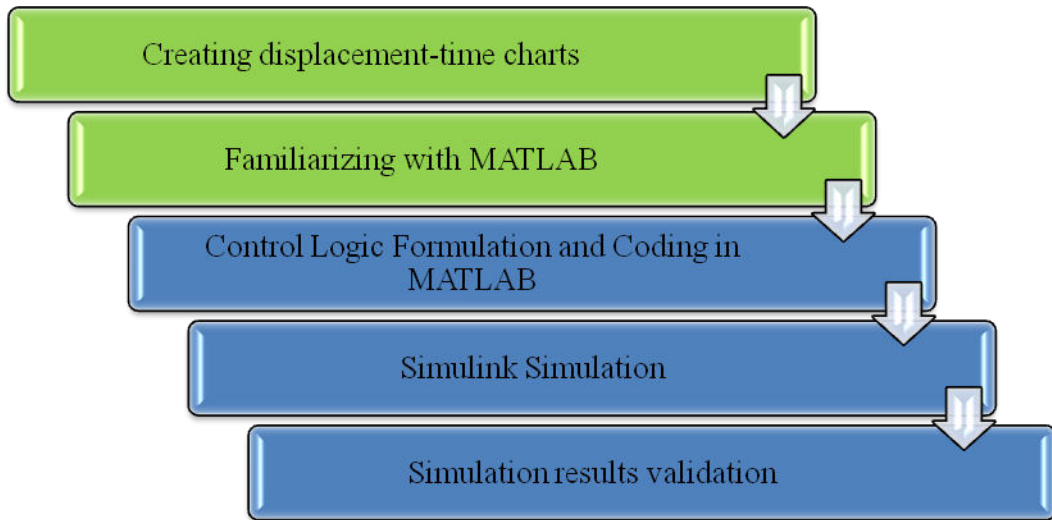




FIGURE 4. Key Project Milestones

 Final Year Project 1

 Final Year Project 2

### 3.5 Project Gantt Chart

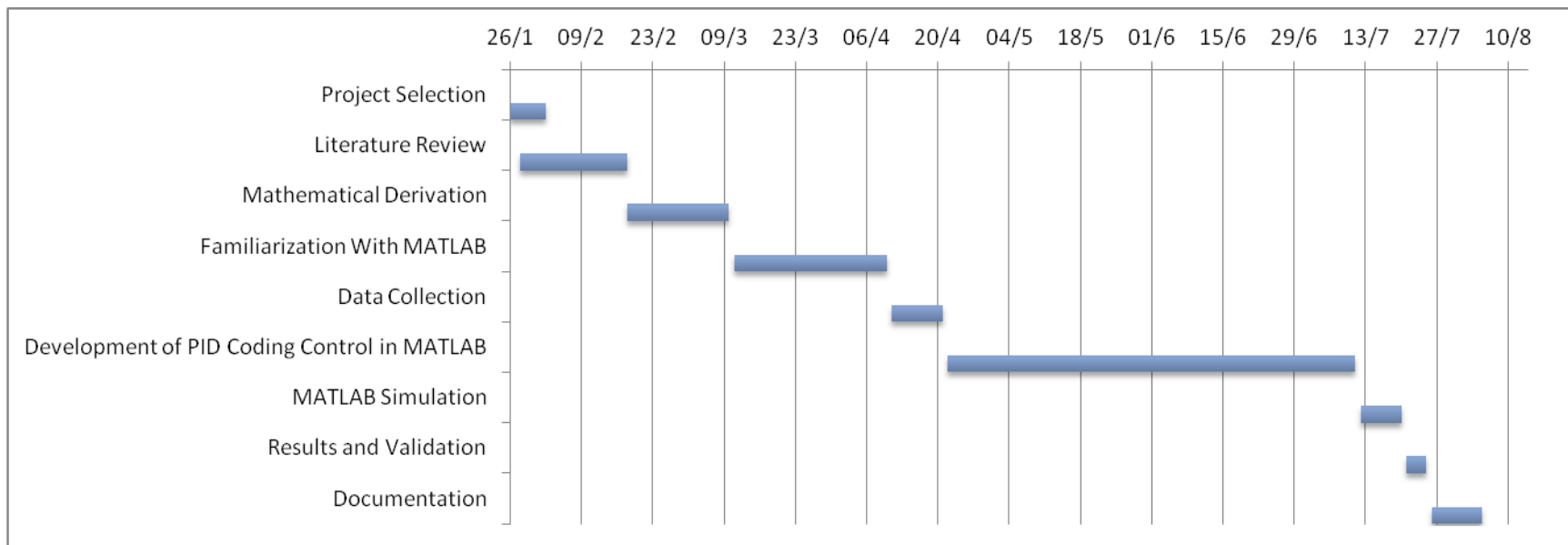


FIGURE 5. Project Gantt Chart



## CHAPTER 4

### RESULTS AND DISCUSSION

#### 4. RESULTS AND DISCUSSION

For an AUV, there are six degrees of freedom involved, which are surge, sway, heave, roll, pitch, and yaw [8]. Surge is motion of the AUV in the x-direction, sway is motion of the AUV in the y-direction, and heave is the motion of the AUV in the z-direction. The AUV can also rotate along the axes. For rotation about x-axis, it is called as roll ( $\phi$ ), rotation about y-axis is known as pitch ( $\theta$ ) and rotation about z-axis is yaw ( $\psi$ ). There are two reference frames involved for the AUV, which are earth-fixed and body-fixed. In earth-fixed reference frame, the vehicle's position and orientation are measured relative to a fixed-point origin defined in the centre of this frame. For body-fixed reference frame, a moving coordinate frame is fixed to the AUV itself. The figure below shows the six degrees of freedom as well as reference frames.

