The modeling and control of depth and pitch of an Autonomous Underwater Vehicle (AUV) using a PID Controller

Thesis submitted for the partial fulfilment of the requirement of the degree of

MASTER IN CONTROL SYSTEM ENGINEERING

Submitted by

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Certificate of Recommendation

This is to certify that **Mr. Avanish Kumar Thakur (002110804008)** has completed his dissertation entitled, "**The modeling and control of depth and pitch of an Autonomous Underwater Vehicle (AUV) using a PID Controller**", under the direct supervision and guidance of Dr. Smita Sadhu Ghosh, Electrical Engineering Department, Jadavpur University. We are satisfied with his work, which is being presented for the partial fulfilment of the degree of Master in Electrical Engineering of Jadavpur University, Kolkata-700032.

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The foregoing thesis is hereby approved as a creditable study of Master in Electrical Engineering and presented in a manner satisfactory to warrant its acceptance as a pre-requisite to the degree for which it has been submitted. It is understood that, by this approval the undersigned does not necessarily endorse or approve any statement made, opinion expressed, or conclusion therein but approve this thesis only for the purpose for which it is submitted.

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Signature of Examiners

Declaration of Originality

I hereby declare that this thesis contains a literature survey and original research work by the undersigned candidate, as part of his Master in Control System Engineering curriculum. All information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

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ABSTRACT

Autonomous Underwater Vehicles (AUVs) have emerged as a transformative technology in the field of marine exploration, research, and industry. This abstract provides an overview of the key aspects of AUVs, including their design, navigation systems, applications, and recent advancements.

Autonomous Underwater Vehicles have evolved into powerful tools that are revolutionizing our understanding of the oceans and their resources. As technology continues to advance, AUVs are poised to play an even more prominent role in scientific research, environmental conservation, and various underwater industries. This abstract offers a glimpse into the exciting world of AUVs and their limitless potential in exploring the mysteries of the deep sea.

Underwater vehicles are becoming increasingly important machines in various applications. They are capable of performing complex tasks underwater, such as detecting and mapping pipelines, exploring underwater terrain, and conducting inspections. However, one common challenge faced by these vehicles is the disturbance caused by the rotation of the thruster at the back, which affects their stability. To address this issue, a control system is needed to compensate for the instability.

In this project, the primary focus is on designing a PID (Proportional-Integral-Derivative) controller to control one degree of motion of the underwater vehicle, specifically the pitch motion. The study is based on the REMUS AUV an underwater vehicle. While there are various researches related to motion controllers for underwater vehicles, ranging from conventional PID controllers to advanced adaptive systems, this project is specifically aimed at designing a PID controller . Despite being a well-established controller, the PID controller is chosen for this project because of its satisfactory performance. The mathematical model of the underwater vehicle is developed by deriving the kinematic and dynamic equations of motion. The equations governing pitch and depth motion are solved using a state-space approach to obtain the system's transfer functions. Subsequently, control blocks for the system equipped with the PID controller are designed using MATLAB Simulink software, and

simulations of the system are conducted. The obtained response is deemed satisfactory, achieving system stability.

Contents

List of Symbols and their Description

Symbol	Description
x	X axis of body fixed reference frame
y	Y axis of body fixed reference frame
z	Z axis of body fixed reference frame
X	X axis of body fixed reference frame
Y	Y axis of body fixed reference frame
Z	Z axis of body fixed reference frame
ϕ	Euler angle in North-South axis. Positive sense is clockwise as seen from back of the vehicle (earth)
θ	Euler angle in pitch plane. Positive sense is clockwise as seen from port of the vehicle (earth)
Ψ	Euler angle in yaw plane. Positive sense is clockwise as seen from above (earth)
u	Linear velocity along longitudinal axis (body)
v	Linear velocity along horizontal plane (body)
w	Linear velocity along depth (body)
p	Angular velocity component about body longitudinal axis
q	Angular velocity component about body lateral axis
r	Angular velocity component about body vertical axis
$\dot{u}$	Time rate of change of velocity along the body
$\dot{v}$	Time rate of change of velocity along the body lateral axis
$\dot{w}$	Time rate of change of velocity along the body vertical axis
$\dot{p}$	Time rate of change of body roll angular velocity about the body longitudinal axis
$\dot{q}$	Time rate of change of body pitch angular velocity about the body lateral axis
$\dot{r}$	Time rate of change of body yaw angular velocity about the body vertical axis
α	Angle of attack
δ_s	Stern planes (elevator) deflection angle.
δ_r	rudder planes deflection angle.
$X_{u\|u\|}$	Cross-flow Drag
$X_{\dot{u}}$	Added Mass
X_{wq}	Added Mass Cross-term

X_{qq}	Added Mass Cross-term
X_{vr}	Added Mass Cross-term
X_{prop}	Propeller Thrust
$Y_{v\|v\|}$	Cross-flow Drag
Y_{uv}	Body Lift Force and Fin Lift
$Y_{\dot{v}}$	Added Mass
$Y_{\dot{r}}$	Added Mass
Y_{ur}	Added Mass Cross Term and Fin Lift
Y_{wp}	Added Mass Cross-term
Y_{pq}	Added Mass Cross-term
$Z_{w\|w\|}$	Cross-flow Drag
$Z_{q\|q\|}$	Cross-flow Drag
Z_{uw}	Body Lift Force and Fin Lift
$Z_{\dot{w}}$	Added Mass
$Z_{\dot{q}}$	Added Mass
Z_{uq}	Added Mass Cross-term and Fin Lift
Z_{vp}	Added Mass Cross-term
Z_{rp}	Added Mass Cross-term
$Z_{uu\delta r}$	Fin Lift Force
$K_{p\|p\|}$	Rolling Resistance
$K_{\dot{p}}$	Added Mass
K_{prop}	Propeller Torque
M_{ww}	Cross-flow Drag
$M_{q\|q\|}$	Cross-flow Drag
M_{uw}	Body and Fin Lift and Munk Moment
$M_{\dot{w}}$	Added Mass
$M_{\dot{q}}$	Added Mass
M_{uq}	Added Mass Cross Term and Fin Lift
M_{vp}	Added Mass Cross-term
M_{rp}	Added Mass Cross-term
$M_{uu\delta s}$	Fin Lift Moment
$N_{v\|v\|}$	Cross-flow Drag

$N_{r\|r\|}$	Cross-flow Drag
N_{uv}	Body and Fin Lift and Munk Moment
$N_{\dot{v}}$	Added Mass
$N_{\dot{r}}$	Added Mass
N_{ur}	Added Mass Cross Term and Fin Lift
N_{wp}	Added Mass Cross Term
N_{pq}	Added Mass Cross Term
$N_{uu\delta r}$	fin Lift Moment
X_{θ}	Hydrostatic
Xu	Axial Drag
$X_{\dot{u}}$	Added Mass
X_{q}	Added Mass Cross Term
Z_{w}	Combined Term
Z_{q}	Combined Term
$Z\dot{w}$	Added Mass
$Z_{\dot{q}}$	Added Mass
$Z\delta_{s}$	Fin Lift
M_{θ}	Hydrostatic
M_{w}	Combined Term
M_{q}	Combined Term
$M_{\dot{w}}$	Added Mass
$M_{\dot{q}}$	Added Mass
W	Measured Vehicle Weight
m	Mass of the Vehicle
B	Measured Vehicle Buoyancy
x_{g}	x Coordinate of CG From Body Fixed Origin
y_{g}	y Coordinate of CG From Body Fixed Origin
z_{g}	z Coordinate of CG From Body Fixed Origin
I_{xx}	Mass Moment of Inertia about x-axis
I_{yy}	Mass Moment of Inertia about y-axis
I_{zz}	Mass Moment of Inertia about z-axis
I_{xy}	Cross Product of Inertia about xy-axes

I_{yz}	Cross Product of Inertia about yz-axes
I_{zx}	Cross Product of Inertia about zx-axes
x_{cb}	x Coordinate of CB From Body Fixed Origin
y_{cb}	y Coordinate of CB From Body Fixed Origin
z_{cb}	z Coordinate of CB From Body Fixed Origin
CG	Center of gravity
CB	Center of Buoyancy
REMUS	Remote Environmental Monitoring UnitS
AUV	Autonomous Underwater Vehicles

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Chapter 1

Introduction

1.1 History and Background

Autonomous Underwater Vehicles (AUVs) have emerged as invaluable tools for exploring the oceans, conducting scientific research, and supporting various underwater missions. The development of AUVs represents a fascinating journey of innovation, driven by the need to overcome the limitations of traditional manned submersibles and remotely operated vehicles (ROVs)[3].

Early Concepts and Inspiration (1950s-1960s) : The concept of autonomous underwater vehicles began to take shape in the mid-20th century. Early pioneers like Jacques Cousteau and Harold "Doc" Edgerton laid the groundwork by inventing underwater cameras and sonar systems, which allowed for remote exploration of the deep sea[3]. Their work inspired future generations to explore the possibilities of unmanned underwater vehicles.

First AUV Prototypes (1960s-1970s) : In the 1960s and 1970s, the United States Navy, along with organizations like the Woods Hole Oceanographic Institution, developed some of the earliest AUV prototypes. These early vehicles were relatively simple and lacked the advanced technology seen in modern AUVs. They were primarily used for oceanographic research and underwater mapping [3].

Technology Advancements (1980s-1990s) : The 1980s and 1990s witnessed significant advancements in AUV technology. Researchers and engineers began incorporating more sophisticated control systems, sensors, and navigation capabilities into these vehicles. The development of efficient propulsion systems and energy sources, such as lithium-ion batteries, extended their operational range and duration.

Commercial and Research Applications (2000s-2010s) : As AUV technology matured, their applications expanded rapidly. AUVs became indispensable tools for marine research, oceanography, and environmental monitoring [3]. They were used to study deep-sea ecosystems, map the seafloor, locate shipwrecks, and gather data on underwater geology. In parallel, industries like offshore oil and gas adopted AUVs for pipeline inspection, underwater maintenance, and exploration tasks.

Military and Defense (2000s-present): The military recognized the strategic value of AUVs for mine countermeasures, reconnaissance, and underwater surveillance. Several countries developed specialized military AUVs for these purposes, enhancing their naval capabilities [3].

Technological Milestones (2010s-present) : In recent years, AUVs have achieved remarkable milestones. They can now operate at greater depths, reach remote oceanic regions, and perform complex tasks autonomously. Advances in artificial intelligence, machine learning, and sensor technology have improved their navigation, obstacle avoidance [2], and data collection capabilities.

Environmental Conservation and Exploration (2010s-present) : AUVs have also played a vital role in environmental conservation efforts, including monitoring and protecting marine sanctuaries and assessing the impact of climate change on oceans [2].

Future Prospects: The future of AUVs is promising, with ongoing research into swarm robotics, bio-inspired design, and enhanced autonomy. These advancements will further expand their applications and make them even more effective tools for exploring and understanding the mysteries of the deep sea [2].

In conclusion, the history and background of Autonomous Underwater Vehicles illustrate a journey of innovation, driven by the desire to unlock the secrets of the world's oceans and address diverse underwater challenges. As AUV technology continues to evolve, it holds the potential to transform our understanding of the oceans and their vital role in our planet's ecosystem.

1.2 Classification of Autonomous Underwater Vehicles (AUVs)

Autonomous Underwater Vehicles (AUVs) can be classified based on various criteria, including their mission profiles, design characteristics, and intended applications. Here's a classification of AUVs based on these factors [3] :

1.2.1. Mission Profile:

a. Profiling AUVs: These AUVs are designed for vertical profiling of the water column. They typically move vertically in the water to collect data on various parameters (e.g., temperature, salinity, and pressure) at different depths.

b. Hovering AUVs: These AUVs are equipped with buoyancy control systems that allow them to hover in a fixed position or follow a specific depth contour. They are used for tasks like detailed seafloor mapping and environmental monitoring.

c. Survey AUVs: Survey AUVs are designed for horizontal movement and are often used for mapping large areas of the seafloor, conducting hydrographic surveys, and inspecting underwater structures.

d. Gliders: Glider AUVs use changes in buoyancy to move up and down in the water, enabling long-endurance missions. They are commonly used for oceanographic research, environmental monitoring, and data collection over extended periods.

e. Hybrid AUVs: These versatile AUVs are designed to perform a combination of tasks, such as profiling, surveying, and gliding, depending on mission requirements.

1.2.2. Design Characteristics:

a. Swarm AUVs: Swarm AUVs operate in groups, coordinating their actions to achieve specific mission objectives. They are valuable for tasks like environmental monitoring, search and rescue, and underwater exploration.

b. Miniature AUVs: Miniature AUVs are compact and lightweight, often used for research in confined or shallow waters. They are portable and easy to deploy.

c. Large AUVs: Large AUVs are designed for deep-sea missions and are equipped with extensive sensor payloads. They have longer endurance and greater depth capabilities.

d. Bio-Inspired AUVs: Some AUV designs are inspired by marine organisms, such as fish or marine mammals, to achieve improved maneuverability and efficiency in challenging underwater environments.

1.2.3. Applications:

a. Scientific Research: AUVs are extensively used for oceanographic research, including studying marine ecosystems, collecting data on water properties, and conducting experiments in the deep sea [3].

b. Environmental Monitoring: AUVs are employed to monitor and assess marine environments, track pollution, and study the impact of climate change on the oceans.

c. Military and Defense: Military AUVs are used for mine countermeasures, underwater surveillance, and reconnaissance in naval operations.

d. Commercial and Industry: AUVs support the offshore oil and gas industry for tasks such as pipeline inspection, underwater maintenance, and offshore platform monitoring.

e. Archaeological Exploration: AUVs are used to explore and document underwater archaeological sites and locate shipwrecks.

f. Search and Rescue: AUVs equipped with imaging and sensing systems assist in search and rescue operations, locating and identifying objects or individuals in underwater environments.

1.2.4. Depth Capability:

a. Shallow-Water AUVs: These AUVs are designed for operations in relatively shallow coastal areas, lakes, and rivers.

b. Mid-Depth AUVs: Mid-depth AUVs can operate in moderately deep waters, often used for scientific research and environmental monitoring in offshore regions.

c. Deep-Sea AUVs: Deep-sea AUVs are engineered to withstand the extreme conditions of the deep ocean and can reach significant depths, making them suitable for deep-sea exploration and geological studies.

These classifications illustrate the diversity and adaptability of Autonomous Underwater Vehicles, allowing them to cater to a wide range of underwater missions and research objectives [2] . The choice of AUV type depends on the specific requirements of the mission and the challenges presented by the underwater environment.

1.3 Literature Survey On REMUS AUV

Introduction:

The REMUS (Remote Environmental Monitoring Unit - Autonomous Underwater Vehicle) family of AUVs has played a crucial role in advancing marine research and technology. Developed by the Woods Hole Oceanographic Institution (WHOI) [35], REMUS AUVs are widely recognized for their versatility and have been utilized across a broad spectrum of scientific, environmental, and defense applications.

Design and Capabilities:

Literature discussing REMUS AUVs emphasizes their robust design and versatile capabilities [1]. Comprehensive research has elucidated the evolutionary development of REMUS AUVs, highlighting enhancements in hull design, propulsion systems, power sources, and sensor payloads [19]. Various models of REMUS have undergone examination, with each being carefully tailored to meet specific mission prerequisites.

Applications:

A recurring theme in the literature revolves around the wide array of applications for REMUS AUVs. These applications encompass the fields of oceanography, marine biology, environmental monitoring, hydrography, archaeology, and national security. Multiple studies have underscored the adaptability of REMUS AUVs in diverse underwater environments, ranging from shallow coastal waters to the profound depths of deep-sea exploration [1].

Mission Planning and Control:

Comprehensive research endeavors have investigated the strategies governing mission planning and control for REMUS AUVs [1]. Scholarly works have delved into the evolution of autonomous navigation systems, the development of mission planning software, and the creation of real-time remote operation interfaces. This emphasis on autonomy has ushered in new possibilities for extended and adaptive missions [2].

Sensor Payloads:

Significant attention in the literature has been directed towards the sensor payloads of REMUS AUVs. It highlights the integration of state-of-the-art sensors, encompassing multibeam sonar, cameras, CTD (Conductivity, Temperature, Depth) sensors, and various environmental and chemical sensors. This integration empowers REMUS AUVs to conduct comprehensive data collection for scientific analysis [3].

Data Acquisition and Processing:

Scholarly studies have scrutinized methodologies for data acquisition, transmission, and processing. Researchers have explored techniques for efficient data storage, surface transmission, and real-time data processing aboard the vehicle [2]. These research endeavors contribute to enhancing the efficiency of data collection during missions.

Environmental Sensing and Monitoring:

Environmental sensing and monitoring using REMUS AUVs occupy central positions in the literature. Research endeavors have harnessed REMUS vehicles to investigate oceanographic phenomena, track marine life, and monitor fluctuations in water quality, temperature, and salinity [2]. These investigations make significant contributions to understanding intricate marine ecosystems.

Scientific Research:

The literature comprehensively documents the scientific discoveries facilitated by REMUS AUVs. Deep-sea exploration, underwater archaeology, marine biology, and geological studies have all reaped substantial benefits from the capabilities of REMUS vehicles [1]. These findings enrich our knowledge of the Earth's oceans.

Operational Challenges and Innovations:

Recognition of operational challenges, including communication constraints and navigation complexities in demanding underwater terrains, is evident in the literature. Researchers have proposed innovative solutions, encompassing enhanced acoustic communication, obstacle-avoidance algorithms, and adaptive mission planning.

Case Studies:

Numerous case studies have been presented, offering distinct illustrations of the successful deployment of REMUS AUVs in real-world scenarios. These case studies furnish valuable insights into specific missions, including significant archaeological discoveries, marine research expeditions, and security operations.

Future Directions:

Discussion papers and reviews have outlined prospective directions for the future of REMUS AUV technology. Anticipated developments include increased autonomy, enhanced energy efficiency, sensor miniaturization, and an extended scope of applications in emerging fields[1].

Conclusion:

The body of literature centered on REMUS AUVs [1] underscores their pivotal role in driving forward marine science and technology. From their robust design and versatile capabilities to their wide array of applications and contributions to scientific endeavors, REMUS AUVs continue to hold a preeminent position in the realm of underwater exploration and research.