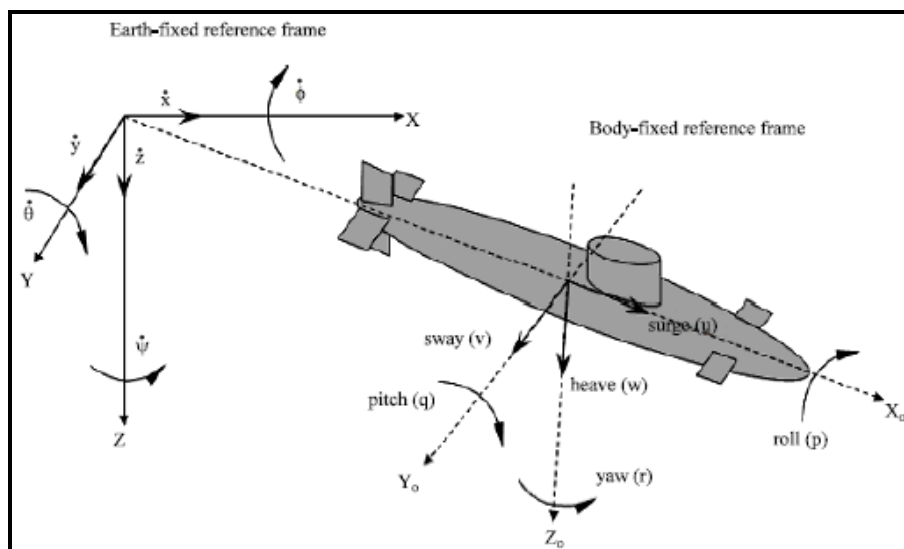


FIGURE 6. AUV Reference Frames and Six Degrees of Freedom

The basic equation used for this project is shown below:

$$M_{RB}\dot{v} + C_{RB}(v)v = \tau_H \dots \dots \dots (1)$$

The equation above consists of rigid body mass matrix ( $M_{RB}$ ), rigid body Coriolis matrix ( $C_{RB}(v)$ ) and total hydrodynamic forces and moments ( $\tau_H$ ) [9]. The rigid body mass matrix is shown below:

$$M_{RB} = \begin{bmatrix} m & 0 & 0 & 0 & mz_G & -my_G \\ 0 & m & 0 & -mz_G & 0 & mx_G \\ 0 & 0 & m & my_G & -mx_G & 0 \\ 0 & -mz_G & my_G & I_x & -I_{xy} & -I_{xz} \\ mz_G & 0 & -mz_G & 0 & I_y & -I_{yz} \\ -my_G & mz_G & 0 & 0 & 0 & I_z \end{bmatrix} \dots \dots \dots (2)$$

In this matrix, the term ‘m’ represents the AUV’s mass, the term ‘I’ represents the moments of inertia while both  $x_G$  and  $z_G$  represent the vehicle positions in local coordinates. ‘ $y_G$ ’ is assumed to be zero provided the port-starboard symmetry.

$$\begin{aligned} m &= 320 \text{ kg} & I_x &= 12 \text{ kg.m}^2 & I_y &= 50 \text{ kg.m}^2 & I_z &= 270 \text{ kg.m}^2 \\ I_{xy} &= 0 & I_{xz} &= 1.2 \text{ kg.m}^2 & I_{yz} &= -0.12 \text{ kg.m}^2 & x_G &= 0 \\ y_G &= 0 & z_G &= 0 \end{aligned}$$

Rigid body is an ideal solid body. Rigid body neglects all kind of deformation, so distance between any two given points on the body remains constant as time progresses even with any external forces applied.

The rigid body Coriolis-centripetal matrix [10] is shown below:

$$C_{RB} = \begin{bmatrix} 0 & 0 & 0 & c_{14} & c_{15} & c_{16} \\ 0 & 0 & 0 & c_{24} & c_{25} & c_{26} \\ 0 & 0 & 0 & c_{34} & c_{35} & c_{36} \\ c_{41} & c_{42} & c_{43} & 0 & c_{45} & c_{46} \\ c_{51} & c_{52} & c_{53} & c_{54} & 0 & c_{56} \\ c_{61} & c_{62} & c_{63} & c_{64} & c_{65} & 0 \end{bmatrix} \dots \dots \dots (3)$$

$$\begin{aligned} c_{14} &= -c_{41} = m(y_G q + z_G r) & -c_{15} &= c_{51} = m(x_G q - w) \\ -c_{16} &= c_{61} = m(x_G r + v) & -c_{24} &= c_{42} = m(y_G p + w) \end{aligned}$$

$$\begin{aligned}
c_{25} = -c_{52} &= m(z_G r + x_G p) & -c_{26} = c_{62} &= m(y_G r - u) \\
-c_{34} = c_{43} &= m(z_G p - v) & -c_{35} = c_{53} &= m(z_G q + u) \\
c_{36} = c_{63} &= m(x_G p + y_G q) & c_{45} = -c_{54} &= -I_{yz} q - I_{xz} p + I_z r \\
c_{46} = -c_{64} &= I_{yz} r + I_{xy} p - I_y q & c_{56} = -c_{65} &= -I_{xz} r - I_{xy} q + I_x p
\end{aligned}$$

Coriolis effect is an apparent deflection of the path of the AUV that moves within a rotating coordinate system. The deflection is observed even when the AUV is moving in a straight path relative to the earth's surface [11]. Coriolis effect is caused due to the rotation of Earth. When the Earth spins in a counter-clockwise direction, movement of the AUV over a long distance will be seen as deflected. Centripetal force is the force acting on the vehicle that causes it to follow a circular path. The direction of this force is towards the centre of the circle.

The total hydrodynamic forces and moments can be expanded further into the following equation:

$$\tau_H = -M_A \dot{v} - C_A v - Dv - g + \tau \dots \dots \dots (4)$$

The above equation consists of added mass ( $M_A$ ), hydrodynamic Coriolis ( $C_A$ ), hydrodynamic damping ( $D$ ), gravity ( $g$ ) and forces and moments generated by the actuators ( $\tau$ ).