1.4 Outline of this thesis

In this project, the primary focus is on designing a PID (Proportional-Integral-Derivative) controller to control one degree of motion of the underwater vehicle, specifically the pitch motion. The study is based on the REMUS AUV an underwater vehicle [1]. While there are various researches related to motion controllers for underwater vehicles, ranging from conventional PID controllers to advanced adaptive systems, this project is specifically aimed at designing a PID controller . Despite being a well-established controller, the PID controller is chosen for this project because of its satisfactory performance. The mathematical model of the underwater vehicle is developed by deriving the kinematic and dynamic equations of motion. The equations governing pitch and depth motion are solved using a state-space approach to obtain the system's transfer functions. Subsequently, control blocks for the system equipped with the PID controller are designed using MATLAB Simulink software, and simulations of the system are conducted. The obtained response is deemed satisfactory, achieving system stability.

Chapter 2

Overview of Autonomous Underwater Vehicles (AUVs)

An Autonomous Underwater Vehicle (AUV) is a type of robotic vehicle designed for underwater operations without human intervention. These vehicles are commonly used in various marine applications, including oceanography, underwater mapping, remote environmental monitoring, and underwater archaeology.

To compute the vehicle coefficients, it's imperative to initiate the process by specifying the vehicle's profile, establishing its mass, understanding its mass distribution and buoyancy characteristics, and subsequently identifying the essential control fin parameters.

Figure 2.1 : The REMUS Autonomous Underwater Vehicle [Prestro 2001]

2.1 AUV Design

The design of the REMUS vehicle's hull is based on the Myring hull profile equations [26],The vehicle profile can have a significant impact on its hydrodynamics, performance, and efficiency, particularly in applications such as autonomous underwater vehicles (AUVs) where minimizing drag and optimizing buoyancy are important considerations.

2.2 Acoustic transducer

The REMUS vehicle comes equipped with a forward-facing sonar transducer, featuring a cylindrical shape with a diameter of 10.1 cm (4.0 inches) .

2.3 Control Fin of AUV

Control fins are commonly designed to be adaptable and serve the purpose of assisting the Autonomous Underwater Vehicle (AUV) in course maintenance, directional changes, and pitch and roll adjustments [19]. Their functionality extends to stabilization, steering capabilities, and the achievement of preferred depth or heading. The significance of control fins is paramount in enhancing the AUV's maneuverability, enabling it to effectively navigate and execute diverse tasks within underwater environments.

2.4 Weight and buoyancy of AUV

The term ' weight and buoyancy of AUV ' pertains to the forces that come into play when a vehicle is submerged in a fluid, such as water. These forces hold immense significance in shaping the behavior of the vehicle within the fluid medium.

A. Vehicle Weight : This term signifies the gravitational force that acts upon the vehicle due to its mass, causing it to be drawn downwards. Generally, the vehicle's weight remains relatively constant, provided its mass remains unchanged.in this thesis we have taken weight of the AUV is W= 299 N.

B. Buoyancy : Buoyancy, conversely, stands for the upward force exerted on a submerged object, and it's generated by the fluid displaced by the object. Buoyancy acts in opposition to the force of gravity. The magnitude of buoyancy is contingent upon the volume of the vehicle and the density of the encompassing fluid. When an object displaces a volume of fluid greater than its own weight, it experiences a net upward buoyant force , which is B=206 N in this model.

In summary, the balance between the vehicle's gravitational weight and the opposing buoyant force it experiences dictates vehicle remains neutrally buoyant in the fluid. management of this equilibrium is of utmost importance for maintaining the preferred depth and stability of underwater vehicles (AUVs).

2.5 Centre of Gravity and Buoyancy

In this model , We assume Centre of gravity with respect to Origin at centre of buoyancy has only z component of vehicle which is z_{cg} is 0.019 m and center of buoyancy wrt origin at vehicle nose has only x component x_{cb} is -0.61 m.

2.6 Inertia Tensor

The inertia tensor of the vehicle is established in reference to the body-fixed origin situated at the center of buoyancy of the vehicle. Given that the products of inertia Ixy, Ixz, and Iyz are significantly smaller in magnitude compared to the moments of inertia Ixx, Iyy, and Izz, we will make the simplifying assumption that they are negligible [1]. This effectively implies that the vehicle exhibits two planes of axial symmetry.

Parameter	Value	Units
I_{xx}	1.77E-01	$kg \cdot m^2$
I_{yy}	3.45E+00	$kg \cdot m^2$
I_{zz}	3.45E+00	$kg \cdot m^2$

Table 2.1 : Moment of Inertia w.r.t. Origin at CB [1].

Chapter 3

Modeling of Autonomous Underwater Vehicle

To get a mathematical model of the vehicle, we divide modeling task into two categories:

- Kinematics : which relates only geometrical aspects of motion and
- Dynamics and Mechanics : which is the analysis of forces causing the motion.

To ascertain the position and orientation of a rigid body, six independent coordinates are required. Therefore, an Autonomous Underwater Vehicle (AUV) possesses six degrees of freedom, abbreviated as 6 DOF.

DOF	Motion	Forces	Linear and angular Velocity	Position
1	Motion in x-direction(Surge)	X	u	x
2	Motion in y-direction(Sway)	Y	v	y
3	Motion in z-direction(Heave)	Z	w	z
4	Rotation about x-axis(Roll)	K	p	ϕ
5	Rotation about y-axis(Roll)	M	q	θ
6	Rotation about z-axis(Roll)	N	r	Ψ

The first three coordinates and their time derivatives are used to represent the position and translation motion along x, y, and z axes, while the last three coordinates and their time derivatives are used to describe the orientation and rotational motion.

3.1. Kinematics

To analyze the motion of a vehicle in 6DOF (Six Degrees of Freedom), a common approach involves the use of two coordinate frames: the body-fixed reference frame and the inertial reference frame. In this setup, the body-fixed reference frame is attached to the vehicle itself and remains fixed with respect to the vehicle's motion. The motion of this body-fixed frame is then described relative to an inertial frame, typically an Earth-fixed frame, which is often treated as an inertial frame for marine vehicles, assuming that the acceleration of a point on the Earth's surface can be neglected. This approach suggests that certain parameters of the vehicle's motion should be expressed in the body-fixed frame, while others should be described in the inertial frame. Specifically: Linear and Angular Velocities: The linear and angular velocities of the vehicle are typically expressed in the body-fixed reference frame. This means that we measure the vehicle's speed and rotational rates from the perspective of the vehicle itself. Position and Orientation: On the other hand, the position and orientation of the vehicle are described with respect to the inertial frame. This means that we determine the vehicle's location and orientation in space relative to a fixed reference point, often an Earth-fixed frame, to account for the Earth's motion. By adopting this two-frame approach, we can effectively analyze the 6DOF motion of a vehicle, taking into account both its translational and rotational movements, while ensuring that we account for the Earth's motion when necessary. This approach is commonly used in the field of vehicle dynamics and control.

In a very general form, the motion of vehicle in 6DOF can be described by the following vectors

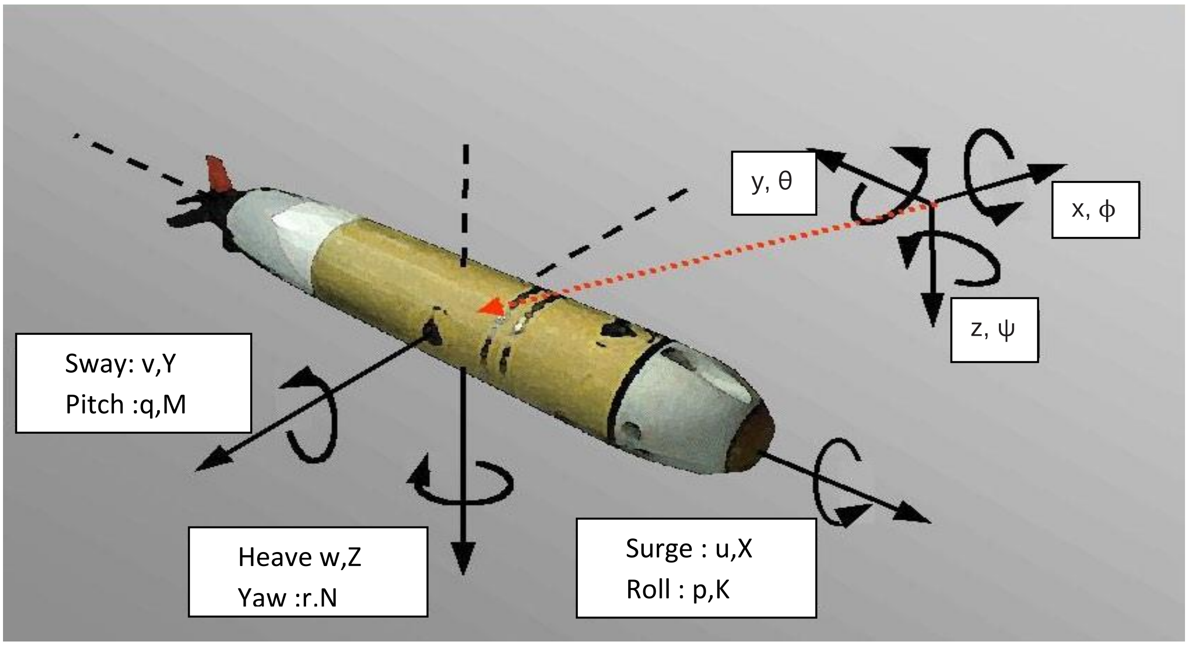

Figure 3.1 : REMUS Body – Fixed and Inertial Coordinate System [Prestro 2001]

$$\eta_1 = [\ x \quad y \quad z\ ]^T \qquad \eta_2 = [\ \phi \quad \theta \quad \psi\ ]^T$$

$$v_1 = [\ u \quad v \quad w\ ]^T \qquad v_2 = [\ p \quad q \quad r\ ]^T \qquad .(3.1)$$

$$\tau_1 = [\,X \quad Y \quad Z\,]^T \qquad\qquad \tau_2 = [\,K \quad M \quad N\,]^T$$

Here η represents the vehicle's spatial location and alignment concerning either the inertial or Earth-fixed reference frame and the body-fixed reference frame. Here , υ is used to denote the vehicle's translational and rotational velocities relative to the body-fixed reference frame. Meanwhile, τ represents the combined forces and moments acting on the vehicle in relation to the body-fixed reference frame.

The subsequent coordinate transformation establishes a connection between translational velocities in body-fixed coordinates and those in inertial or earth-fixed coordinates.

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} = T_I(\eta_2) \begin{bmatrix} u \\ v \\ w \end{bmatrix} \qquad ..(3.2)$$

Where

$$T_1(\eta_2) = \begin{bmatrix} \cos\Psi\cos\theta & -\sin\Psi\cos\phi + \cos\Psi\sin\theta\sin\phi & \sin\Psi\sin\theta + \cos\psi\sin\theta\cos\phi \\ \sin\Psi\cos\theta & \cos\Psi\cos\phi + \sin\Psi\sin\theta\sin\phi & -\cos\psi\sin\phi + \sin\Psi\sin\theta\cos\phi \\ -\sin\theta & \cos\theta\sin\Psi & \cos\theta\cos\phi \end{bmatrix} \qquad ..(3.3)$$

The next coordinate transformation establishes a connection for rotational velocities between body-fixed and earth-fixed coordinates,

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = T_2(\eta_2) \begin{bmatrix} p \\ q \\ v \end{bmatrix} \qquad ..(3.4a)$$

Here

$$T_2(\eta_2) = \begin{bmatrix} 1 & \sin\phi\tan\theta & \cos\phi\tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi\,/\cos\theta & \cos\phi\,/\cos\theta \end{bmatrix} \qquad ..(3.4b)$$

3.2. Dynamics of Autonomous underwater Vehicle

Dynamics is further divided into translational motion and rotational motion of the vehicle.

The subsequent equations describe the motion of a rigid body in six degrees of freedom, delineated in relation to body-fixed coordinates as Follows The initial three equations pertain to translational movements, while the subsequent three equations concern rotational motion.

$$\mathrm{m}[\dot{\mathrm{u}} - \mathrm{vr} + \mathrm{wq} - \mathrm{x_g}(\mathrm{q}^2 + \mathrm{v}^2) + \mathrm{y_g}(\mathrm{pq} - \dot{\mathrm{r}}) + \mathrm{z_g}(\mathrm{pr} + \dot{\mathrm{q}})] = \mathrm{X_{ext}}$$

$$\mathrm{m}[\dot{\mathrm{v}} - \mathrm{wp} + \mathrm{ur} - \mathrm{y_g}(\mathrm{r}^2 + \mathrm{p}^2) + \mathrm{z_g}(\mathrm{qr} - \dot{\mathrm{p}}) + \mathrm{x_g}(\mathrm{pq} + \dot{\mathrm{r}})] = \mathrm{Y_{ext}}$$

$$\mathrm{m}[\dot{\mathrm{w}} - \mathrm{uq} + \mathrm{vp} - \mathrm{z_g}(\mathrm{p}^2 + \mathrm{q}^2) + \mathrm{x_g}(\mathrm{pq} - \dot{\mathrm{r}}) + \mathrm{y_g}(\mathrm{pr} + \dot{\mathrm{p}})] = \mathrm{Z_{ext}}$$

..(3.5)

$$\mathrm{I_{xx}}\dot{\mathrm{p}} + \left(\mathrm{I_{zz}} - \mathrm{I_{yy}}\right)\mathrm{qr} - (\dot{\mathrm{r}} + \mathrm{pq})\,\mathrm{I_{xz}} + (\mathrm{r}^2 - \mathrm{q}^2)\mathrm{I_{yz}} + (\mathrm{pr} - \dot{\mathrm{q}})\mathrm{I_{xy}} + m\left[y_g(\dot{w} - uq + vp) - z_g(\dot{v} - wp + ur)\right] = K_{ext}$$

$$\mathrm{I_{yy}}\dot{\mathrm{q}} + (\mathrm{I_{xx}} - \mathrm{I_{zz}})\mathrm{rp} - (\dot{\mathrm{p}} + \mathrm{qr})\,\mathrm{I_{xy}} + (\mathrm{p}^2 - \mathrm{r}^2)\mathrm{I_{xz}} + (\mathrm{qp} - \dot{\mathrm{r}})\mathrm{I_{yz}} + m\left[z_g(\dot{u} - vr + wq) - x_g(\dot{w} - uq + vp)\right] = M_{ext}$$

$$\mathrm{I_{zz}}\dot{\mathrm{r}} + \left(\mathrm{I_{yy}} - \mathrm{I_{xx}}\right)\mathrm{pq} - (\dot{\mathrm{q}} + \mathrm{rp})\,\mathrm{I_{yz}} + (\mathrm{q}^2 - \mathrm{p}^2)\mathrm{I}_{xy} + (\mathrm{rq} - \dot{\mathrm{p}})\mathrm{I_{xz}} + m\left[x_g(\dot{v} - wp + ur) - y_g(\dot{u} - vr + wq)\right] = N_{ext}$$

Here m is the mass of AUV , these equations do not account for the center of buoyancy terms, which are zero-valued. With the body-fixed coordinate system centered at the vehicle's center of buoyancy, we can define the following diagonal inertia tensor :

$$\mathrm{I_0} = \begin{bmatrix} \mathrm{I_{xx}} & 0 & 0 \\ 0 & \mathrm{I_{yy}} & 0 \\ 0 & 0 & \mathrm{I_{zz}} \end{bmatrix}$$

The products of inertia for the vehicle's inertia are relatively small.so the term Ixy ,Ixz and so on terms can be neglected because it has very small values . Now we can simplify the above equations as follows after neglecting the product of Inertia:

$$m[\dot{u} - vr + wq - x_g(q^2 + v^2) + y_g(pq - \dot{r}) + z_g(pr + \dot{q})] = X_{ext}$$

$$m[\dot{v} - wp + ur - y_g(r^2 + p^2) + z_g(qr - \dot{p}) + x_g(pq + \dot{r})] = Y_{ext}$$

$$m[\dot{w} - uq + vp - z_g(p^2 + q^2) + x_g(pq - \dot{r}) + y_g(pr + \dot{p})] = Z_{ext}$$

..(3.6)

$$I_{xx}\dot{p} + (I_{zz} - I_{yy})qr + m[y_g(\dot{w} - uq + vp) - z_g(\dot{v} - wp + ur)] = K_{ext}$$

$$I_{yy}\dot{q} + (I_{xx} - I_{zz})rp + m[z_g(\dot{u} - vr + wq) - x_g(\dot{w} - uq + vp)] = M_{ext}$$

$$I_{zz}\dot{r} + (I_{yy} - I_{xx})pq + m[x_g(\dot{v} - wp + ur) - y_g(\dot{u} - vr + wq)] = N_{ext}$$

We can also simplify these equations by considering y_g is small as compare to other terms so we can neglect this term.

$$m[\dot{u} - vr + wq - x_g(q^2 + v^2) + z_g(pr + \dot{q})] = X_{ext}$$

$$m[\dot{v} - wp + ur + z_g(qr - \dot{p}) + x_g(pq + \dot{r})] = Y_{ext}$$

$$m[\dot{w} - uq + vp - z_g(p^2 + q^2) + x_g(pq - \dot{p})] = Z_{ext}$$

…(3.7)

$$I_{xx}\dot{p} + (I_{zz} - I_{yy})qr + m[-z_g(\dot{v} - wp + ur)] = K_{ext}$$

$$I_{yy}\dot{q} + (I_{xx} - I_{zz})rp + m[z_g(\dot{u} - vr + wq) - x_g(\dot{w} - uq + vp)] = M_{ext}$$

$$I_{zz}\dot{r} + (I_{yy} - I_{xx})pq + m[x_g(\dot{v} - wp + ur)] = N_{ext}$$

3.3 Effect of External Forces and Moments

In the equations of motion for the vehicle, external forces and moments.

$$F_{ext} = F_{hydrostatic} + F_{lift} + F_{drag} + F_{control}$$

The combined forces and moments acting on the vehicle within the depth plane can be represented as :

$$X_{ext} = X_{HS} + X_{u|u|}u|u| + X_{\dot{u}}\dot{u} + x_{wq}wq + x_{qq}q^2 + x_{vr}vr + x_{rr}r^2 + X_{prop}$$

$$Y_{ext} = Y_{HS} + Y_{v|v|}v|v| + Y_{\dot{v}}\dot{v} + Y_{\dot{r}}\dot{r} + Y_{r|r|}r|r| + Y_{ur}ur + Y_{wp}wp + y_{pq}pq + Y_{uv}uv + Y_{uu}\,\delta_r\ u^2\delta_r$$

$$Z_{ext} = Z_{HS} + Z_{w|w|}w|w| + Z_{q|q|}q|q| + Z_{\dot{w}}\dot{w} + Z_{\dot{q}}\dot{q} + Z_{uq}uq + Z_{vp}vp + Z_{rp}rp + Z_{uw}uw + Z_{uu}\,\delta_s\ u^2\delta_s$$

$$K_{ext} = K_{HS} + K_{p|p|}p|p| + K_{\dot{p}}\dot{p} + K_{prop}$$

$$M_{ext} = M_{HS} + M_{w|w|}w|w| + M_{\dot{w}}\dot{w} + M_{\dot{q}}\dot{q} + M_{q|q|}q|q| + M_{uq}uq + M_{vp}vp + M_{rp}rp + M_{uw}uw_{+}M_{uu\,\delta_s}u^2\delta_s \qquad \text{…. (3.8)}$$

$$N_{ext} = N_{HS} + N_{v|v|}v|v| + N_{r|r|}r|r| + N_{\dot{v}}\dot{v} + N_{\dot{r}}\dot{r} + N_{ur}ur + N_{wp}wp + N_{pq}pq + N_{uv}uv_{+}\,N_{uu\delta_r}*\ u^2\delta_r$$

Here we have used some special notation for drag coefficient like u|u| instead of u^2 because drag always opposes vehicle motion so ensure the correct sign, we consider u|u| not u^2 .