The added mass matrix is shown below:

$$M_A = \begin{bmatrix} -X_{\dot{u}} & 0 & 0 & 0 & 0 & 0 \\ 0 & -Y_{\dot{v}} & 0 & 0 & 0 & -Y_{\dot{r}} \\ 0 & 0 & -Z_{\dot{w}} & 0 & -Z_{\dot{q}} & 0 \\ 0 & 0 & 0 & -K_{\dot{p}} & 0 & 0 \\ 0 & 0 & -M_{\dot{w}} & 0 & -M_{\dot{q}} & 0 \\ 0 & -N_{\dot{v}} & 0 & 0 & 0 & -N_{\dot{r}} \end{bmatrix} \dots \dots \dots (5)$$

All the terms in the matrix above are zero-frequency added mass coefficients and these are assumed to be constant. When the AUV is operating without the effects of wave, these terms are applied.

$$\begin{array}{cccc}
X_{\dot{u}} = -1.42 & Y_{\dot{v}} = -38.4 & Y_{\dot{r}} = -2.5 & Z_{\dot{w}} = -42.2 \\
Z_{\dot{q}} = 2.5 & K_{\dot{p}} = 1 & M_{\dot{w}} = 2.2 & M_{\dot{q}} = -8.9 \\
N_{\dot{v}} = 2.2 & N_{\dot{r}} = -8.9 & & 
\end{array}$$

The hydrodynamic Coriolis matrix is shown below:

$$C_A = \begin{bmatrix} 0 & 0 & 0 & 0 & a_{15} & a_{16} \\ 0 & 0 & 0 & a_{24} & 0 & a_{26} \\ 0 & 0 & 0 & a_{34} & a_{35} & 0 \\ 0 & a_{42} & a_{43} & 0 & a_{45} & a_{46} \\ a_{51} & 0 & a_{53} & a_{54} & 0 & a_{56} \\ a_{61} & a_{62} & 0 & a_{64} & a_{65} & 0 \end{bmatrix} \dots\dots\dots(6)$$

$$-a_{15} = a_{24} = -a_{42} = a_{51} = Z_{\dot{w}}w + Z_{\dot{q}}q$$

$$a_{16} = -a_{34} = a_{43} = -a_{61} = Y_{\dot{v}}v + Y_{\dot{r}}r$$

$$-a_{26} = a_{35} = a_{53} = a_{62} = X_{\dot{u}}u$$

$$-a_{45} = a_{54} = N_{\dot{v}}v + N_{\dot{r}}r$$

$$a_{46} = -a_{64} = M_{\dot{w}}w + M_{\dot{q}}q$$

$$-a_{56} = a_{65} = K_{\dot{p}}p$$

When it comes to damping, it can be further broken down to three damping components, which are linear damping( $D_l$ ), forward speed damping( $D_u$ ) and nonlinear damping( $D_{nl}$ ).

$$Dv = D_l v + uD_u v + D_{nl} v \dots\dots\dots(7)$$

Linear damping matrix is shown in the following page:

$$D_l = \begin{bmatrix} X_u & 0 & 0 & 0 & 0 & 0 \\ 0 & Y_v & 0 & 0 & 0 & -Y_r \\ 0 & 0 & Z_w & 0 & Z_q & 0 \\ 0 & 0 & 0 & K_p & 0 & 0 \\ 0 & 0 & M_w & 0 & M_q & 0 \\ 0 & -N_v & 0 & 0 & 0 & N_r \end{bmatrix} \dots\dots\dots(8)$$

$$X_u = 13.5 \quad Y_v = 1.0 \quad Y_r = 5.0 \quad Z_w = 66.6 \quad Z_q = 9.67$$

$$K_p = 0 \quad M_w = 30.7 \quad M_q = 6.87 \quad N_v = 36.0 \quad N_r = 5.0$$

Forward speed damping takes into account of the damping forces acting on the AUV as it moves forward. These damping terms increases proportionally with the speed. The forward-speed damping matrix is shown below:

$$D_u = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & Y_{uv} & 0 & 0 & 0 & -Y_{ur} \\ 0 & 0 & Z_{uw} & 0 & Z_{uq} & 0 \\ 0 & 0 & 0 & K_{up} & 0 & 0 \\ 0 & 0 & M_{uw} & 0 & M_{uq} & 0 \\ 0 & -N_{uv} & 0 & 0 & 0 & N_{ur} \end{bmatrix} \dots\dots\dots(9)$$

$$Y_{uv} = 28.6 \quad Y_{ur} = 5.22 \quad Z_{uw} = 28.6 \quad Z_{uq} = 5.22 \quad K_{up} = 1.0$$

$$M_{uw} = 24.0 \quad M_{uq} = 2.0 \quad N_{uv} = 24.0 \quad N_{ur} = 2.0$$

The nonlinear damping matrix is shown below:

$$D_{nl} = \begin{bmatrix} D_{11} & 0 & 0 & 0 & 0 & 0 \\ 0 & D_{22} & 0 & 0 & 0 & -D_{62} \\ 0 & 0 & D_{33} & 0 & D_{53} & 0 \\ 0 & 0 & 0 & D_{44} & 0 & 0 \\ 0 & 0 & D_{35} & 0 & D_{55} & 0 \\ 0 & -D_{26} & 0 & 0 & 0 & D_{66} \end{bmatrix} \dots\dots\dots(10)$$

$$D_{11} = X_{|u|u}|u| \quad D_{22} = Y_{|v|v}|v| \quad D_{26} = N_{|r|v}|r| \quad D_{33} = Z_{|w|w}|w|$$

$$D_{35} = M_{|q|w}|q| \quad D_{44} = K_{|p|p}|p| \quad D_{53} = Y_{|w|q}|w| \quad D_{55} = M_{|q|q}|q|$$

$$D_{62} = Y_{|v|r}|v| \quad D_{66} = N_{|r|r}|r|$$

For this project, AUV is considered as a neutrally buoyant vehicle where the weight of the vehicle is equal to the buoyancy force acting on it. Theoretically, distance

between buoyancy centre and gravity centre will cause moment to be generated as roll, pitch and yaw. The matrix for the gravity is shown below:

$$g = \begin{bmatrix} 0 \\ 0 \\ 0 \\ (z_G W - z_B B) \cos \theta \sin \varphi \\ (z_G W - z_B B) \sin \theta + (x_G W - x_B B) \cos \theta \cos \varphi \\ -(z_G W - z_B B) \cos \theta \sin \varphi \end{bmatrix} \dots\dots\dots(11)$$

The restoring force in the model is used to counter the hydrodynamic forces acting on the AUV. It is a variable force that causes the AUV to gain equilibrium in a physical system. If the model is disturbed from its equilibrium position, the restoring force will direct the model back to its intended position. In this project, the restoring force will be utilised to ensure the vehicle reaches its desired position. The equation for restoring force is shown below:

$$\tau = K_p \begin{bmatrix} x_d - x_a \\ y_d - y_a \\ z_d - z_a \\ \phi_d - \phi_a \\ \theta_d - \theta_a \\ \psi_d - \psi_a \end{bmatrix} + K_I \begin{bmatrix} \ddot{x}_d - \ddot{x}_a \\ \ddot{y}_d - \ddot{y}_a \\ \ddot{z}_d - \ddot{z}_a \\ \ddot{\phi}_d - \ddot{\phi}_a \\ \ddot{\theta}_d - \ddot{\theta}_a \\ \ddot{\psi}_d - \ddot{\psi}_a \end{bmatrix} + K_d \begin{bmatrix} \dot{x}_d - \dot{x}_a \\ \dot{y}_d - \dot{y}_a \\ \dot{z}_d - \dot{z}_a \\ \dot{\phi}_d - \dot{\phi}_a \\ \dot{\theta}_d - \dot{\theta}_a \\ \dot{\psi}_d - \dot{\psi}_a \end{bmatrix} \dots\dots\dots(12)$$

In the equation above, the first matrix represents displacement; the second matrix represents acceleration while the third matrix represents velocity. All the terms with the subscript ‘d’ represents desired setpoint while the terms with subscript ‘a’ denotes actual setpoint. The proportional parameter ( $K_p$ ) of the PID control creates a simple constant. The further the vehicle is away from its target, the higher the gain of  $K_p$  required to return it to its intended position. When the  $K_p$  gets too large, the system will experience large oscillations and longer time to get to the desired setpoint.

To counter the undesirable effects of  $K_p$ , derivative parameter ( $K_D$ ) of the PID control will act as a dampener to reduce the oscillations.  $K_D$  reduces the energy away from the model as a function of the rate of change of the overall PID control output. Although the two parameters can function well, there is a possibility of presence of constant error between the actual setpoint and desired setpoint. To rectify this error,

integral parameter ( $K_I$ ) is introduced.  $K_I$  will produce an opposing force that is a function of time. As time passes and there is a deflection present, the  $K_I$  will add a little force to bring it back on target with each PID cycle.

In this project, a Simulink model based on an equation derived from another set of equations. Expanding the previous equations, the author has come up with the equation stated below:

$$\dot{v} = [\tau - (C_{RB} + C_A + D_l + D_{nl})v - g] \left[ \frac{1}{M_{RB} + M_A} \right] \dots \dots \dots (13)$$

For this model, six inputs are fed into the model. Since the input can be any numbers, the author fixed on six random inputs. The inputs fed into the model are shown below:

$$\text{Input} = \begin{bmatrix} 12 \\ 10 \\ 8 \\ 6 \\ 4 \\ 2 \end{bmatrix} \dots \dots \dots (14)$$

The input represents surge, sway, heave, roll, pitch and yaw inputs respectively. In order to design a PID controller, certain constraints need to be defined in order to have an objective to achieve. The constraints are listed below:

- Rise time less than 3s.
- Settling time less than 30s.
- Steady-state error less than 1%.
- Overshoot less than 22%.

Rise time is defined as the time taken for the output to rise from 10% to 90% of its final value. Settling time is defined as the time required for the output to reach and remain stays within 5% of the final, steady-state value. Steady-state error is the difference between the values of input and output of the system. The last constraint is overshoot. Overshoot is the maximum value reached by the response curve. The percentage of overshoot encountered is measured from the desired output of the system.

## 4.1 Simulink Models

The figure below shows the Simulink model developed by the author for this project.