The expansion of these equations results in nonlinear equations for hydrostatic forces and moments . These expression will be substituted in the above equations.

$$\begin{gathered}
X_{HS} = -(W - B)\sin\theta \\
Y_{HS} = (W - B)\cos\theta\sin\phi \\
Z_{HS} = (W - B)\cos\theta\cos\phi \\
K_{HS} = -(y_g W - y_b B)\cos\theta\cos\phi - (z_g W - z_b B)\cos\theta\sin\phi \\
M_{HS} = -(z_g W - z_b B)\sin\theta - (x_g W - x_b B)\cos\theta\cos\phi \\
N_{HS} = -(x_g W - x_b B)\cos\theta\sin\phi - (y_g W - y_b B)\sin\theta
\end{gathered} \qquad (3.9)$$

Parameter	Value	Units	Description
$X_{u\|u\|}$	-1.62E+00	kg/m	Cross-flow Drag
$X_{\dot{u}}$	-9.30E-01	kg	Added Mass
X_{wq}	-3.55E+01	kg/rad	Added Mass Cross-term
X_{qq}	-1.93E+00	Kg.m/rad	Added Mass Cross-term
X_{vr}	3.55E+01	m/rad	Added Mass Cross-term
X_{prop}	9.25E+00	N	Propeller Thrust
$Y_{v\|v\|}$	-1.31E+02	kg/m	Cross-flow Drag
Y_{uv}	-2.86E+01	kg/m	Body Lift Force and Fin Lift
$Y_{\dot{v}}$	-3.55E+01	kg	Added Mass
$Y_{\dot{r}}$	1.93E+00	Kg.m/rad	Added Mass
Y_{ur}	5.22E+00	kg/rad	Added Mass Cross Term and Fin Lift
Y_{wp}	3.55E+01	kg/rad	Added Mass Cross-term
Y_{pq}	1.93E+00	kg/(m.rad)	Added Mass Cross-term
$Z_{w\|w\|}$	-1.31E+02	kg/m	Cross-flow Drag
$Z_{q\|q\|}$	-6.32E-01	kg·m/rad^2	Cross-flow Drag
Z_{uw}	-2.86E+01	kg/m	Body Lift Force and Fin Lift
$Z_{\dot{w}}$	-3.55E+01	kg	Added Mass
$Z_{\dot{q}}$	-1.93E+00	Kg.m/rad	Added Mass
Z_{uq}	-5.22E+00	kg/rad	Added Mass Cross-term and Fin Lift
Z_{vp}	-3.55E+01	kg/rad	Added Mass Cross-term
Z_{rp}	1.93E+00	kg/rad	Added Mass Cross-term
$Z_{uu\delta r}$	-9.64E+00	kg/(m.rad)	Fin Lift Force

Table 3.1 : Standard REMUS Non-Linear Maneuvering Coefficients: Forces(Prestero. 2001 :[1])

Parameter	Value	Units	Description
$K_{p\|p\|}$	-1.30E-03	$kg \cdot m^2/rad^2$	Rolling Resistance
$K_{\dot{p}}$	-1.41E-02	$kg \cdot m^2/rad$	Added Mass
K_{prop}	-5.43E-01	$N \cdot m$	Propeller Torque
M_{ww}	3.18E+00	kg	Cross-flow Drag
$M_{q\|q\|}$	-9.40E+00	$kg \cdot m^2/rad^2$	Cross-flow Drag
M_{uw}	2.40E+01	kg	Body and Fin Lift and Munk Moment
$M_{\dot{w}}$	-1.93E+00	$kg \cdot m$	Added Mass
$M_{\dot{q}}$	-4.88E+00	$kg \cdot m^2/rad$	Added Mass
M_{uq}	-2.00E+00	kg.m/rad	Added Mass Cross Term and Fin Lift
M_{vp}	-1.93E+00	kg.m/rad	Added Mass Cross-term
M_{rp}	4.86E+00	$kg \cdot m^2/rad^2$	Added Mass Cross-term
$M_{uu\delta s}$	-6.15E+00	kg/rad	Fin Lift Moment
$N_{v\|v\|}$	-3.18E+00	kg	Cross-flow Drag
$N_{r\|r\|}$	-9.40E+00	$kg \cdot m^2/rad^2$	Cross-flow Drag
N_{uv}	-2.40E+01	kg	Body and Fin Lift and Munk Moment
$N_{\dot{v}}$	1.93E+00	$kg \cdot m$	Added Mass
$N_{\dot{r}}$	-4.88E+00	$kg \cdot m^2/rad$	Added Mass
N_{ur}	-2.00E+00	$kg \cdot m/rad$	Added Mass Cross Term and Fin Lift
N_{wp}	-1.93E+00	$kg \cdot m/rad$	Added Mass Cross Term
N_{pq}	-4.86E+00	$kg \cdot m^2/rad^2$	Added Mass Cross Term
$N_{uu\delta r}$	-6.15E+00	kg/rad	fin Lift Moment

Table 3.2 : Standard REMUS Non-Linear Maneuvering Coefficients: Momentum (Prestero. 2001 :[1])

Chapter 4

Depth and Pitch Control Model

The objective is to maintain the AUV at a particular height above the seafloor. This is achieved by changing the pitch of the vehicle. A two loop controller is used for this purpose. The inner loop controller, PD controller controls the pitch and the outer loop controller, P controller controls the depth of the vehicle

Linearizing the AUV Equations

We will linearize the all equations of motion which is described in chapter 3 and provide a concise overview of the linearization process for vehicle kinematics, dynamics, and mechanics.

4.1. Linearization of AUV Kinematics

We are going to consider depth plane motion only, we have to only consider Taking into account the surge velocity (u), heave velocity (w), and pitch rate (q) relative to the body, as well as the vehicle's forward position (x), depth (z), and pitch angle (θ) relative to the Earth's frame of reference.

Now from the equation (3.3) we can write:

$$\dot{x} = \cos\theta u + \sin\theta w$$

$$\dot{z} = -\sin\theta u + \cos\theta\, w \tag{4.1}$$

$$\dot{\theta} = q$$

We will proceed with the linearization of these equations under the assumption that the vehicle's motion comprises minor deviations from a stable reference point. Here, 'U' signifies the steady-state forward velocity of the vehicle. Considering heave and pitch rate are linearize to zero and by using Maclaurin expansion of the trigonometric terms and neglecting higher order terms, the linearized kinematic equations are:

$$\dot{x} = u + \theta w$$
$$\dot{z} = -U\theta + w \quad (4.2)$$
$$\dot{\theta} = q$$

4.2. Linearization of AUV Dynamics

Similarly for dynamics equations, all the Smaller terms are set to zero and out of plane vehicle motion equations are neglected. The dynamics equations are:

$$X = m\left(\dot{u} + wq - x_g q^2 + z_g \dot{q}\right)$$
$$Z = m\left(\dot{w} - uq - z_g q^2 - x_g \dot{q}\right) \quad (4.3)$$
$$M = I_{yy}\dot{q} + m\left(z_g(\dot{u} + wq) - x_g(\dot{w} - uq)\right)$$

Now, using the linearization, the above equations are reduced to

$$X = m\left(\dot{u} + z_g \dot{q}\right)$$
$$Z = m\left(\dot{w} - Uq - x_g \dot{q}\right) \quad (4.4)$$
$$M = I_{yy}\dot{q} + m\left(z_g(\dot{u} + wq) - x_g(\dot{w} - Uq)\right)$$

Similarly, for force balance and moment balance equations, all the terms which have smaller value are set to zero and out of plane motion equations are neglected. The Mechanics equations after linearization are:

$$X = X_{\dot{u}}\dot{u} + X_q q + X_u u + X_\theta \theta$$
$$Z = Z_{\dot{w}}\dot{w} + Z_{\dot{q}}\dot{q} + Z_w w + Z_q q + Z_{\delta_s}\delta_s \quad (4.5)$$
$$M = M_{\dot{w}}\dot{w} + M_{\dot{q}}\dot{q} + M_w w + M_q q + M_\theta \theta + M_{\delta_s}\delta_s$$

4.3 Linearization of equations of motion:

After merging the equations (4.2) and (4.5), We will get :

$$(m - x_{\dot{u}})\dot{u} + m z_g \dot{q} - X_u u - X_q q - X_\theta \theta = 0$$
$$(m - z_{\dot{w}})\dot{w} - \left(m x_g + z_{\dot{q}}\right)\dot{q} - Z_w w - \left(mU + z_q\right)q = Z_{\delta_s}\delta_s \quad (4.6)$$
$$m z_g \dot{u} - \left(m x_g + M_{\dot{w}}\right)\dot{w} + \left(I_{yy} - M_{\dot{q}}\right)\dot{q} - M_w w + \left(m x_g U - M_q\right)q - M_\theta \theta = M_{\delta_s}\delta_s$$

Here we can consider z_g is very small as compare to other terms. By decoupling heave and pitch from surge, we derive the following equations of motion:

$$(m - Z_{\dot{w}})\dot{w} - (mx_g + z_{\dot{q}})\dot{q} - Z_w w - (mU + z_q)q = Z_{\delta_s}\delta_s \tag{4.7}$$

$$-(mx_g + M_{\dot{w}})\dot{w} + (I_{yy} - M_{\dot{q}})\dot{q} - M_w w + (mx_g U - M_q)q - M_\theta \theta = M_{\delta_s}\delta_s$$

Similarly , kinematic equations (4.2) can be written as

$$\dot{z} = -U\theta + w \tag{4.8}$$

$$\dot{\theta} = q$$

Parameter	Value	Units	Description
X_θ	8.90E+00	$kg \cdot m/s^2$	Hydrostatic
Xu	-1.35E+01	kg/s	Axial Drag
$X_{u^\cdot}$	-9.30E-01	kg	Added Mass
X_q	-5.78E-01	$kg \cdot m/s$	Added Mass Cross Term
Z_w	-6.66E+01	kg/s	Combined Term
Z_q	-9.67E+00	$kg \cdot m/s$	Combined Term
$Zw^\cdot$	-3.55E+01	kg	Added Mass
$Z_q^\cdot$	-1.93E+00	$kg \cdot m$	Added Mass
$Z\delta_s$	-5.06E+01	$kg \cdot m/s^2$	Fin Lift
M_θ	-5.77E+00	$kg \cdot m^2/s^2$	Hydrostatic
M_w	3.07E+01	$kg \cdot m/s$	Combined Term
M_q	-6.87E+00	$kg \cdot m^2/s$	Combined Term
$Mw^\cdot$	-1.93E+00	kg.m	Added Mass
$Mq^\cdot$	-4.88E+00	$kg\ m^2$	Added Mass
$Z\delta_s$	-3.46E+01	$kg\ m^2/s^2$	Fin Lift

Table 4.1 : Linearize maneuvering Cofficient (Prestero. 2001 :[1])

4.4 Matrix Form of Linearized equation of motion

If heave velocity is less, we can neglect it with respect to other terms so that the kinematics and dynamics equations can be written into following matrix form:

$$\begin{bmatrix} \mathrm{I_{yy}} - \mathrm{M_{\dot{q}}} & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{\mathrm{q}} \\ \dot{\mathrm{z}} \\ \dot{\theta} \end{bmatrix} + \begin{bmatrix} -M_q & 0 & -M_\theta \\ 0 & 0 & U \\ -1 & 0 & 0 \end{bmatrix} \begin{bmatrix} q \\ z \\ \theta \end{bmatrix} = \begin{bmatrix} M_{\delta_s} \\ 0 \\ 0 \end{bmatrix} [\, \delta_s \,] \tag{4.9}$$

$$\begin{bmatrix} \dot{\mathrm{q}} \\ \dot{\mathrm{z}} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \frac{M_q}{\mathrm{I_{yy}} - \mathrm{M_{\dot{q}}}} & 0 & \frac{M_\theta}{\mathrm{I_{yy}} - \mathrm{M_{\dot{q}}}} \\ 0 & 0 & -U \\ 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} q \\ z \\ \theta \end{bmatrix} + \begin{bmatrix} \frac{M_{\delta_s}}{\mathrm{I_{yy}} - \mathrm{M_{\dot{q}}}} \\ 0 \\ 0 \end{bmatrix} [\, \delta_s \,] \tag{4.10}$$

Now we can relate the above equation with standard state space equation:

$$\dot{\mathrm{X}} = \mathrm{Ax} + \mathrm{Bu} \tag{4.11}$$

After substitute the coefficient we can get:

$$A = \begin{bmatrix} -0.82 & 0 & -0.69 \\ 0 & 0 & -1.54 \\ -1 & 0 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} 4.16 \\ 0 \\ 0 \end{bmatrix} \tag{4.12}$$

4.5. Control system Design

Now,we can examine the development of a straightforward vehicle controller based on the state equations (4.10) . This illustrative controller, resembling the actual vehicle controller, comprises an inner proportional and derivative (PD) pitch loop and an outer proportional depth loop. We will design each of these controllers step by step.

4.5.1 Transfer Function of the Model

Initially, we aim to obtain the transfer function for the inner pitch loop, which connects the input stern plane angle δs to the output vehicle pitch angle θ. Through the Laplace transform of Equation (4.10), we can represent this open-loop transfer function as follows:

$$G1(s) = \frac{\theta_s(s)}{\delta_s(s)} = \frac{\frac{M_{\delta_s}}{I_{yy}-M_{\dot{q}}}}{s^2 - \frac{M_N}{I_{yy}-M_{\dot{q}}}s - \frac{M_\theta}{I_{yy}-M_{\dot{q}}}}$$

(4.13)

Pitch control is done by PD controller with general transfer function given by

$$\frac{\delta_s(s)}{e_\theta(s)} = -K_p(T_d s + I)$$

Where K_p is proportional Gain and T_d is derivative time constant. Because of difference between the vehicle stern angle is applied. Positive stern angle create negative torque around Y axis that force the vehicle diving down (negative pitch rate) .

Here $e_\theta(\text{error in pitch}) = \theta_d(\text{desired pitch}) - \theta(\text{Actual Pitch})$,

Similarly , our objective is to determine the transfer function of the outer depth loop, which establishes the relationship between the input vehicle pitch angle θd and the resulting vehicle depth z.

$$G2(s) = \frac{z(s)}{\theta(s)} = -\frac{U}{s} \quad (4.14)$$

Depth control is done by P controller with general transfer function given by

$$\frac{\theta_d(s)}{e_z(s)} = \gamma$$

And

After putting the value in equation (4.13) and (4.14) , we get,

$$G1(s) = \frac{-3.18}{s^2+1.09s+0.52} \quad \ldots.(4.15)$$

$$G2(s) = -\frac{1.54}{s} \quad \ldots (4.16)$$

4.5.2 Open loop response of the system

For designing the pitch motion controller, transfer function equation (4.15) is considered. Open loop respond of the system is obtain by constructing the following block is Matlab Simulink software.

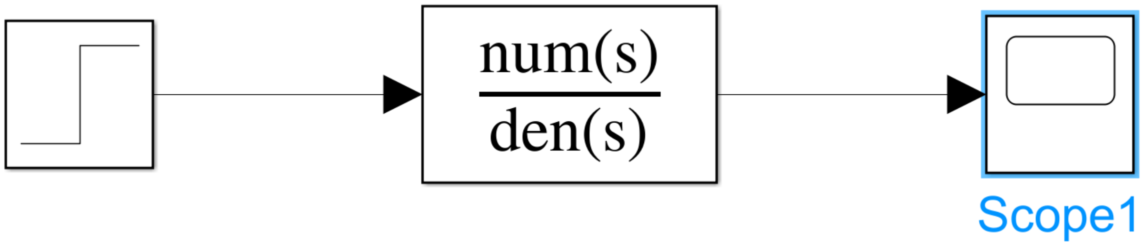

Figure 4.1 : Open loop pitch control block

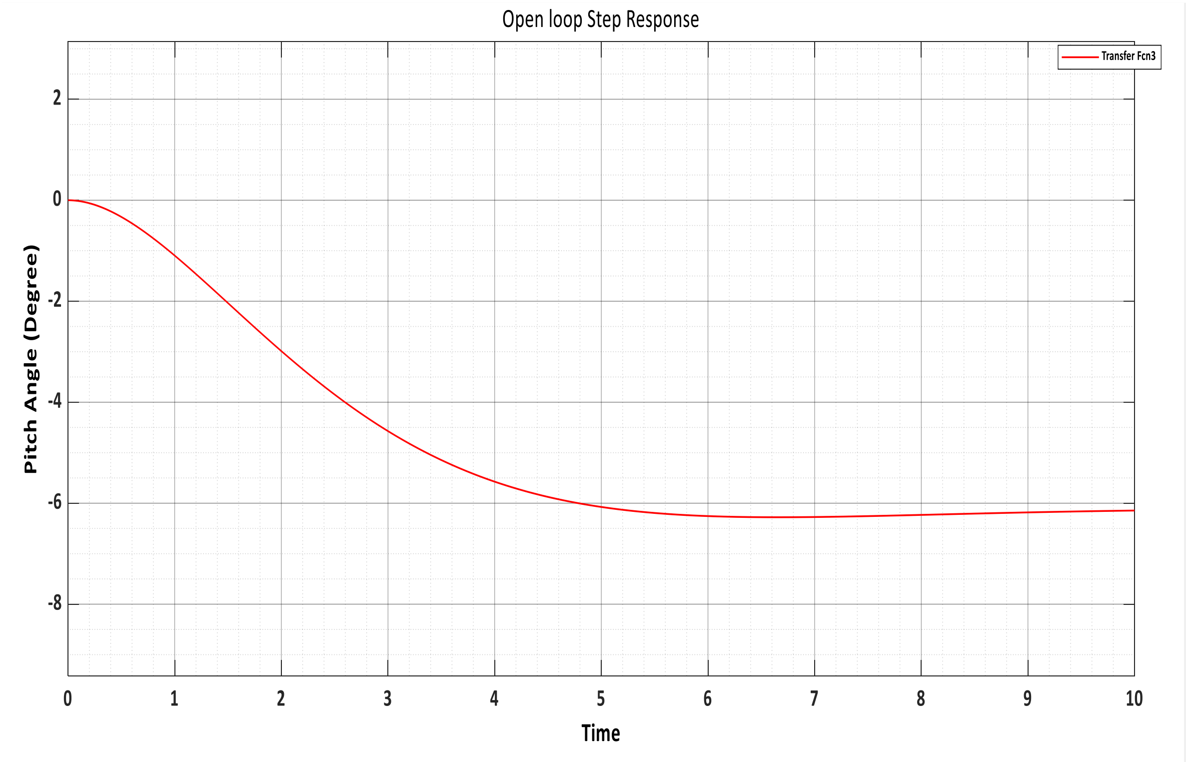

Figure 4.2 : Open loop step response of Pitch

We will design a proportional-Derivative (PD) for inner loop , and a Proportional for outer loop the whole block diagram give the depth plane control.