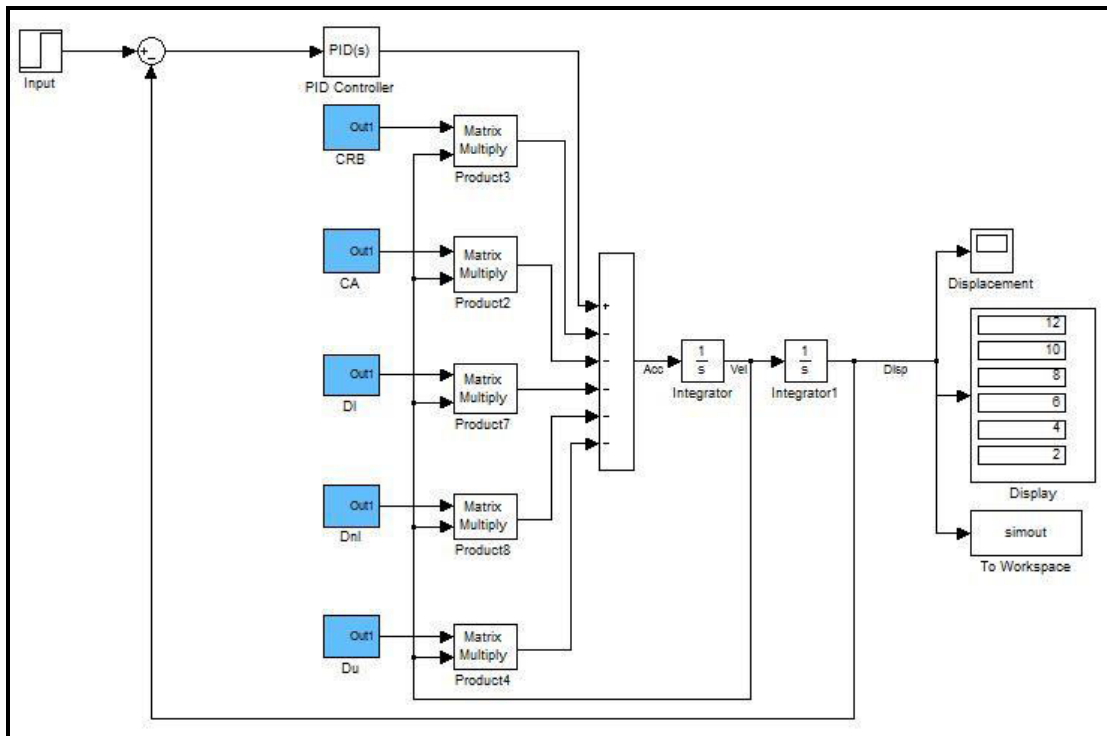


FIGURE 7. Simulink Model for AUV

The figure below shows the example of an expanded view of the blue blocks in the original Simulink model.

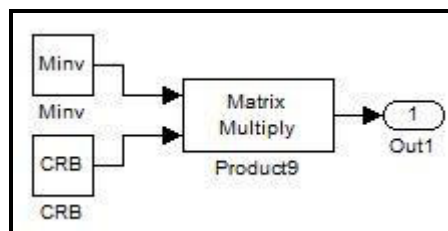


FIGURE 8. Subsystem Expansion



In the Simulink model, the input given to the system is in the form of step input. Each of the blue blocks indicates terms determined from Equation 12. The values from the blue blocks as well as the step input are directed towards the summing junction. The step input would be channeled to the positive point while all the other hydrodynamic forces would be channeled to the negative points of the summing junction. The output from the summing junction will be the acceleration of the vehicle. By integrating it twice, the author obtains the displacement of the vehicle. This final output is transferred to a scope, a display as well as to workspace of the MATLAB. Apart from that, the displacement data is also transmitted to another summing junction so that difference between desired output and actual output can be calculated. The difference value is then sent to the PID controller, which will then correct the final output. For this project, the simulation time is set at 100s while the solver used for Simulink is Runge-Kutta 4<sup>th</sup> Order. Runge-Kutta is used since it provides better estimation of the slopes. The four approximations used are provided below.

$$k_1 = f(y(t_0), t_0) \dots\dots\dots (15)$$

$$k_2 = f(y(t_0) + k_1 h_2, t_0 + h_2) \dots\dots\dots (16)$$

$$k_3 = f(y(t_0) + k_2 h_2, t_0 + h_2) \dots\dots\dots (17)$$

$$k_4 = f(y(t_0) + k_3 h, t_0 + h) \dots\dots\dots (18)$$

Parameter  $k_1$  is the slope estimate at the beginning of the time step while  $k_2$  is the slope estimate at the midpoint. Parameter  $k_3$  is another slope estimate at the midpoint and finally, parameter  $k_4$  is the slope estimate at the endpoint. By calculating these four parameters, a final estimate is obtained [12].

$$y(t_0 + h) = y(t_0) + \frac{k_1 + 2k_2 + 2k_3 + k_4}{6} h \dots\dots\dots (19)$$

As can be observed in the equation,  $k_2$  and  $k_3$  have higher weightings compared to  $k_1$  and  $k_4$ . This is done since it is expected that higher weighting at midpoint provide better estimate of the slope.

## 4.2 Gain Tuning

In this project, the author decided to determine the gains of the PID controller using manual tuning. Extra care is taken while tuning the PID controller since certain values will cause the system to be unstable. The chart below shows the displacement of the AUV model without any PID controller equipped to it. The subsequent chart shows the displacement of the AUV model with PID controller equipped to it.

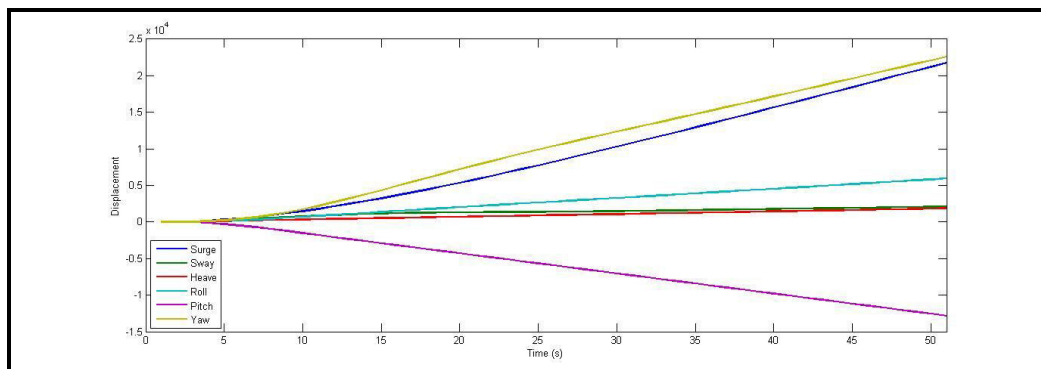


FIGURE 9. Displacement of AUV without PID Controller

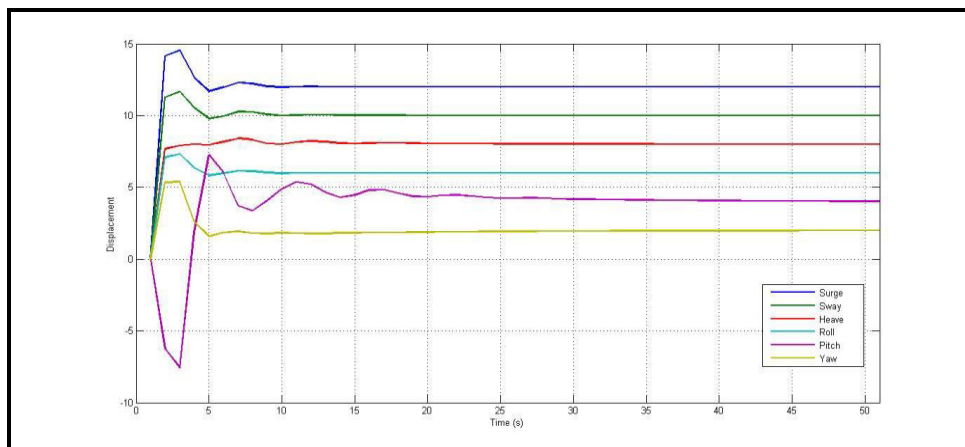


FIGURE 10. Displacement of AUV with PID Controller

From the graphs above, it can be seen that there is a significant change once PID is equipped to the AUV. For example, the surge input required is 12m. Without PID, the AUV goes astray up to the point of 20000m. These huge amounts of surge displacement as well as other displacements are due to hydrodynamic forces acting on the vehicle. If PID is equipped to the vehicle, it goes to the specified point. PID is

able to take into account the hydrodynamic forces and adjusts itself to get to the desired setpoint.

From trial and error, the gains are determined. Once it is determined, the gains are increased and decreased 5% respectively to see its affect on the displacement-time charts. The table below shows the difference between the gain values for the PID controller.

TABLE 1. Gain Value Difference for PID

	<b>Actual</b>	<b>5% Increase</b>	<b>5% Decrease</b>
<b>Kp</b>	0.33	0.3465	0.3135
<b>Ki</b>	0.012	0.0126	0.0114
<b>Kd</b>	1.159	1.21695	1.10105

The following tables represent the characteristics of the outputs obtained from the respective controllers.

#### 4.2.1 Actual PID Controller

TABLE 2. Response Characteristics for Actual PID

	<b>Rise time (s)</b>	<b>Settling time (s)</b>	<b>Steady-state error (%)</b>	<b>Overshoot (%)</b>	<b>Undershoot (%)</b>
<b>Surge</b>	0.6786	7.915	0	21.4	0
<b>Sway</b>	0.7083	8.331	0	16.914	0
<b>Heave</b>	0.8327	13.1847	0.05	5.0485	0
<b>Roll</b>	0.6762	7.9817	0	21.98	0
<b>Pitch</b>	0.4786	27.1262	0.675	80.7645	187.9949
<b>Yaw</b>	0.2984	24.6771	0.4	170.4198	0

From the table provided, it can be seen that all the rise time of the outputs fall within the constraint set. The same goes to the settling time as well as steady-state error. However, the pitch and yaw outputs had an enormous overshoot phenomena. Apart

from that, the pitch output also experiences huge undershoot. When gains are changed to rectify these two outputs, other outputs becomes unstable.

#### 4.2.2 PID Controller with 5% Increase

TABLE 3. Response Characteristics for PID (5% Gain Increase)

	Rise time (s)	Settling time (s)	Steady-state error (%)	Overshoot (%)	Undershoot (%)
<b>Surge</b>	0.6462	7.9935	0	23.7926	0
<b>Sway</b>	0.6746	8.4197	0	18.5881	0
<b>Heave</b>	0.7929	14.0309	0.05	7.4227	0
<b>Roll</b>	0.644	8.0204	0	24.2309	0
<b>Pitch</b>	0.4301	29.2616	0.6	105.2052	215.9087
<b>Yaw</b>	0.2843	23.5734	0.35	181.4103	0

In the table above, it can be seen that all the rise time of the outputs fall within the constraint set. Besides, the rise times are also slightly lesser compared to the actual rise times. This may be due to the higher value of proportional gain compared to the actual value of proportional gain. Most of the settling times are slightly longer compared to the actual settling times. This is caused by the proportional gain increase, which makes the time to settle to be longer. For the steady-state error, the model does not experience much change. For both overshoot and undershoot, both the parameters undergo increase from the actual controller.

### 4.2.3 PID Controller with 5% Decrease

TABLE 4. Response Characteristics for PID (5% Gain Decrease)

	Rise time (s)	Settling time (s)	Steady-state error (%)	Overshoot (%)	Undershoot (%)
<b>Surge</b>	0.7143	8.0103	0	23.3925	0
<b>Sway</b>	0.7456	8.322	0	18.4753	0
<b>Heave</b>	0.8765	12.5425	0.0625	3.8285	0
<b>Roll</b>	0.7117	8.0248	0	23.8349	0
<b>Pitch</b>	0.4689	27.6721	0.7	62.1965	166.5887
<b>Yaw</b>	0.3141	24.9454	0.4	174.9663	0

From the table above, it is observed that the rise time becomes longer than the actual gains. Once proportional gain is decreased, it takes longer for the model to rise from 10% to 90% of its steady-state value. It can be seen that all the rise times of the outputs fall within the constraint set. Besides, the rise times are also slightly lesser compared to the actual rise times. This may be due to the higher value of proportional gain compared to the actual value of proportional gain. Most of the settling times are slightly longer compared to the actual settling times. This is caused by the proportional gain increase which makes the time to settle to be longer. For the steady-state error, the model does not experience much change. For both overshoot and undershoot, both the parameters undergo increase from the actual controller.

The charts generated for all the inputs are attached in the appendices.

## CHAPTER 5

### CONCLUSION AND RECOMMENDATIONS

#### 5. CONCLUSION AND RECOMMENDATIONS

##### 5.1 Conclusion

The first phase of this project focuses on the effects of various parameters on the displacement of the AUV model. In total, three parameters that are investigated are hydrodynamic Coriolis, added mass and damping. By using Runge-Kutta 4<sup>th</sup> Order equation, the displacement of the model is determined. Runge-Kutta is used instead of simple Euler equation due to its stability.