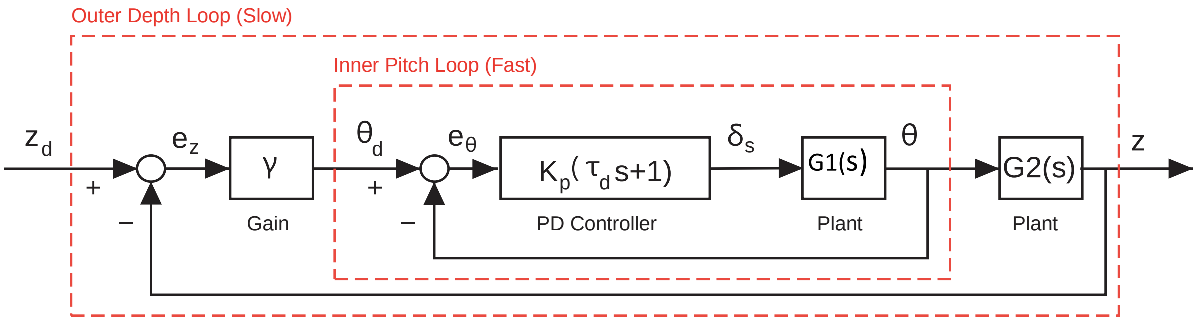

Figure : 4.3 Depth plane Control System Block Diagram

Now we are going to use random value through hit and trial for controller parameter and got some case where system is optimal .

Controller	Case 1	Case 2	Case 3	Case 4
Kp	-10.345	-0.1872	-4.732	-1.853
Kd	-2.174	-0.2237	-2.479	-1.593
Filter gain	100	129.9	206.8	3.5813.9

Table 4.2 : PD controller Parameters

Response of each case is plotted in below figures :

Case 1:

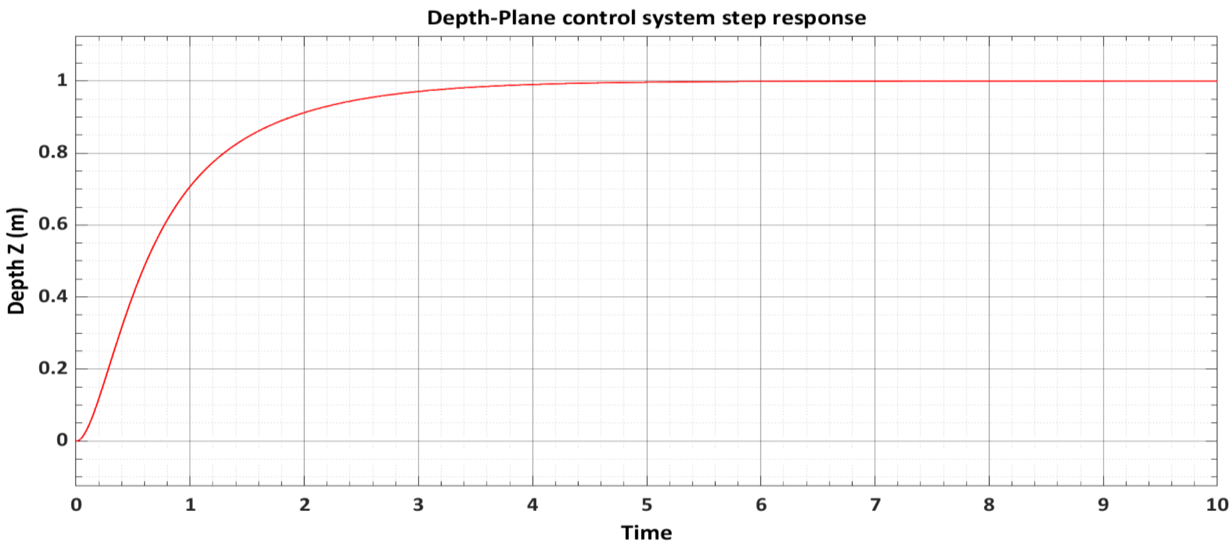

Figure 4.4 :Depth plane control (case 1)

Case 2 :

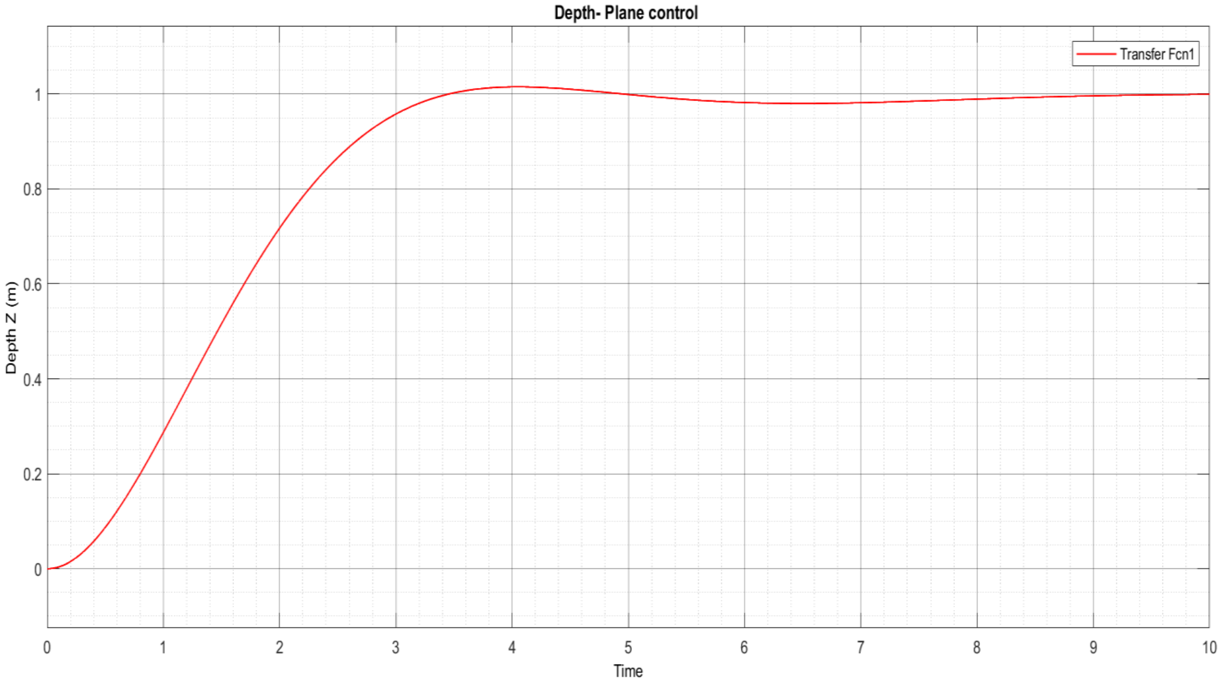

Figure 4.5 :Depth plane control case 2

Case 3 :

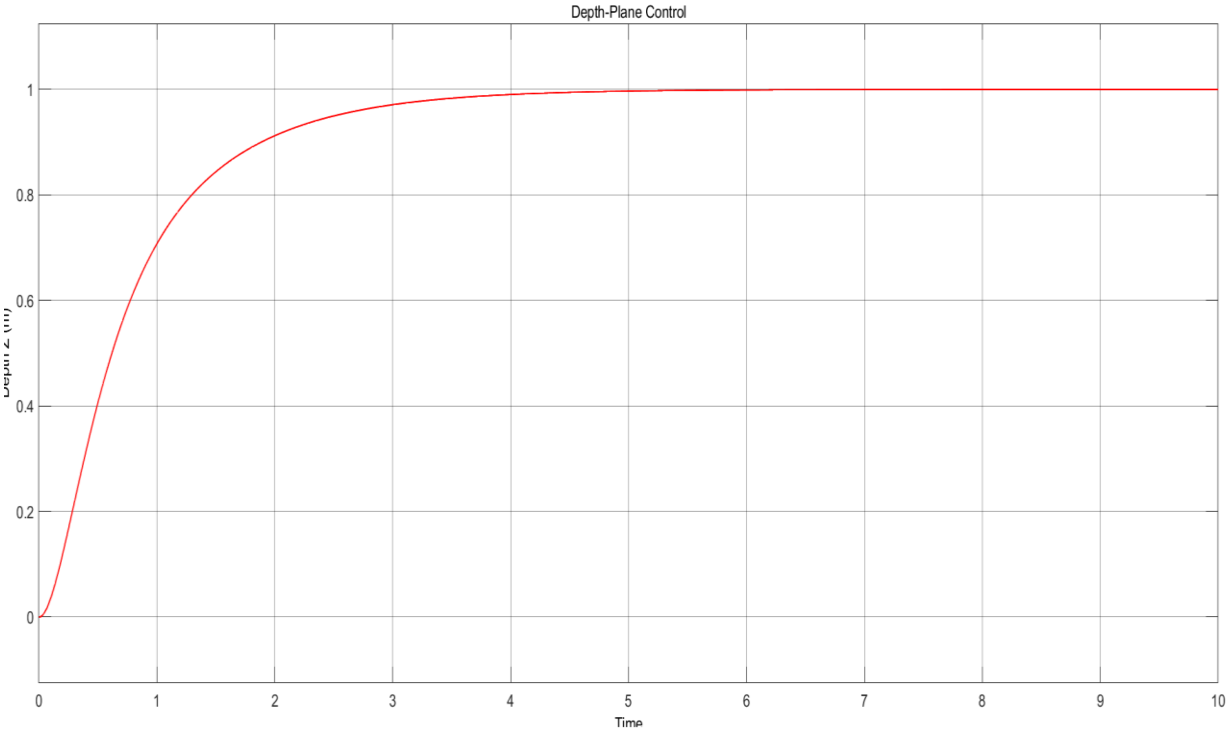

Figure 4.6 :Depth plane control case 3

4.5.3 Designing PID controller for pitch motion

When designing a PID controller, it's essential to consider the impact of each controller component. For instance, a proportional controller (Kp) can effectively reduce the rise time but cannot completely eliminate steady-state error. On the other hand, an integral controller (Ki) is instrumental in eradicating steady-state error but tends to lead to a slower response time. Increasing the derivative controller (Kd) contributes to enhanced stability and a reduction in overshoot. The distinctive characteristics of each controller are summarized in Table below:

Controller	Rise time	Overshoot	Settling time	Steady state error
Kp	Decrease	Increase	Small change	Decrease
Ki	Decrease	Increase	Increase	Eliminated
Kd	Small change	Decrease	Decrease	No change

Table 4.3 : Characteristics of controller

PID controller is designed in Matlab Simulink by using PID control block. The control block for the pitch motion is shown in the figure:

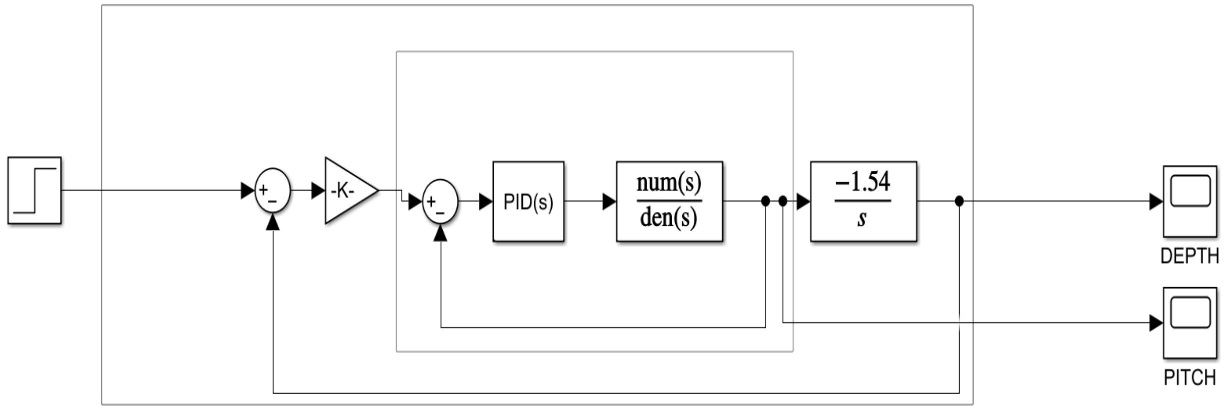

Figure 4.7 : Depth plane control System Block Diagram with PID controller

Controller	Case 1	Case 2	Case 3	Case 4	Case 5
Kp	-0.299	-0.5647	-0.1803	-1.199	-8.729
Ki	-0.0374	-0.00773	-0.02528	-0.0365	-4.398
Kd	-0.4702	-0.1008	-0.2475	-1.158	-3.965
Filter gain	205.8	1.568	129.9	3.58	13.51

Table 4.4 : PID controller Parameter for different cases

Results of each case is plotted in the below figure :

Case 1 :

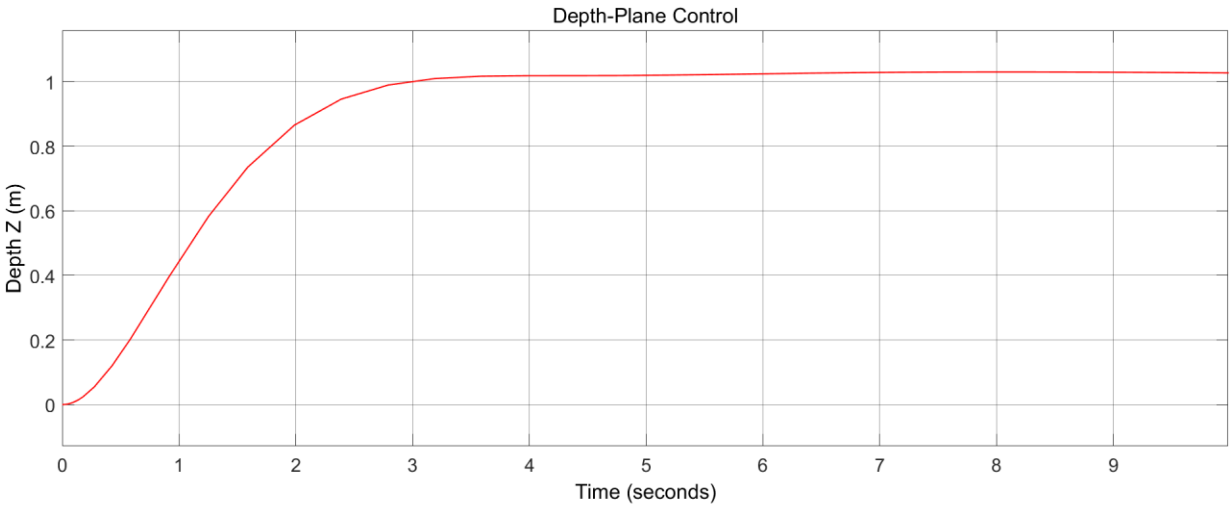

Figure 4.8 : Depth Response (case 1)

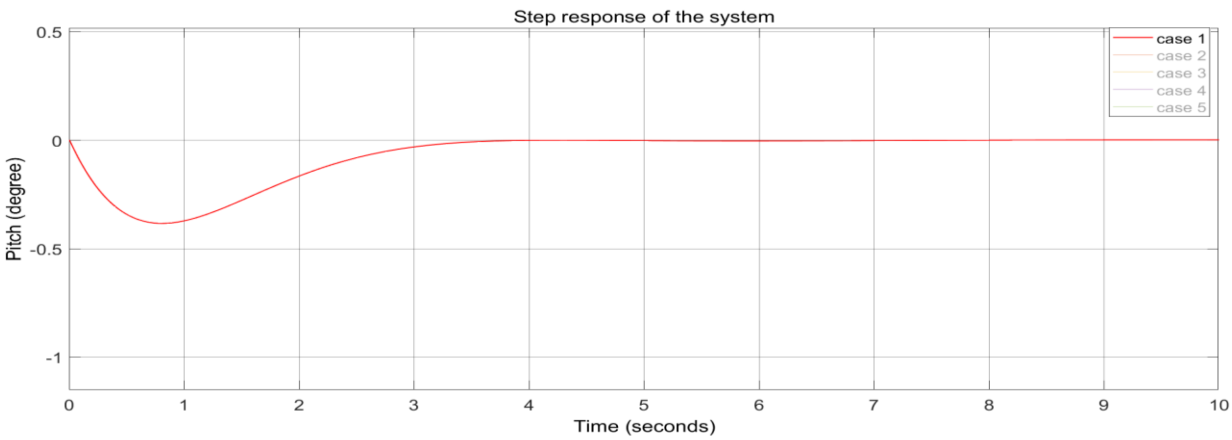

Figure 4.9 : Pitch Response (case 1)

Case 2 :

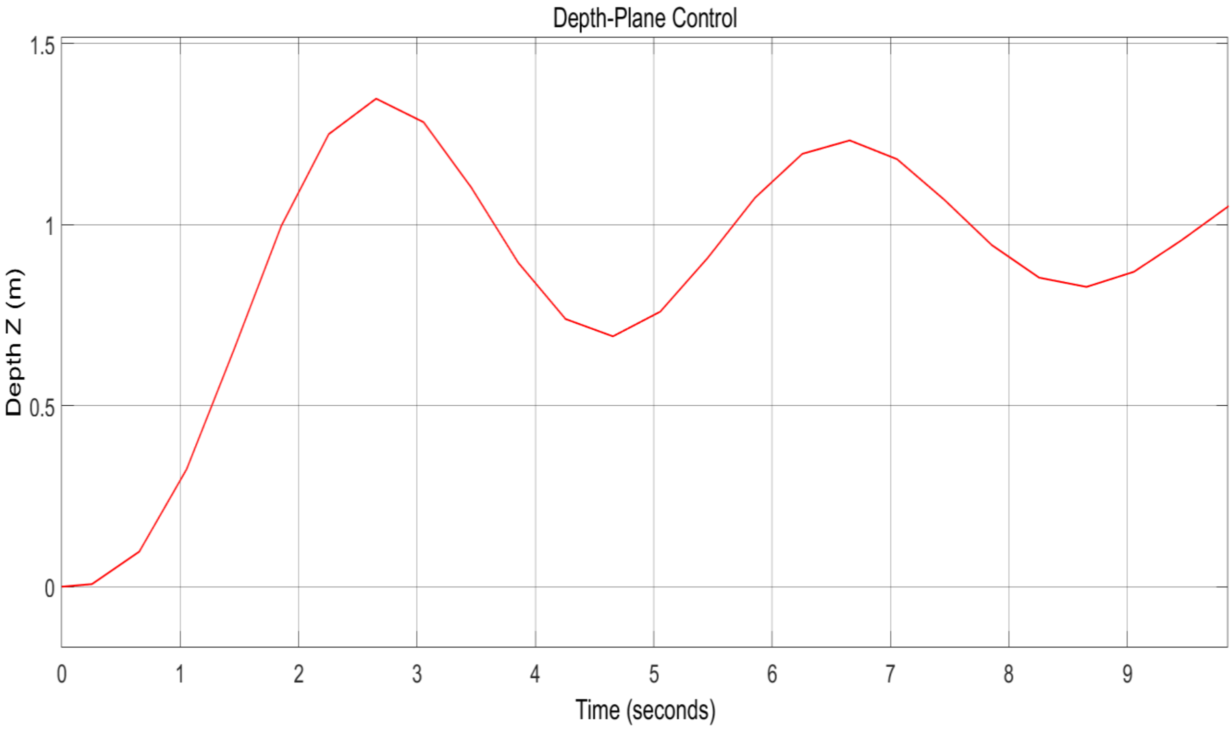

Figure 4.10 : Depth Response (case 2)

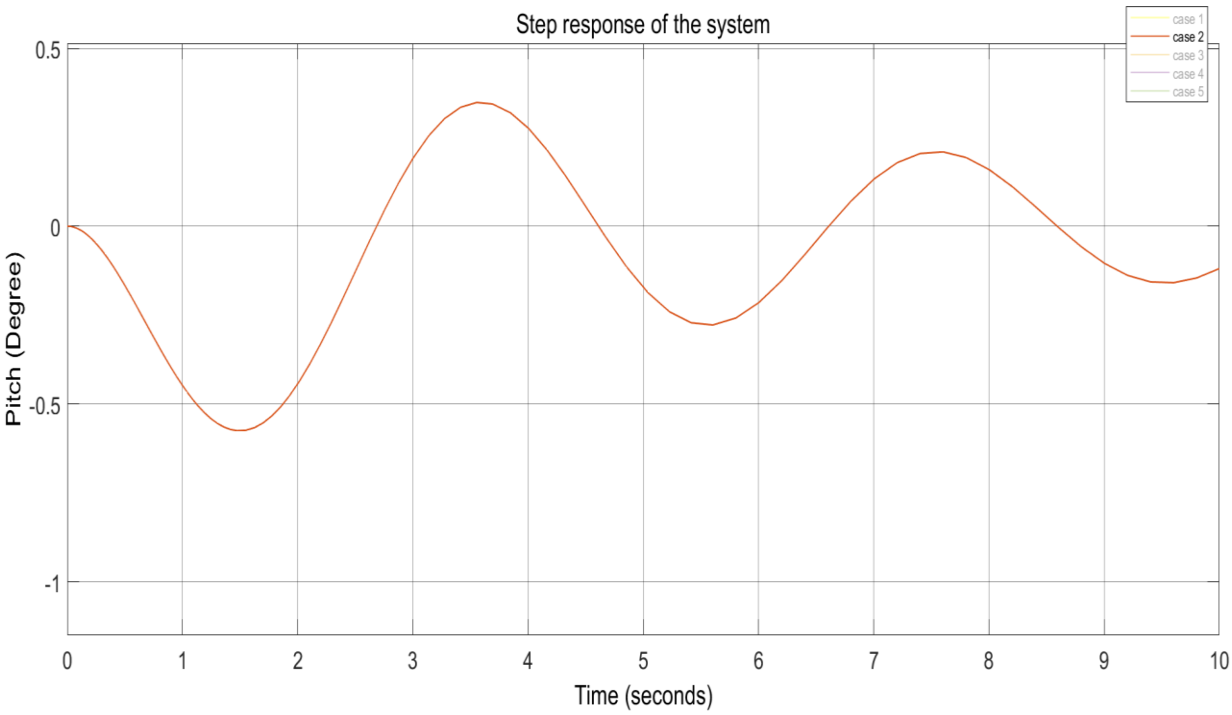

Figure 4.11 : Pitch Response (case 2)

Case 3 :

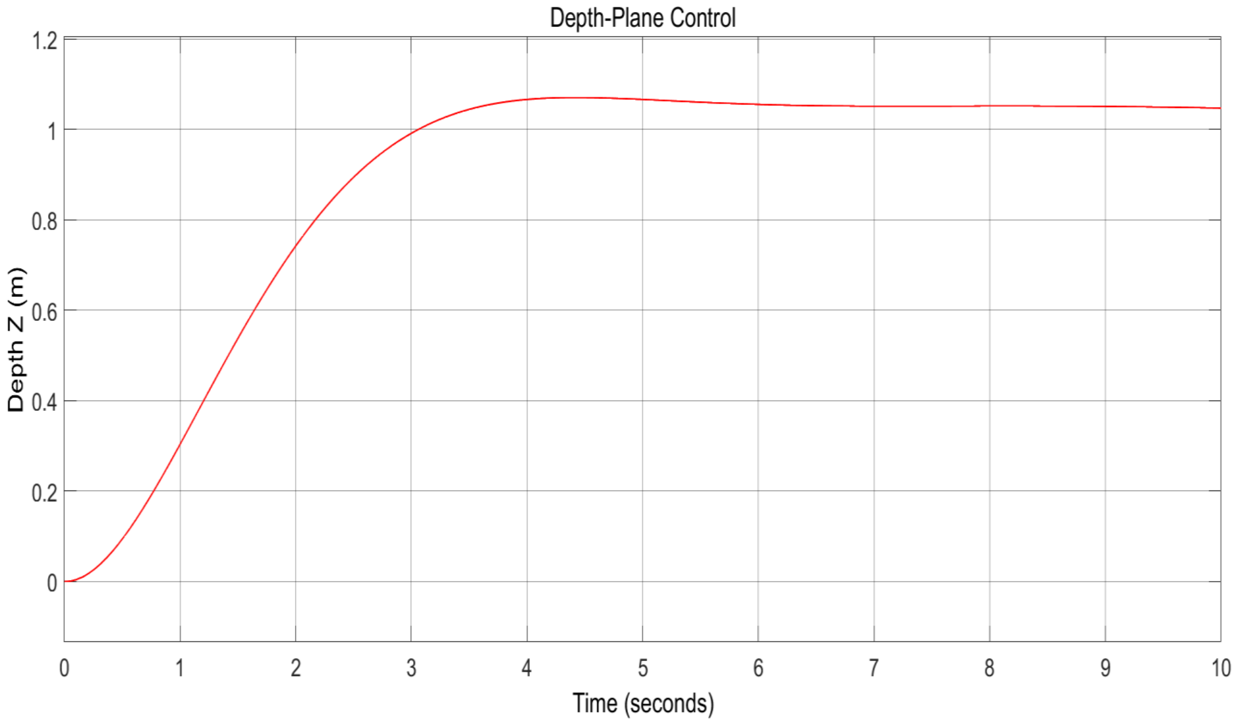

Figure 4.12 : Depth Response (case 3)

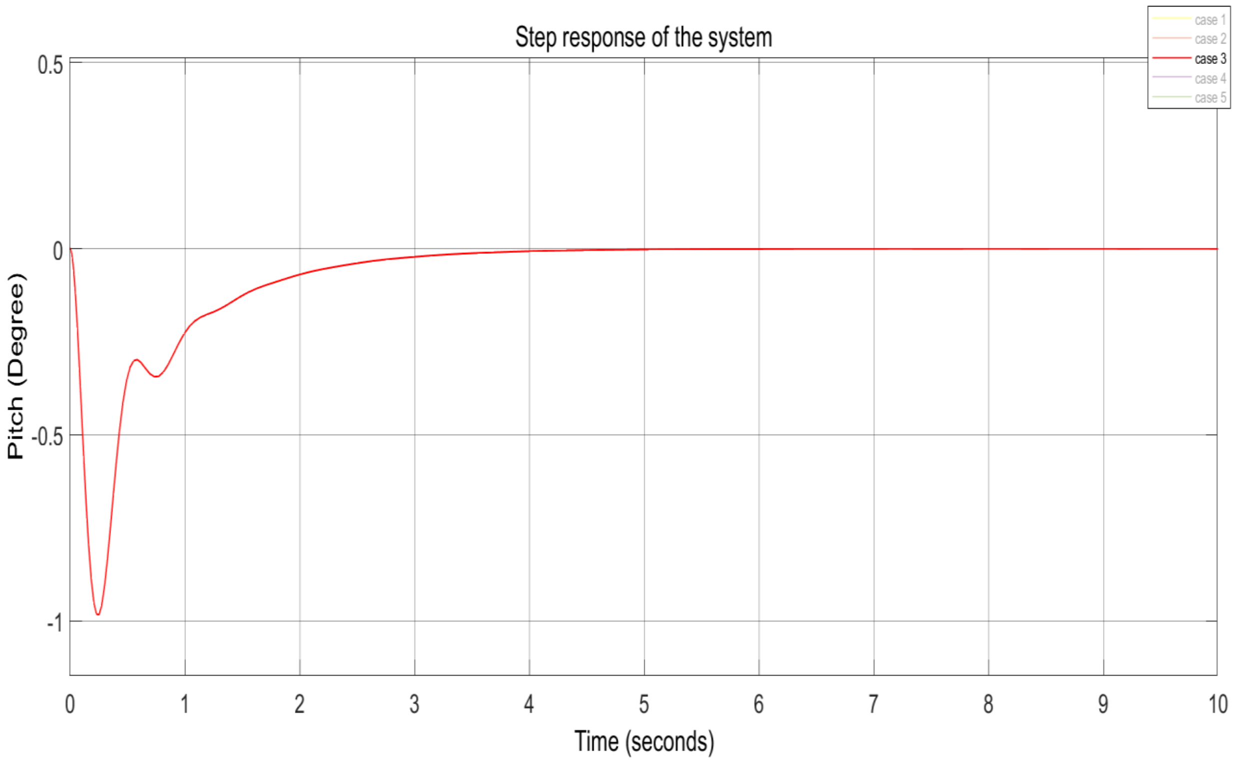

Figure 4.13: Pitch Response (case 3)

Case 4 :

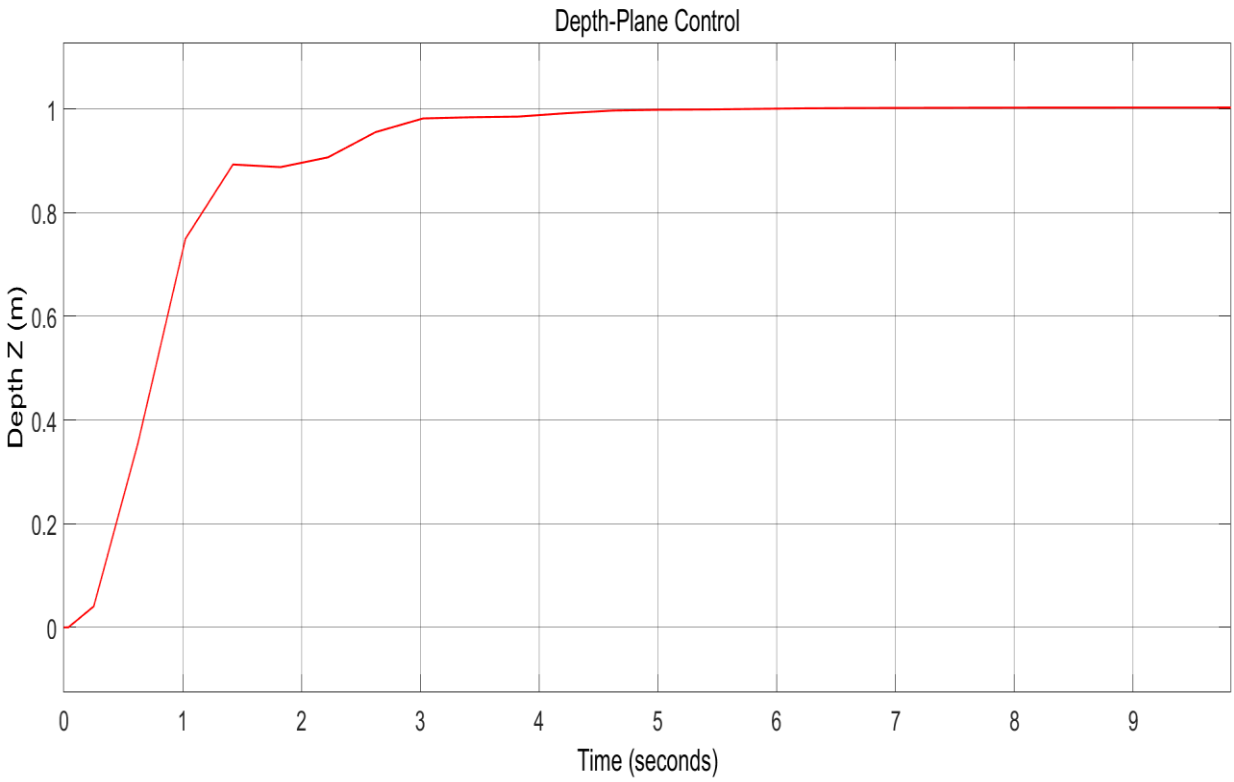

Figure 4.14 : Depth Response (case 4)

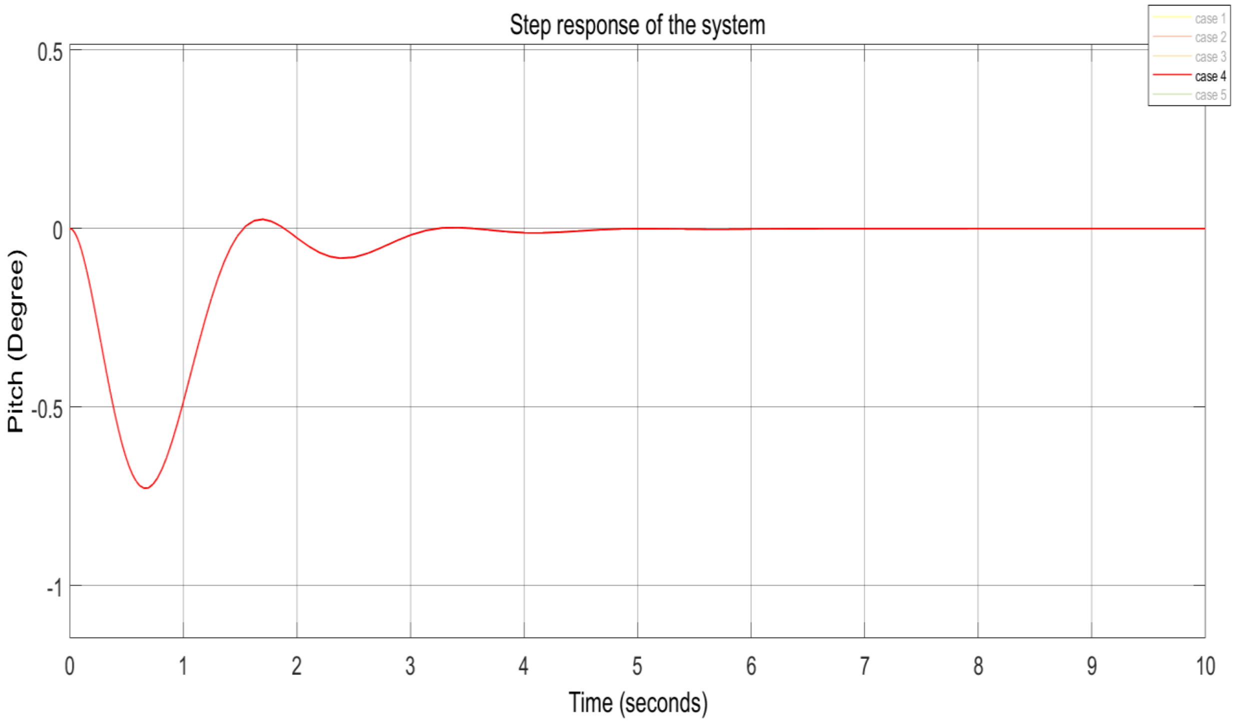

Figure 4.15 : Pitch Response (case 4)

Case 5 :

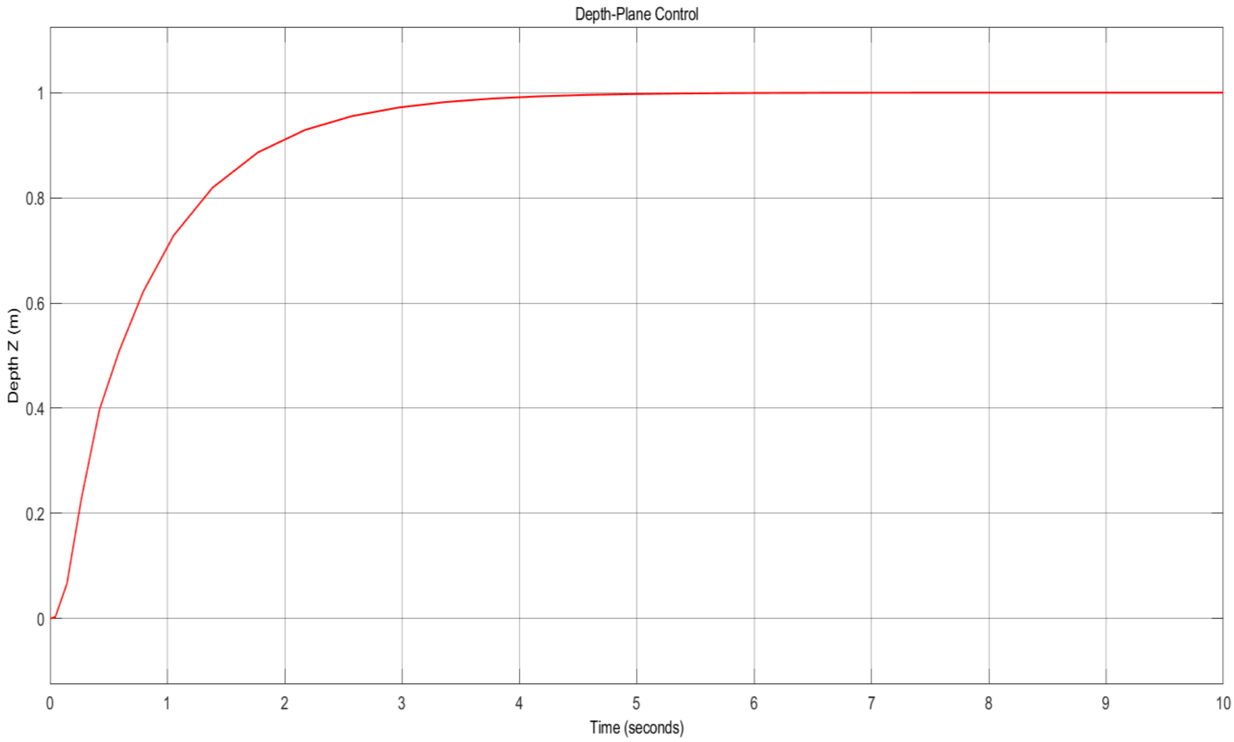

Figure 4.16 : Depth Response (case 5)

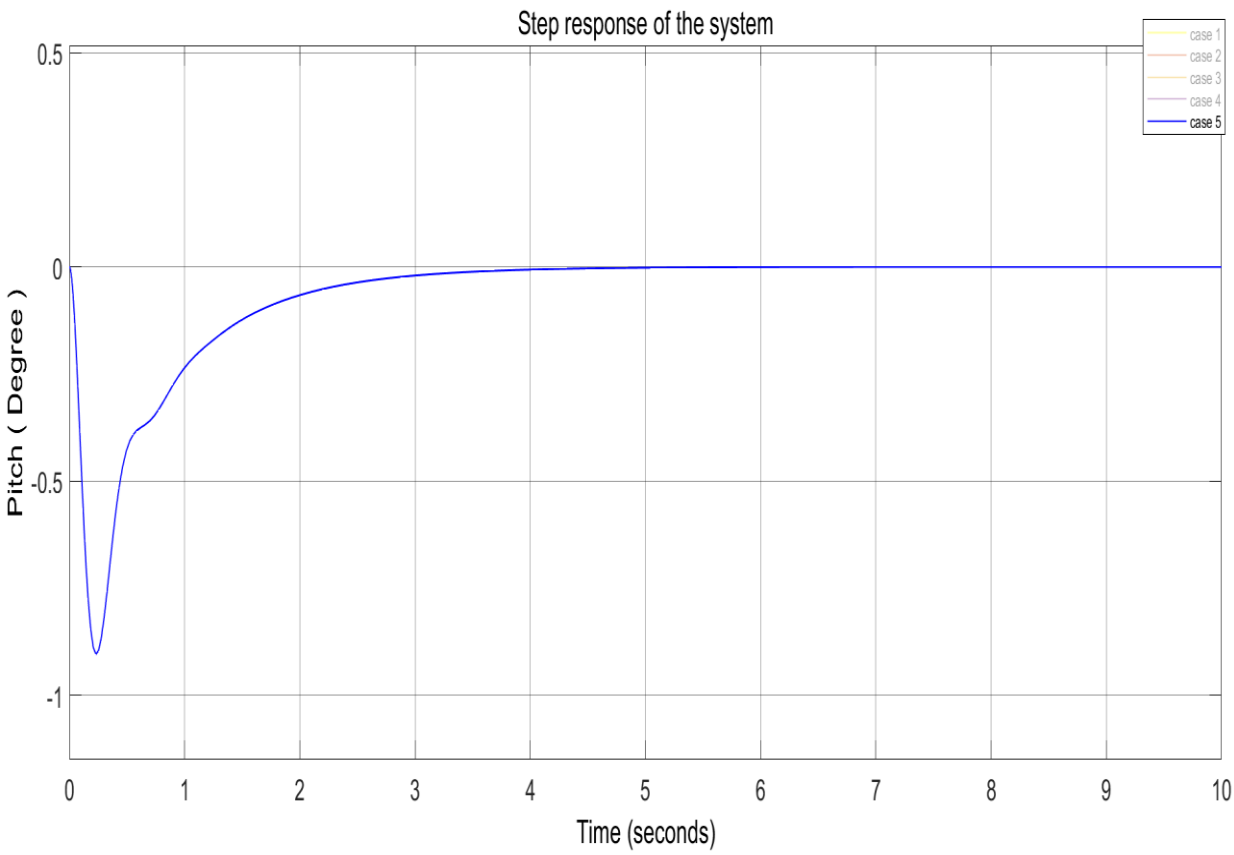

Figure 4.17 : Pitch Response (case 5)

After merging all the results of depth and pitch control

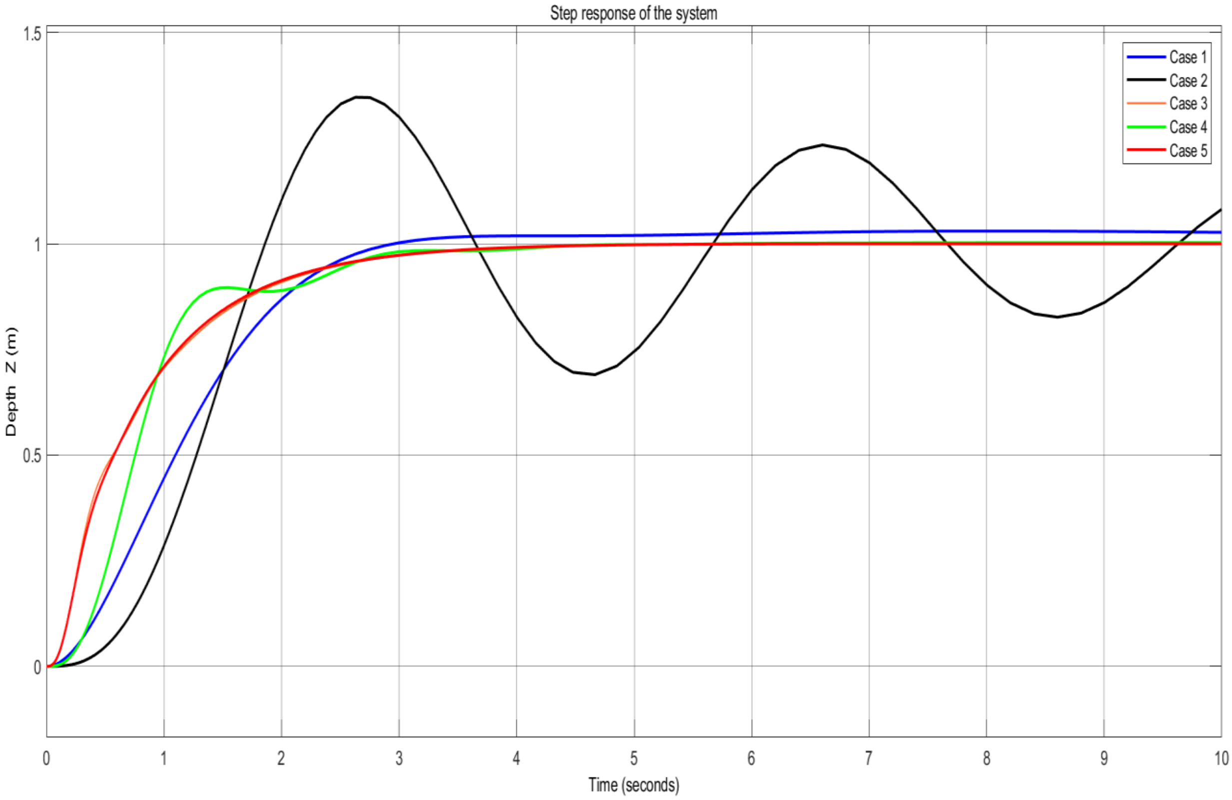

Figure 4.18 : Depth response in different case

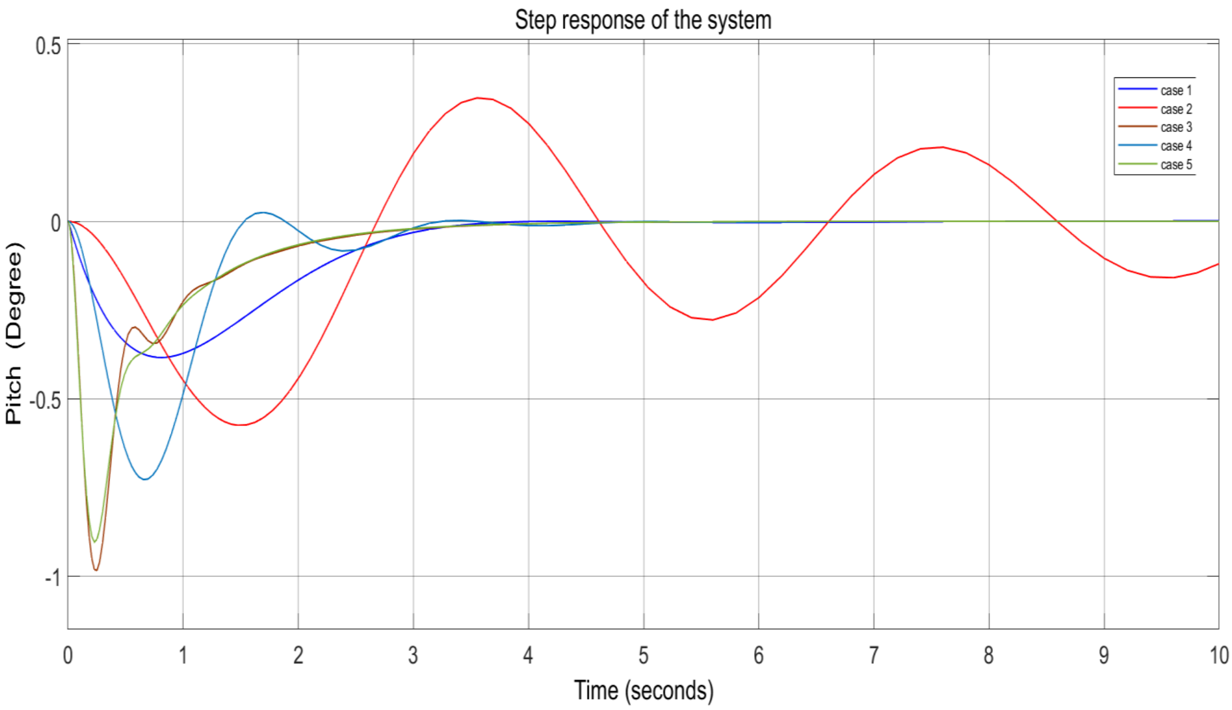

Figure 4.19 Pitch Response in different case

Performance	Case 1	Case 2	Case 3	Case 4	Case 5
Rise time (s)	1.8760	1.1468	2.1846	1.8294	1.7139
Settling time (s)	3.1114	9.8925	4.8266	3.1016	3.2756
Overshoot (%)	0.2972	24.7772	2.2222	0	0.003
Closed loop stability	Stable	Stable	Stable	Stable	Stable

Table 4.5 : Performance characteristic of depth control through PID Controller

From the figure , we can observe that when a depth command of 1 meter is input, the vehicle exhibits a noticeable downward deflection in its pitch angle. This negative pitch angle motion is a result of the controlled adjustments made to the vehicle's surfaces.

Analysing the plotted data, it becomes evident that both the depth and pitch angle converge to their respective desired values in approximately the same amount of time. This convergence suggests that once the vehicle reaches its intended depth, the pitch angle returns to a neutral position, which is zero degrees. This observation provides compelling evidence that the pitch control system, as designed in this project, is operating effectively.

As the vehicle's depth changes, the pitch angle responds accordingly, either tilting upward (positively) or downward (negatively) to maintain stability and alignment with the desired depth set point. The presented data and observations affirm that the pitch controller implemented in this project fulfills its intended purpose. It successfully regulates the pitch angle of the vehicle in response to changes in depth commands, ensuring that the vehicle maintains its desired depth and stability throughout its operation.

Chapter 5

Simulation of the AUVS

In this chapter, our first task is to conclude the formulation of the equations governing the motion of the vehicle. Following this, we embark on creating a numerical approximation method for not only the equations of motion but also the kinematic equations that bridge the relationship between the vehicle's motion in the body-fixed coordinate frame and its motion in the inertial or Earth-fixed reference frame. To cap it off, we employ this numerical approximation to construct a computer simulation model that accurately represents the vehicle's motion.

This chapter commences with the finalization of the equations that describe the vehicle's motion. Subsequently, we delve into the development of a numerical approximation technique. This technique extends to encompass both the equations of motion and the kinematic equations that facilitate the translation of motion between the body-fixed coordinate frame and the inertial reference frame, which remains fixed with respect to the Earth. To achieve a comprehensive understanding of the vehicle's dynamics and behavior, we leverage this numerical approximation method to construct a computer simulation. This simulation serves as a valuable tool for simulating and analyzing the vehicle's motion, offering insights and predictions about its behavior under various conditions and scenarios.

5.1 Merged Nonlinear Equation of Motion

By merging the equations governing the rigid-body dynamics of the vehicle (as shown in Equation 3.6) with the equations detailing the forces and moments acting upon the vehicle (as indicated in Equation 3.8), we attain a unified set of nonlinear equations that govern the motion of the REMUS vehicle across its six degrees of freedom.

This refers to the movement known as "surge," which involves the translation of the vehicle along its x-axis.

$$(m - X_{\dot{u}})\dot{u} + m\, z_{g\,\dot{q}} - my_g\dot{r} = X_{HS} + X_{u|u|}u|u| + \left(x_{wq} - m\right)wq + \left(x_{qq} + mx_g\right)q^2 + (x_{vr} + m)vr + \left(x_{rr} + mx_g\right)r^2 - my_g pq - m\, z_g\, pr + X_{prop} \quad \text{…. (5.1)}$$

This denotes the motion called "sway," which pertains to the translation of the vehicle along its y-axis.

$$(m - Y_{\dot{v}})\dot{v} - m\, z_{g\,\dot{p}} + \left(mx_g - Y_{\dot{r}}\right)\dot{r} = Y_{HS} + Y_{v|v|}v|v| + Y_{r|r|}r|r| + my_g r^2 + (Y_{ur} - m)ur + \left(Y_{wp} + m\right)wp + \left(y_{pq} - mx_g\right)pq + Y_{uv}uv + my_g p^2 + mz_g qr + Y_{uu}\,\delta_r\ u^2\delta_r \quad \text{…. (5.2)}$$

This term signifies the movement term “Heave”, which include the vertical translation of the vehicle along its z-axis.

$$(m - Z_{\dot{w}})\dot{w} + m\, y_{g\,\dot{p}} - \left(mx_g + Z_{\dot{q}}\right)\dot{q} = Z_{HS} + Z_{w|w|}w|w| + Z_{q|q|}q|q| + \left(Z_{uq} + m\right)uq + \left(Z_{vp} - m\right)vp + \left(Z_{rp} - mx_g\right)rp + Z_{uw}uw + mz_g(p^2 + q^2) - m\, y_g\, rq + Z_{uu\delta_s} *\ u^2\delta_s \quad \text{……….. (5.3)}$$

This describes the action known as "roll," which involves the rotation of the vehicle around its x-axis.

$$-mz_g\dot{v} + my_g\dot{w} + \left(I_{xx} - K_{\dot{p}}\right)\dot{p} = K_{HS} + K_{p|p|}p|p| - \left(I_{xx} - I_{yy}\right)qr + m(uq - vp) - mz_g(wp - ur) + K_{prop} \quad \text{…. (5.4)}$$

This expression represents the motion called "pitch," referring to the rotation of the vehicle around its y-axis.

$$mz_g\dot{u} - \left(mx_g - M_{\dot{w}}\right)\dot{w} + \left(Iyy - M_{\dot{q}}\right)\dot{q} = M_{HS} + M_{w|w|}w|w| + M_{q|q|}q|q| + \left(M_{uq} - mx_g\right)uq + \left(M_{vp} + mx_g\right)vp + \left[M_{rp} - (I_{xx} - I_{zz})\right]rp + mz_g(vr - wq) + M_{uw}uw_{+}M_{uu\,\delta_s}u^2\delta_s \quad \text{…. (5.5)}$$

This indicates the movement termed "yaw," which pertains to the rotation of the vehicle around its z-axis.

$$-mz_g\dot{u} + (mx_g - N_{\dot{v}})\dot{v} + (I_{zz} - N_{\dot{r}})\dot{r} = N_{HS} + N_{v|v|}v|v| + N_{r|r|}r|r| + (N_{ur} - mx_g)ur + (N_{wp} + mx_g)wp + [N_{pq} - (I_{yy} - I_{xx})]pq - my_g(vr - wq) + N_{uv}uv_{+} N_{uu\,\delta_r}\, u^2\delta_r \quad \text{.... (5.6)}$$

Above equations can be summaries in the form of matrix

$$\begin{bmatrix} m - X_{\dot{u}} & 0 & 0 & 0 & mx_g & -mx_g \\ 0 & m - Y_{\dot{v}} & 0 & -mz_g & 0 & mx_g - Y_{\dot{r}} \\ 0 & 0 & m - Z_{\dot{w}} & my_g & -mx_g - Z_{\dot{q}} & 0 \\ 0 & -mz_g & my_g & I_{xx} - K_{\dot{p}} & 0 & 0 \\ mz_g & 0 & -mx_g - M_{\dot{w}} & 0 & I_{yy} - M_{\dot{q}} & 0 \\ -my_g & mx_g - N_{\dot{v}} & 0 & 0 & 0 & I_{zz} - N_{\dot{r}} \end{bmatrix} \begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \\ \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} X \\ Y \\ Z \\ K \\ M \\ N \end{bmatrix} \quad (5.7)$$

$$\begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \\ \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} m - X_{\dot{u}} & 0 & 0 & 0 & mx_g & -mx_g \\ 0 & m - Y_{\dot{v}} & 0 & -mz_g & 0 & mx_g - Y_{\dot{r}} \\ 0 & 0 & m - Z_{\dot{w}} & my_g & -mx_g - Z_{\dot{q}} & 0 \\ 0 & -mz_g & my_g & I_{xx} - K_{\dot{p}} & 0 & 0 \\ mz_g & 0 & -mx_g - M_{\dot{w}} & 0 & I_{yy} - M_{\dot{q}} & 0 \\ -my_g & mx_g - N_{\dot{v}} & 0 & 0 & 0 & I_{zz} - N_{\dot{r}} \end{bmatrix}^{-1} \begin{bmatrix} X \\ Y \\ Z \\ K \\ M \\ N \end{bmatrix} \quad (5.8)$$

5.2 MATLAB Simulation

The model code operates by computing, at each time step, the forces and moments acting on the vehicle based on its speed and attitude. These forces dictate the vehicle's accelerations in the body-fixed reference frame and the rates of change relative to the Earth. Subsequently, these accelerations are employed to estimate the updated vehicle velocities, which, in turn, serve as the inputs for the subsequent modeling time step.

We will provide two inputs

- Initial Conditions or initial vehicle state vector
- Control inputs encompass the vehicle's pitch fin and stern plane angles.

5.3 Simulink Model

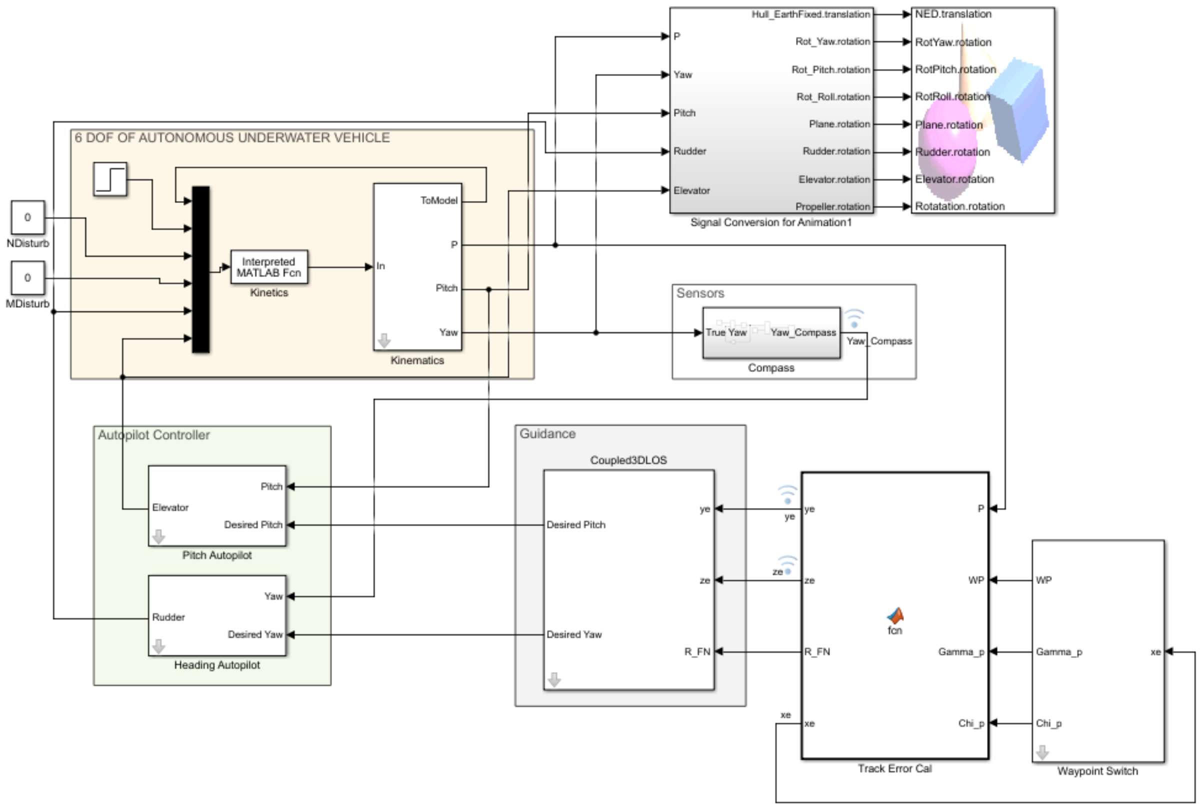

Figure 5.1 : AUV SIMULINK MODEL

I have implemented the REMUS AUV in the simulink model .
where we set initial velocity of the AUV as 1.5 ,initial yaw 68.5 , and propeller thrust X_{prop} is set as Step Input .

We have consider a vector containing various state variables and control inputs for the AUV. These variables include linear velocities (u, v, w), angular velocities (p, q, r), orientation angles (phi, theta), propeller thrust (Xprop), disturbances in surge (MDisturb set to be Zero) and sway (NDisturb set to be Zero) directions, rudder angle (rudder), and elevator angle (elevator).

The kinematic model calculates various hydrodynamic forces and moments based on the AUV's current state variables and control inputs which is Step input. These include forces and moments in surge (X), sway (Y), heave (Z), roll (K), pitch (M), and yaw (N) directions.

The kinematic model returns a vector Out containing the time derivatives (rates of change) of the AUV's state variables. These derivatives describe how the AUV's linear and angular velocities, as well as its orientation angles, change over time based on the applied control inputs and hydrodynamic forces.

In essence, this model represents a dynamic model of the AUV's behaviour, taking into account its physical properties, control inputs, and the hydrodynamic forces acting on it. It provides a mathematical representation of how the AUV's state variables evolve over time, making it a fundamental component for simulating and controlling the AUV's motion and behavior in a given environment.

With the help of Simulink, I have meticulously constructed a simulation model that commences by setting precise initial conditions for the vehicle and simulating the application of propeller thrust. The overarching goal is to comprehensively investigate and discern the characteristic behavior and performance traits exhibited by the REMUS Autonomous Underwater Vehicle (AUV) under various dynamic scenarios and environmental conditions. This simulation serves as a valuable tool for gaining profound insights into the AUV's capabilities, response mechanisms, and mission readiness.

Objective of this Simulation: To plot the roll, pitch, yaw , X,Y,Z , u,v and w of an Autonomous Underwater Vehicle (AUV), with Initial conditions we set initial velocity of the AUV as 1.5 ,initial yaw 68.5 , and propeller thrust X_{prop} is set as Step Input .

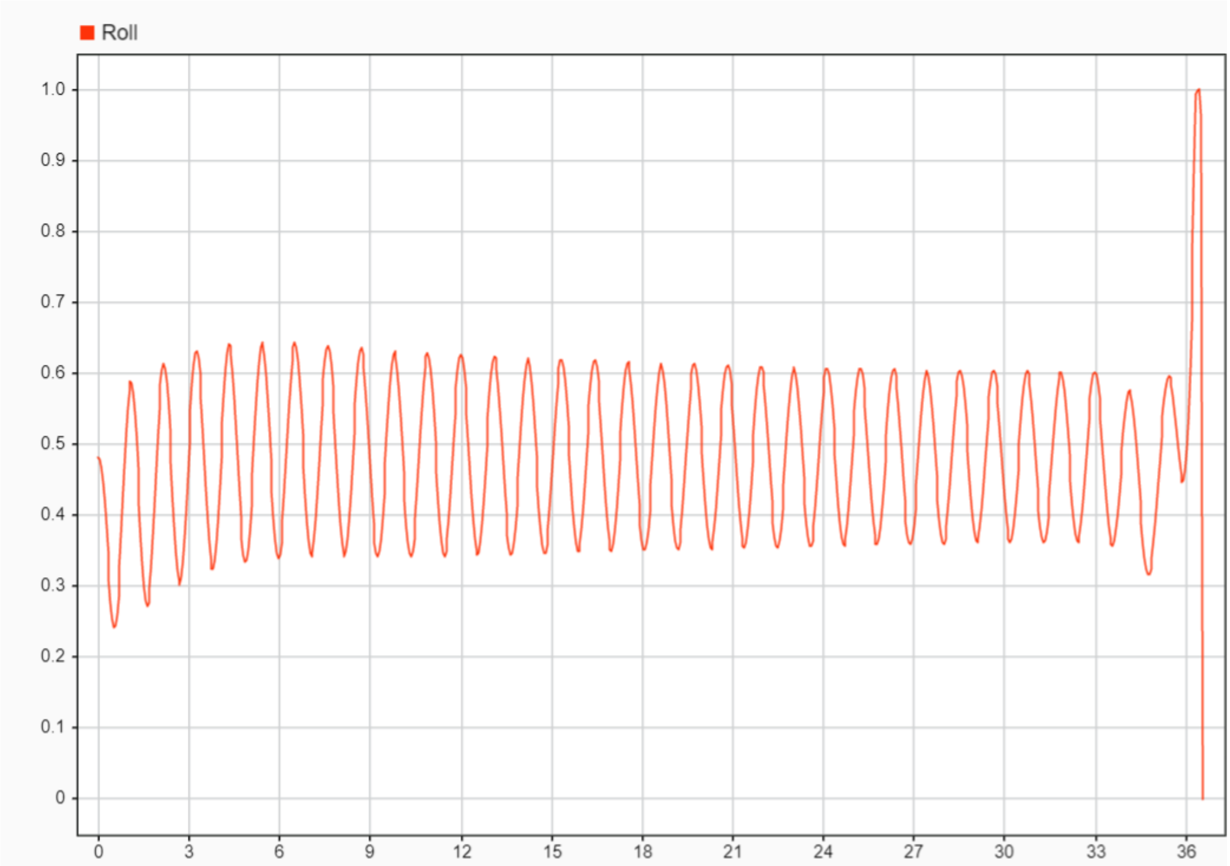

Figure 5.2 : Roll vs Time graph for Initial condition

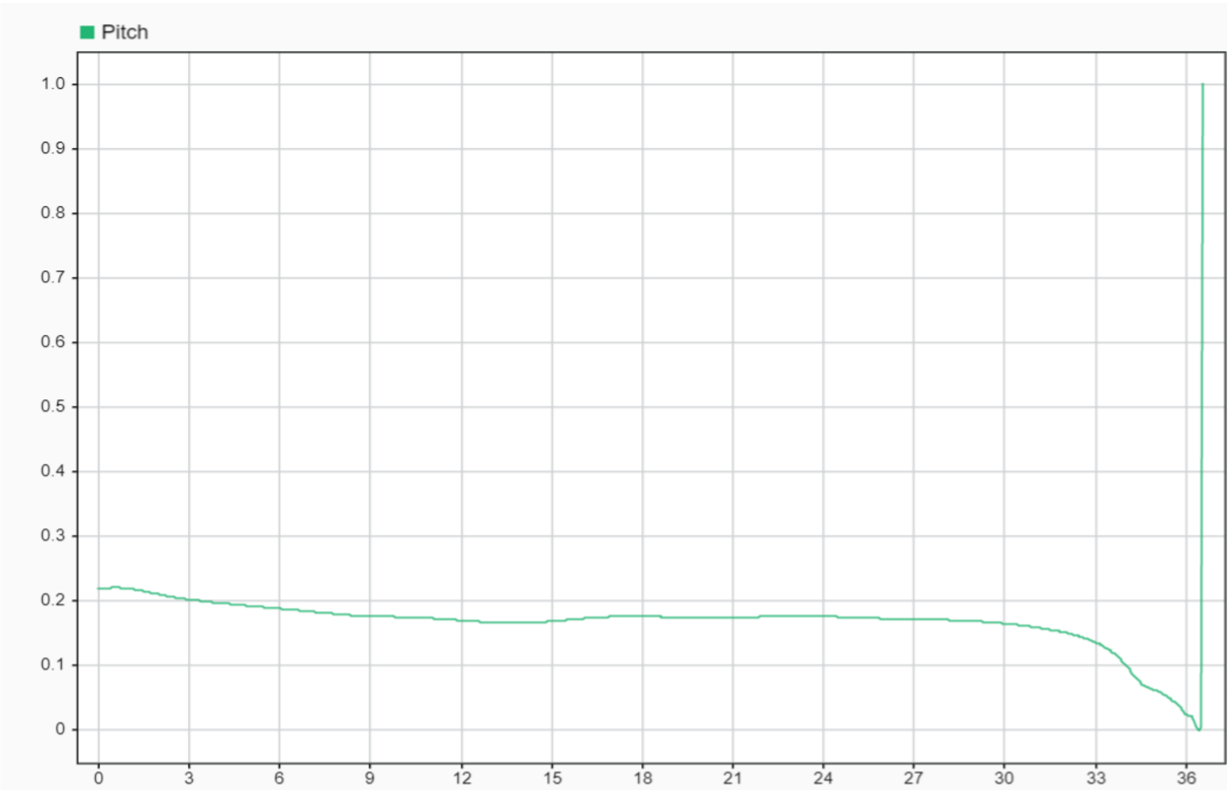

Figure 5.3: Pitch vs Time graph

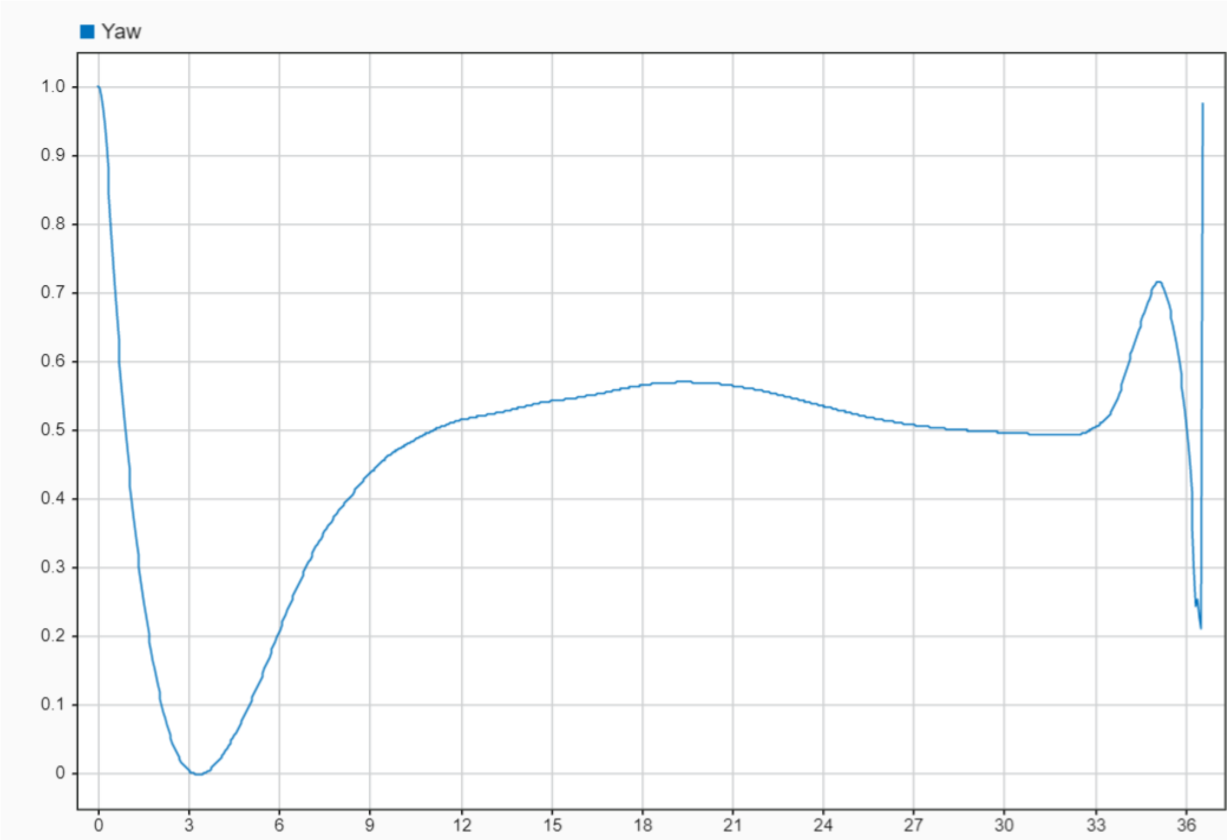

Figure 5.4: Yaw vs Time graph

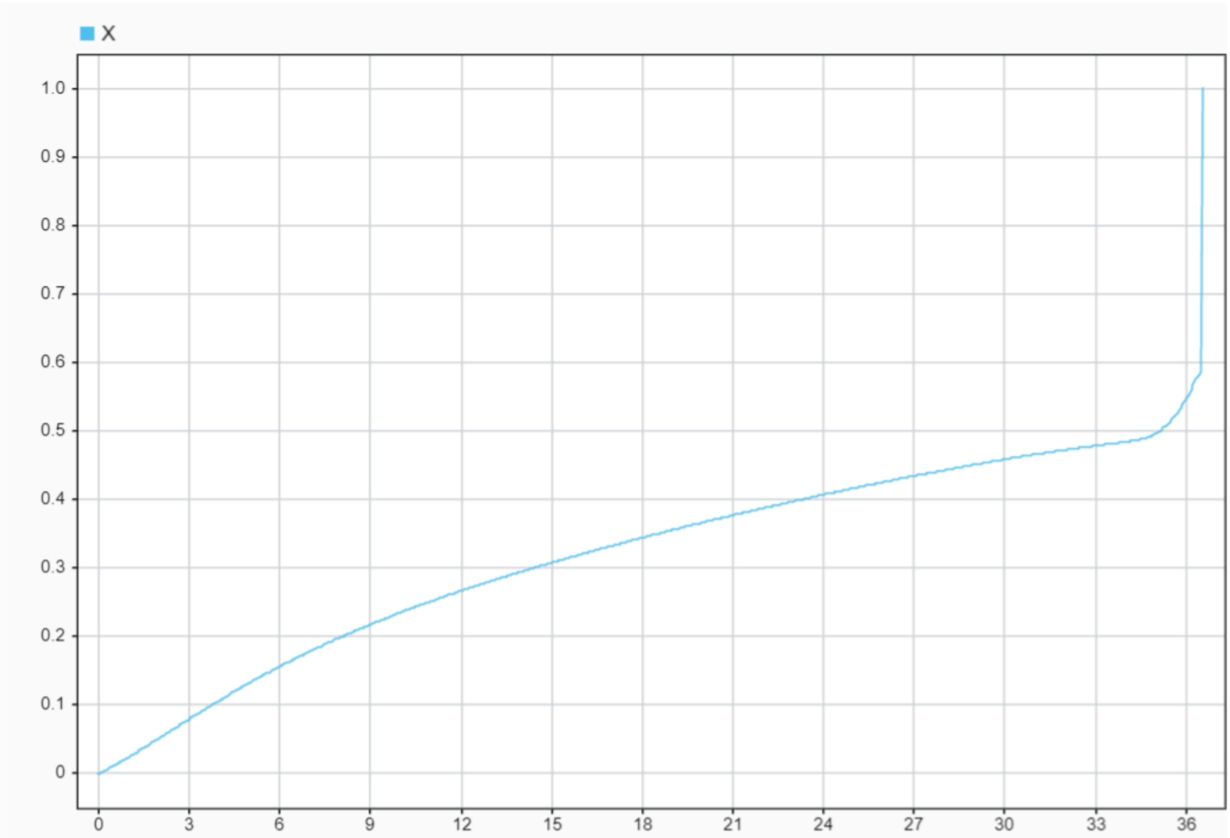

Figure 5.5: X vs Time graph

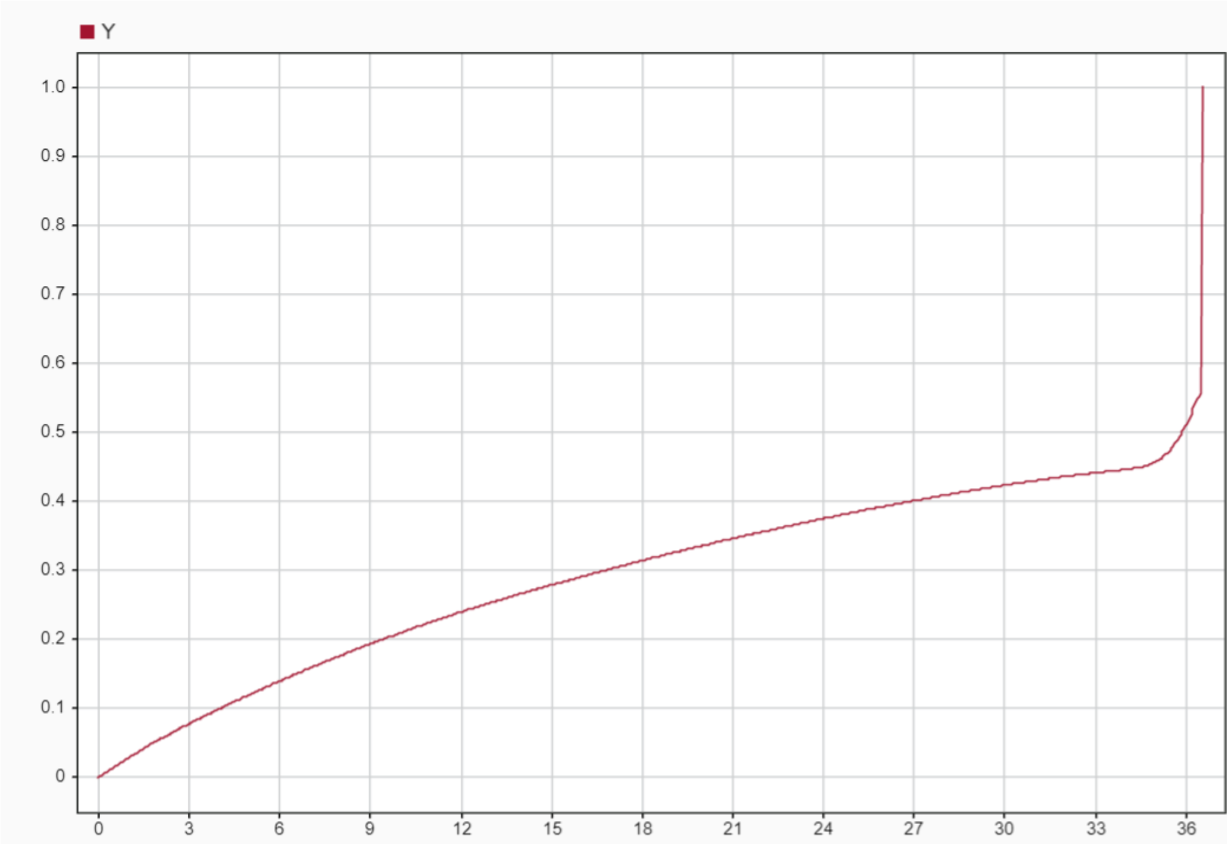

Figure 5.6 Y vs Time graph

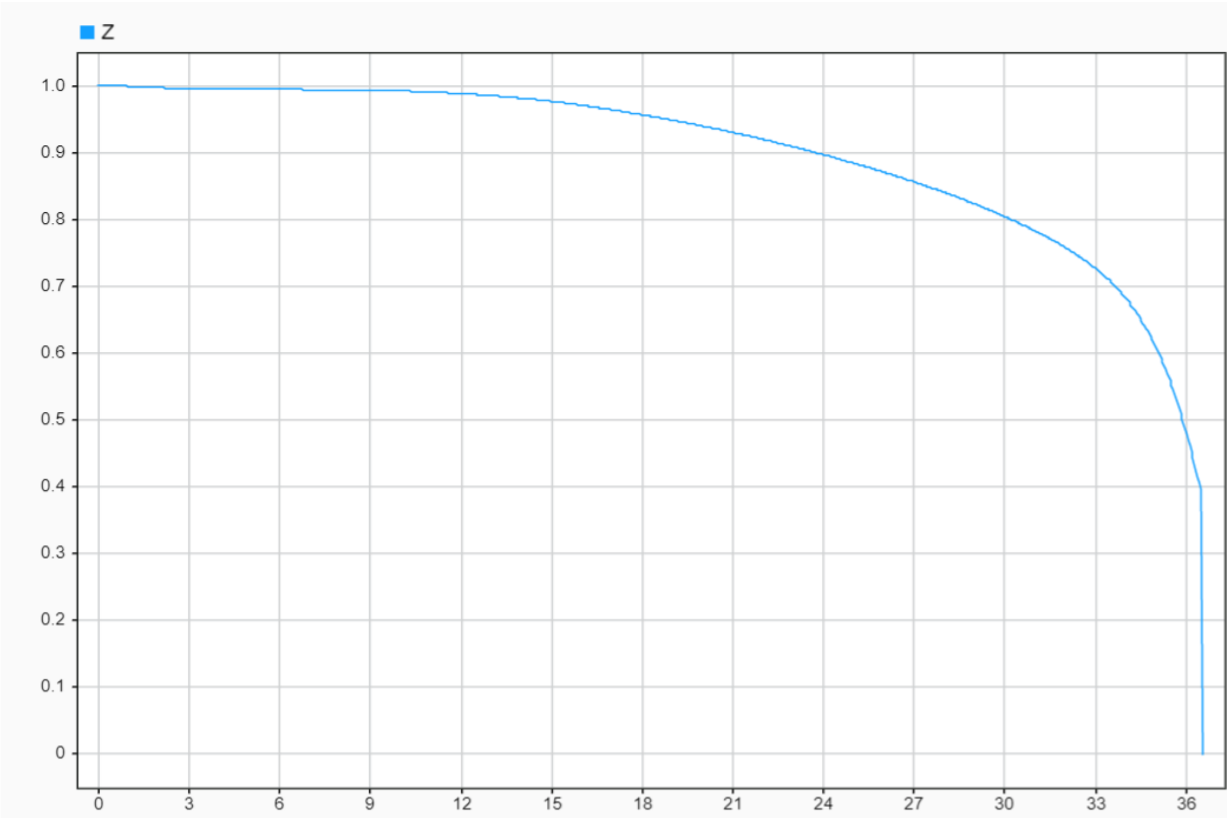

Figure 5.7 Z vs Time graph

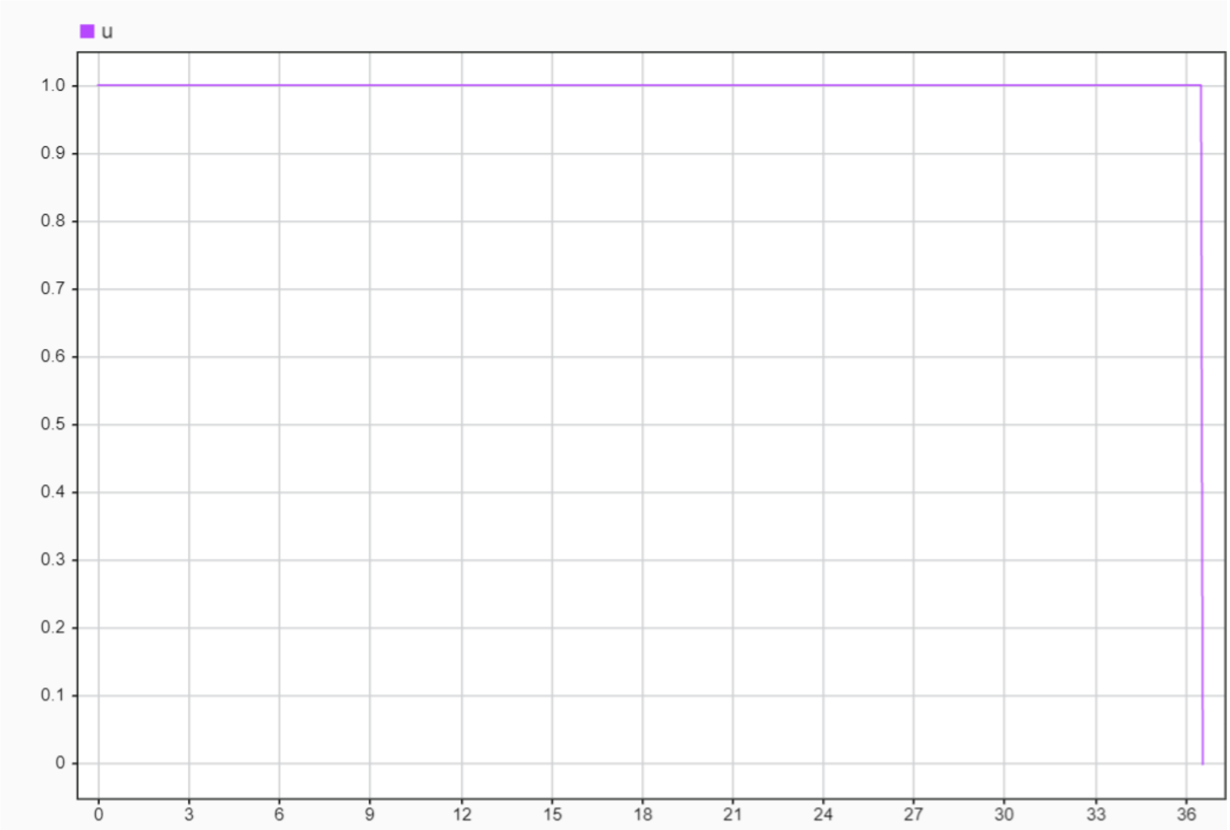

Figure 5.8 Surge velocity(u) vs Time graph

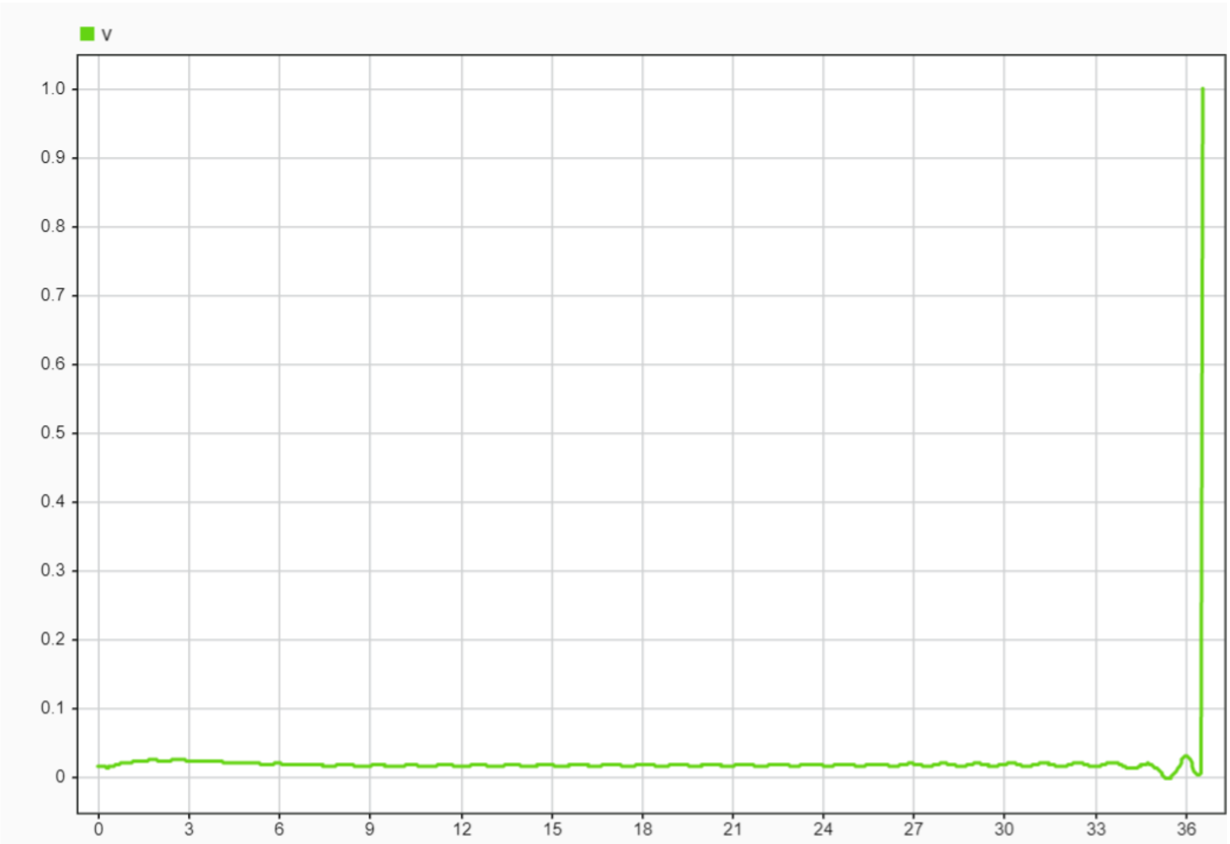

Figure 5.9 Sway velocity(v) vs Time graph

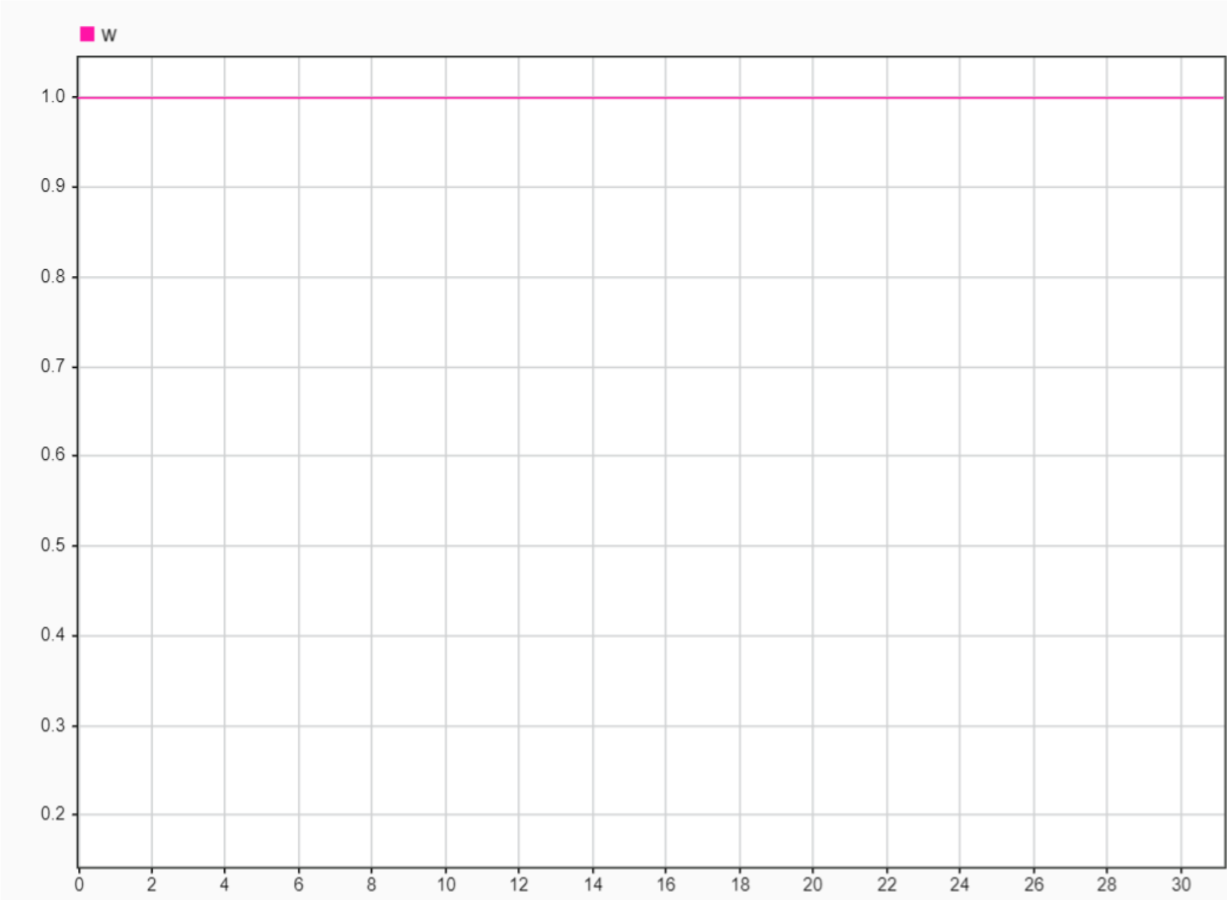

Figure 5.10 w(Heave velocity) vs Time graph

Chapter 6

Conclusion

In this project, we have developed a simulation for the pitch motion controller of an underwater vehicle. We began by formulating the equations of motion for the vehicle, which involved deriving both kinematic and dynamic equations for the rigid body. In addition to the pitch motion controller, we have also designed a combined pitch and depth controller. Conventionally, this controller is responsible for the inner loop control of the vehicle, while the outer loop control involves heading and sway control. To design the controllers, we utilized a state space approach and implemented them in Matlab Simulink. Our process began with creating an open-loop block diagram to obtain the open-loop response. Subsequently, we designed a PID controller for pitch motion. The values for each PID controller were determined using a built-in PID controller tuner. For the combined pitch and depth control, we introduced an outer loop for the pitch controller. The depth controller was designed using proportional gain control, and a similar tuning method was applied to determine the values for the combined PID pitch controller and proportional depth control. To evaluate the performance of our designed controller, we compared the results with other PID-based controller projects for underwater vehicles. Despite working with simulated models due to limitations, the controller's performance was found to be acceptable.

5.1 Future Scope

Future improvements or further work on this project, we recommend to control the depth and pitch of the AUV through Advance Adaptive Control System controller. Building a real prototype of an underwater vehicle and implementing the control system on it. Working with a real prototype would provide more convincing results, and the effectiveness of the control strategies could be further validated through experiments.

Chapter 7

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