The loading input is done from six directions, which are surge, sway, heave, roll, pitch and yaw directions. By analyzing the charts generated, it is determined that each parameter affects the displacement of the model to a certain extent. The results from these charts prove that a controller is necessary to control the motion of the AUV model so that the model would not go astray. The controller designed must be able to make the model to reach required destination as quick as possible.

Initially, it is planned to use MATLAB's System Identification Tool and PID Tuner in order to design a PID controller. However, after few trials, it is decided that Simulink simulation would be a better choice since it can be simplified to few block diagrams and the gains can be fine-tuned manually although it is more time-consuming compared to PID Tuner.

In Simulink, the model without PID is first simulated to obtain the displacement experienced by the model. After the simulation, a PID controller is equipped and its gains are changed using the method of trial-and-error. Once the appropriate gains are

determined for the constraints set, the gain values are increased and reduced by 5% respectively. This is done to investigate the effect of the gains to the model's rise time, settling time, overshoot as well as steady state error.

From the tests conducted in MATLAB, the aim of this project which is to get the AUV to the desired setpoint with minimal rise time, settling time, steady-state error, overshoot and undershoot have been achieved.

## **5.2 Recommendations for Future Work**

One of the major drawbacks that might affect the accuracy of data produced is overdependence on mathematical models. Although mathematical model is accurate, using data from actual prototype testing will be more accurate since it occurs in the real environment. Therefore, mathematical model should be used along with actual practical testing.

Apart from that, the PID controller selected for the AUV is a basic PID. To improve the control system of the AUV, more advanced PID can be used. One such example of advanced PID is fuzzy logic PID controller. This type of PID is not used in this project by the author due to the need for experience in handling this controller and based on the constraints set, the classic PID controller is sufficient to achieve that.

It is also observed that for two outputs which are pitch and yaw, the overshoot cannot be reduced while undershoot could not be eliminated. The author recommends devising a separate controller for these two outputs so that the overshoot and undershoot can be reduced or eliminated.

## CHAPTER 6

### REFERENCES

- [1] Woods Hole Oceanographic Institution, 'Autonomous Underwater Vehicles'. [Online]. Available: <http://www.whoi.edu/main/auvs>. [Accessed: 06- Jun- 2015].
- [2] R. Wynn et al., 'Autonomous Underwater Vehicles (AUVs): Their past, present and future contributions to the advancement of marine geoscience', *Marine Geology*, vol. 352, pp. 451-468, 2014.
- [3] National Instruments, 'PID Theory Explained', 2011. [Online]. Available: <http://www.ni.com/white-paper/3782/en/>. [Accessed: 07- Jul- 2015].
- [4] B. Kada and Y. Ghazzawi, 'Robust PID Controller Design for an UAV Flight Control System', in *World Congress on Engineering and Computer Science 2011*, San Francisco, 2011.
- [5] A. Salih et al., 'Flight PID Controller Design for A UAV Quadrotor', *Scientific Research and Essays*, vol. 5, no. 23, pp. 3660-3667, 2010.
- [6] S. Ayutthaya et al., 'Autonomous Underwater Vehicle for Coastal Survey', in *International Ocean and Polar Engineering Conference*, Busan, 2014, pp. 410-414.
- [7] G. Elnashar, 'Performance and Stability Analysis of an Autonomous Underwater Vehicle Guidance and Control', in *International Conference on Modeling, Identification and Control (ICMIC)*, Cairo, 2013, pp. 67-73.
- [8] F. Wang et al., 'Modeling and Motion Control Strategy for Autonomous Underwater Vehicles', in *International Conference on Mechatronics and Automation*, Changchun, 2015, pp. 4851-4856.



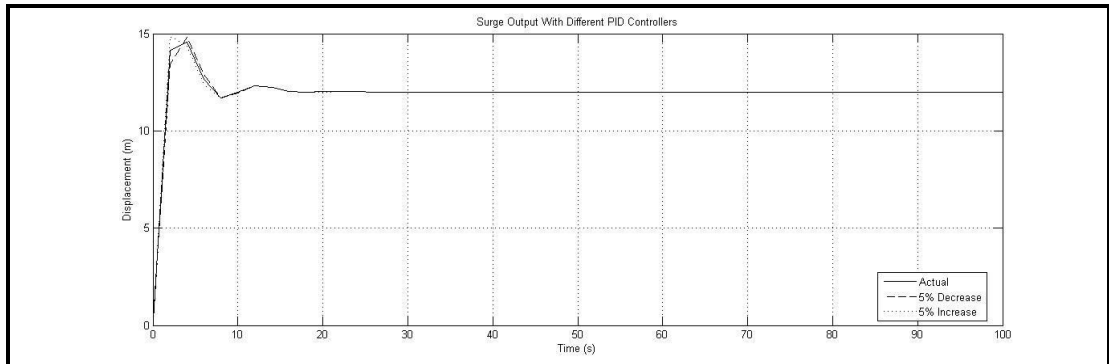
- [9] A. Mohd Amiruddin, 'Development of Computer Code in MATLAB to Simulate AUV Dynamics', Undergraduate, University of Technology PETRONAS, 2014.
- [10] X. Liang et al., 'Dynamic Modeling and Computer Simulation for Autonomous Underwater Vehicles with Fins', *JCP*, vol. 8, no. 4, 2013.
- [11] A. Briney, 'How Does the Coriolis Effect Impact Earth?'. *About.com Education*. [Online].  
Available: <http://geography.about.com/od/physicalgeography/a/coriolis.htm>.  
[Accessed: 13- Jul- 2015].
- [12] E. Cheever, 'Fourth Order Runge-Kutta', *Linear Physical Systems Analysis*. [Online]. Available: <http://lpsa.swarthmore.edu/NumInt/NumIntFourth.html>.  
[Accessed: 06- Jul- 2015].

# CHAPTER 7

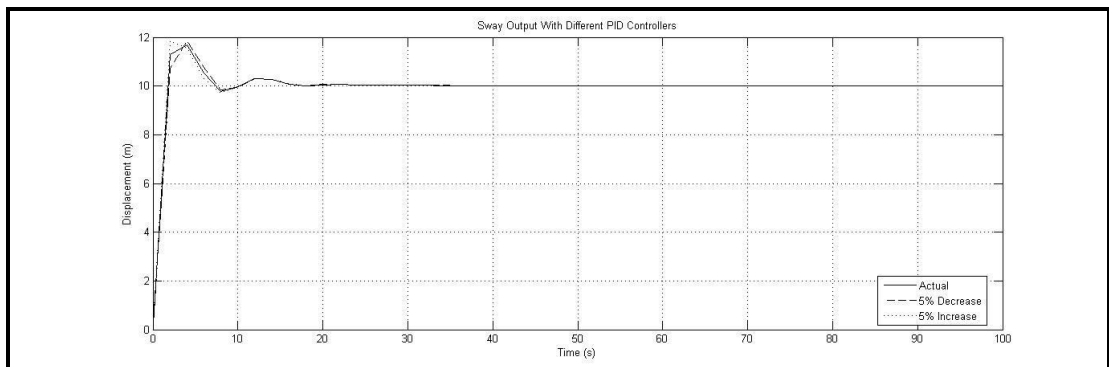
## APPENDICES

### 7.1 Charts for Displacements with PID

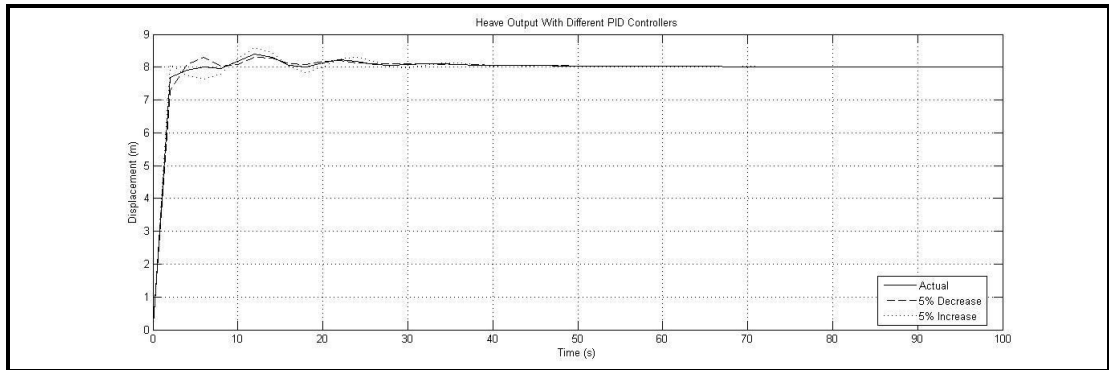
For surge output:



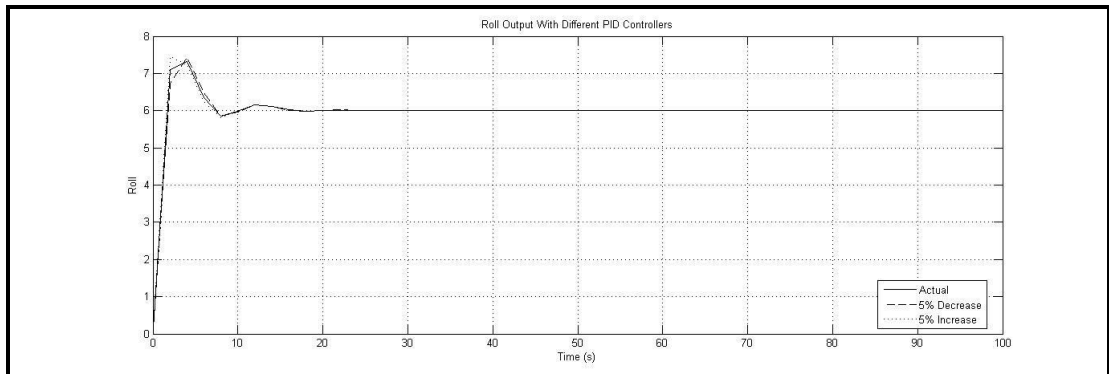
For sway output:



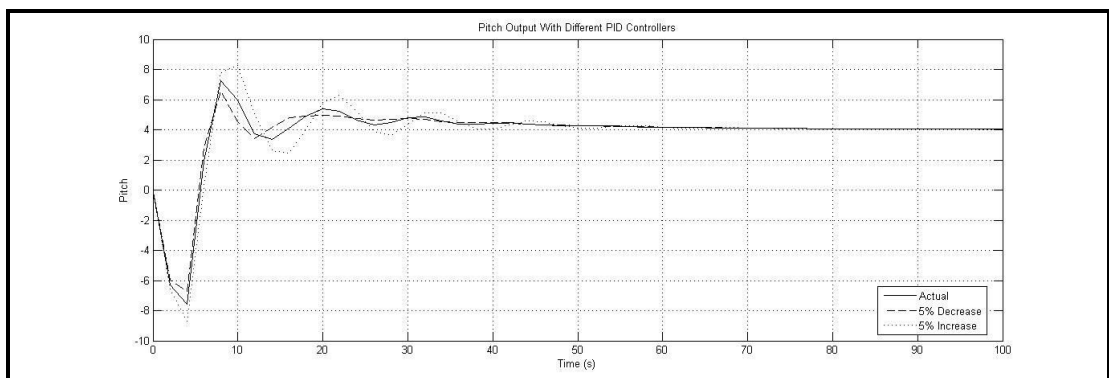
For heave output:



For roll output:



For pitch output:



For yaw output:

