# Adaptive Depth Control Algorithms for an Autonomous Underwater Vehicle

*Thesis submitted in partial fulfilment of the requirements for the degree of*

**Master of Technology**
**in**
**Electrical Engineering**
**(Specialization: Control & Automation)**

*by*

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**ODISHA, PIN-769008, INDIA.**

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**ODISHA, PIN-769008, INDIA.**

*Dedicated to*
*my loving  parents,*
*brothers ,sister-in-law, Trisha and Aditya*

# Department of Electrical Engineering

## National Institute of Technology, Rourkela

## राष्ट्रीय प्रौद्योगिकी संस्थान, राउरकेला

# CERTIFICATE

*This is to certify that the work in the thesis entitled "Adaptive Depth Control Algorithms for an Autonomous Underwater Vehicle "by Mr. Biranchi Narayan Rath, submitted to National Institute of Technology, Rourkela for the award of Master of Technology with the specialization in Control & Automation in the Department of Electrical Engineering, is a record of an bonafide research work carried out by him in the Department of Electrical Engineering under my supervision and guidance. The results in the thesis have not been submitted for any degree or academic award elsewhere.*

*Place: NIT Rourkela*
*Date: 30th May 2014*

*Prof. Bidyadhar Subudhi*
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# Abstract

Research on Autonomous Underwater Vehicle (AUV) has been increasing in the recent years. They find application in defence organisation for underwater mine detection and region surveillance, in oil/gas industries for detection of leakage in the pipelines, in commercial purpose for the presence of microscopic life, concentration of various elements, in debris field mapping and in many other marine industries.

The thesis develops adaptive controller algorithms for steering AUV along a desired at a constant forward speed. This thesis mainly focuses on depth plane control problem of a single AUV. Control of AUV is difficult because of the fact that's it is an underactuated system and its dynamics is influenced by ocean currents and hydrodynamic effects. These effects cause modelling inaccuracies of AUV's dynamics. So in order to achieve robustness against parameter uncertainty, adaptive depth control algorithms are being proposed.

In the thesis two different controllers are proposed to address the depth plane control problem of an AUV. In one case, the dynamics of an AUV is derived under the assumptions that the pitch angle of AUV is small in the diving plane motion of the vehicle and linearizing the dynamics of AUV about some operating point. Model Reference Adaptive Controller (MRAC), using MIT rule is used to design the kinematics of an AUV and the dynamics is being controlled by using Fuzzy Logic Controller (FLC). However in the second case the controller has been designed by using the concept of Lyapunov Backsteeping approach where the kinematics is being first controlled in terms of pitch angle from the desired depth information. Using the

information the dynamics is being controlled. However in the latter case the controller has been developed without any constraint on pitch angle variations. Subsequently, the thesis presents simulation environment using MATLAB/SIMULINK to visualize the effect of controllers developed in providing the desired depth information inspite of dynamics uncertainties.

# Contents

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# List of Abbreviations

| | |
|---|---|
| AUV | : Autonomous Underwater Vehicle |
| DOF | : Degree Of Freedom |
| ROV | : Remotely Operated Vehicle |
| UUV | : Unmanned Underwater Vehicle |
| MRAC | : Model Reference Adaptive Controller |
| FLC | : Fuzzy Logic Controllers |
| MP | : Membership Function |

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# Chapter 1

# INTRODUCTION

# Chapter 1
# Introduction

## 1.1 Background

Underwater vehicle are basically are of three types: Remotely Operated Vehicle (RUV), Autonomous Underwater Vehicle (AUV) and Unmanned Underwater Vehicle (UUV). AUV is a robot equipped with suitable sensors and actuators which enable it to navigate in sea environment. The first AUV was developed by Stan Murphy and Bob Francois at the Applied Physics Laboratory at the University of Washington. Since then research on AUV has been increasing. MAYA AUV by NIO was the first indigenously developed AUV in India. Basically control of an AUV refers to the ability of the vehicle to navigate in sea environment without any human intervention. AUV is very useful in number of interesting applications such as underwater mine detection, region surveillance, oil/gas industries for inspection of in the pipelines and other marine related industries. It is also useful in environment monitoring for the presence of microscopic life, concentration of various elements and debris field mapping. AUV like AUV150 by CSIR-CMERI, India, TALISMAN by BAE systems and ALISTER 100 by eca Robotics, Starfish 2 USA navy by Blue star find applications in defence and other military application. MAYA AUV by NIO, India, and MARUM AUV by University of BREMEN, Sea Duane 2 from Flinders University Adelaide Australia and SeaCat AUV by RUVSA are used for marine research/environment studies. Some AUV are also used in air crash investigation like AUV Abyss by GEOMAR - Helmholtz Centrum . In most of the application it is required that it should follow a desired path like scanning, surveillance or pipeline of a desired region. However it's very challenging as AUV dynamic being very complex, time varying, non linear and uncertain. Control of AUV is difficult because of the fact that's it is an underactuated system and its dynamics is influenced by ocean currents and hydrodynamic effects. These effects cause modelling inaccuracies of AUV's dynamics. So in order to achieve robustness against parameter uncertainty, adaptive control algorithms for diving manoeuvres of AUVs is of considerable importance.

## 1.2 Literature Review

In order to achieve the path following control of an AUV the error between the path parameters and the AUV position and orientation need to be reduced to zero. For this the control inputs to the AUV are thrusters force and the orientation of the rudders, stern and bows angle. As the complete dynamics is nonlinear six DOF equation of motion with coupled and non linear terms involving added mass, hydrodynamic damping and external disturbances. So its becomes very difficult to achieve the accurate path following by using the conventional controllers feedback linearization have been implemented for AUV path following. In sliding mode control design [1], the approach is based on input-output signals in terms of dive-plane depth measurement and commands signals. A non-linear gain-scheduling controller is also being proposed for control of an AUV [2] where the control is done in vertical plane. In another design the dynamics of AUV is written in strict-feedback form and then a stable adaptive nonlinear controller for dive control of an AUV is being designed by using Lyapunov-based Backstepping method [3]. A neural network adaptive controller has been also proposed for depth plane control of an AUV [4]. In the fuzzy sliding-mode controller design approach [5] AUV's pitch motion is considered accompanied with the disturbance of ocean current. Linear matrix inequality processing (LMI) method is being proposed [6] for the design of a robust controller for dive plane control of an AUV whereby the disturbances and control constraint is also being considered. An indirect robust controller is being designed whereby the uncertainties are being handles by formulating the uncertainty bounds into the cost function and converting the robust control problem into its equivalent optimal control problem [7]. A T–S fuzzy- model –based controller [8] have been also designed where the AUV in the presence of parametric uncertainties are represented by T–S fuzzy model and then inorder to achieve robustness of the depth control a sufficient condition is being derived by using a Lyapunov function in the form of linear matrix inequalities (LMIs).The control of AUVs in the dive plane using the state-dependent riccati equation method is also being proposed [9]. Adaptive control have been also proposed [12][13][14][15].In such approach the dynamic feedback loop is used for generating the estimates of unknown controller parameters for uncertainties compensation.

## 1.3 Motivation

There has been increasing demand in the use of AUV in the scientific and commercial field which drive the researchers in this field. Path following is just one of those field. The development of control law for an AUV is complex and is very challenging of the fact it's an underactuated system and the precise hydrodynamic coefficient of AUVs is very difficult to be obtained.

## 1.4 Objectives

The objective of the thesis is to design an adaptive depth controller for an AUV, considering thrusters force and rudder plane angle as control input which will steer the AUV onto the desired path, while maintaining the surge velocities.

## 1.5 Problem Statement

Depth following requires the vehicle to attain and follow a desired depth without time restriction defined in an inertial coordinate system. It is desired that an adaptive controller is to be designed using identified model of AUV, so that the inaccuracies of the AUV parameters can be considered. The designed adaptive controller is required to generate control law which will enable the AUV to follow a desired path.

## 1.6 Thesis Organisation

The thesis is structured as following:

- Chapter 2 deals with dynamics and kinematics study of an AUV and an open loop study of an AUV with certain modelling assumptions.
- In chapter 3, an adaptive controller approach has been presented for the depth plane control of an AUV in which system identification technique based on Model Reference Adaptive Controller (MRAC) using MIT Rule has been used for the dynamics control of an AUV and Fuzzy Logic Controller (FLC) is employed for modelling the AUV dynamics. Subsequently, simulation environment using MATLAB/SIMULINK to visualize the effect of controllers

developed in providing the desired depth information inspite of dynamics uncertainties is being presented.

- In chapter 4, a Lyapunov based Backstepping controller is being proposed for the depth plane control of an AUV which compensate for the any uncertainties owing to the dynamics and subsequently, simulation environment using MATLAB/SIMULINK to visualize the effect of controllers developed in providing the desired depth information is being presented.
- Chapter 5 concludes the thesis and scopes of extension of present work are also discussed.

# Chapter 2

# MODELLING OF AN AUTONOMOUS UNDERWATER VEHICLE

# Chapter 2
# Modelling Of an Autonomous Underwater Vehicle

## 2.1 Introduction

The motion of an AUV in 6 DOF is defined by a two coordinate system as shown and the earth-fixed frame being the inertial frame[18][19] as shown in Fig 2.1.

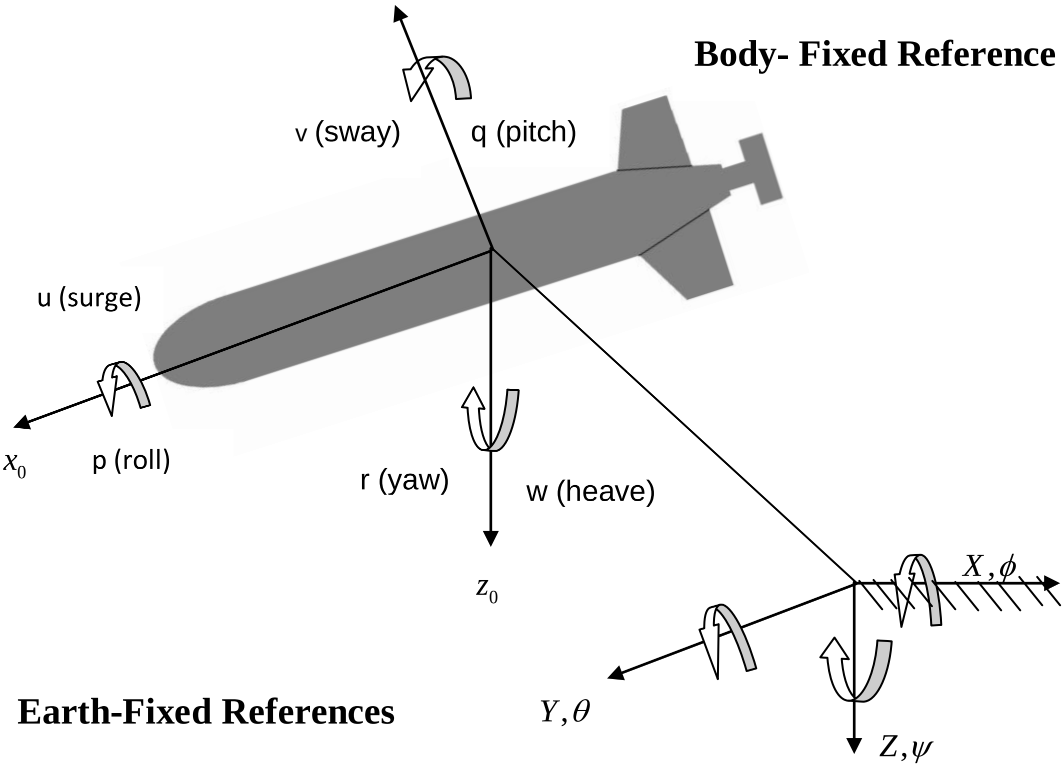


Figure 2.1: AUV with reference system

## 2.2 AUV'S Kinematics in Six DOF

The kinematic equations which gives an idea regarding the geometrical aspects of motion, can be described in vector form as [18][19]

$$\begin{pmatrix} \dot{\eta}_1 \\ \dot{\eta}_2 \end{pmatrix} = \begin{pmatrix} J_1(\eta_2) & 0_{3\times3} \\ 0_{3\times3} & J_2(\eta_2) \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\Rightarrow \dot{\eta} = J(\eta)\nu \qquad (2.1)$$

where $\eta_1 = [x, y, z]^T$ and $\eta_2 = [\phi, \theta, \psi]^T$ are respective position and orientation vector , $\nu_1 = [u, v, w]^T$ and $\nu_2 = [p, q, r]^T$ are respective velocity and angular rate vector in body fixed frame and the jacobian transformational matrices $J_1(\eta_2)$ and $J_2(\eta_2)$ [18][19] are as following :

$$J_1(\eta_2) = \begin{pmatrix} \cos\varphi\cos\theta & -\sin\varphi\cos\phi + (\cos\varphi\sin\theta\sin\phi) & (\sin\varphi\sin\phi) + (\cos\varphi\cos\phi\sin\theta) \\ \sin\varphi\cos\theta & \cos\varphi\cos\phi + \sin\phi\sin\theta\sin\varphi & -\cos\varphi\sin\phi + \sin\theta\sin\varphi\cos\phi \\ -\sin\theta & \cos\theta\sin\phi & \cos\theta\cos\phi \end{pmatrix} \quad (2.2)$$

$$J_2(\eta_2) = \begin{pmatrix} 1 & \sin\varphi\tan\theta & \cos\varphi\tan\theta) \\ 0 & \cos\varphi & -\sin\phi \\ 0 & \sin\phi/\cos\theta & \cos\phi/\cos\theta \end{pmatrix} \quad (2.3)$$

## 2.3 AUV'S Dynamics in Six DOF

The six degree of freedom (DOF) nonlinear equations of motion which described the dynamical behaviour of an AUV as indicated [18][19] .

$$\tau = M(\nu)\dot{\nu} + C(\nu)\nu + D(\nu)\nu + g(\eta) \quad (2.4)$$

where $\tau$ is the propulsion forces and moment vector , $M(\nu) \in \mathrm{R}^{6\times6}$ is the inertia matrix, $C(\nu) \in \mathrm{R}^{6\times6}$ is the matrix of coriolis and centripetal term, $g(\eta) \in \mathrm{R}^{6}$ is the gravitational forces and moments vector and $D(\nu)$ denotes the damping matrix.

## 2.4 Kinematics and Dynamics in three DOF for Desired Depth Control

For implementation of path following control in x-y plane only three degree of freedom is being considered. Considering the term forward position, surge velocity, depth, pitch rate, pitch angle and heave velocity and keeping all other terms set at zero.

All other terms are set to zero. Considering these assumptions the kinematics equation of motion in three DOF is given as [20]:

$$\begin{aligned} \dot{x} &= (\cos\theta)u + (\sin\theta)w \\ \dot{z} &= -(\sin\theta)u + (\cos\theta)w \\ \dot{\theta} &= q \end{aligned} \tag{2.5}$$

Similarly the dynamics in three DOF is given as:

$$\begin{aligned} [M - x_{\dot{u}}]\dot{u} &= [x_{wq} - M]wq + x_u u + x_{u|u|}u^2 - (W - B)\sin\theta + T \\ [M - z_{\dot{w}}]\dot{w} &= [z_{uq} + M_{uq}]uq + z_w w + z_{w|w|}w|w| + (W - B)\cos\theta \\ [I_y - M_{\dot{q}}]\dot{q} &= M_{wu}(wu) + M_q q + M_{q|q|}q|q| + z_B B\sin\theta + x_B B\cos\theta + u^2 M_{\delta s}\delta s \end{aligned} \tag{2.6}$$

## 2.5 Results and Discussions

Simulations are performed using MATLAB for open loop study of the autonomous underwater vehicle. For the above simulations, INFANTE AUV parameters [21] used as given Table A.1 and Table A.2.The surge velocity is set at 0.5m/sec and other terms are set at zero..

To study the open loop characteristics of the AUV, the thruster force and the rudder angles are kept constant at 100 N and 22.9 degree respective. As the rudder angle is fixed, the AUV should follow a circular path in the x-y plane as shown in Fig. 2.2. As COG is more than the COB, the AUV will eventually will sink with the increase in the depth as shown in Fig 2.3. From these simulations it can be concluded that the considered AUV dynamics is suitable for further control development.

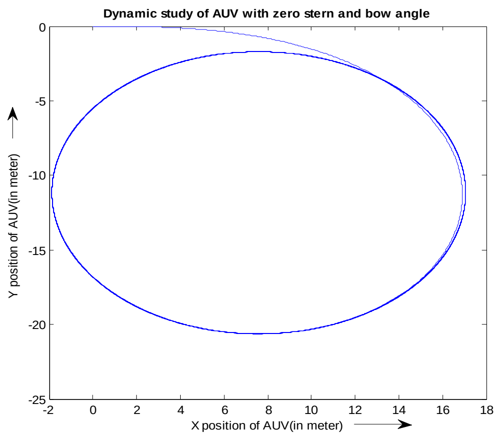


Figure 2.2: Study of AUV in x-y plane

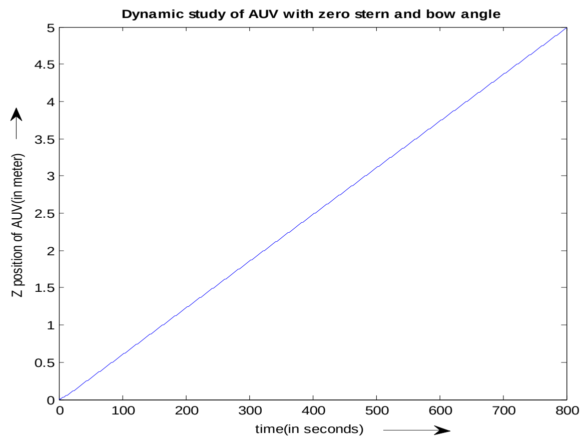


Figure 2.3: Study of AUV in z plane

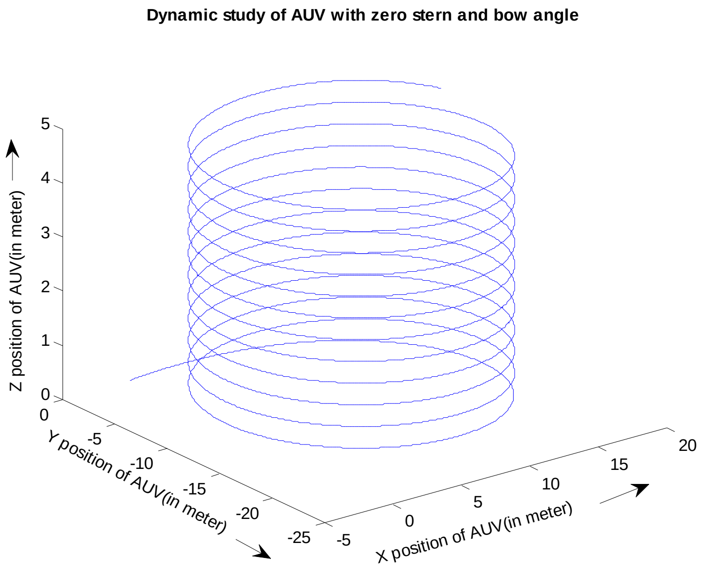


Figure 2.4: Study of AUV in xyz plane

A further study has been done for different stern angles:

**<u>Case 1</u>**: Positive Stern angle

Path of AUV changes with the changes made in the stern angle. As shown in Fig 2.5 and Fig 2.6 with the increase in the stern angle the vehicle will eventually sink thus resulting in the increase in the depth.

**Case 2**: Negative Stern angle

As shown in Fig.2.7 and Fig.2.8, with the increase in the stern angle in the negative direction with reference to body-fixed frame, the AUV will rise up resulting in the decreasing of the depth.

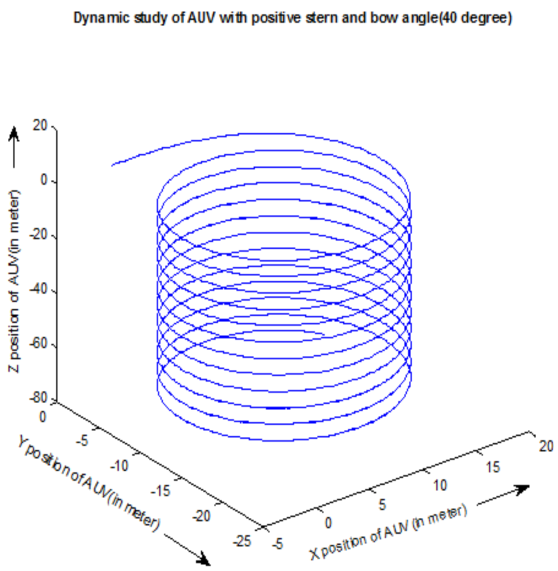


Figure 2.5: Study of AUV with positive Stern angle (40 degree)

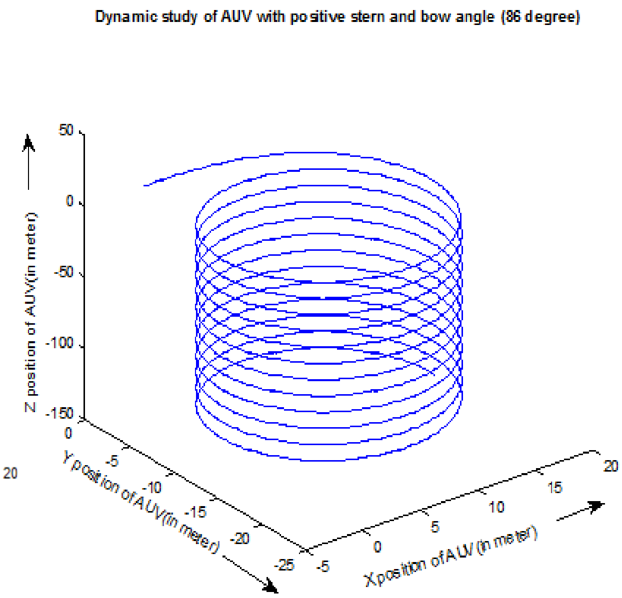


Figure 2.6: Study of AUV with positive Stern angle (86 degree)

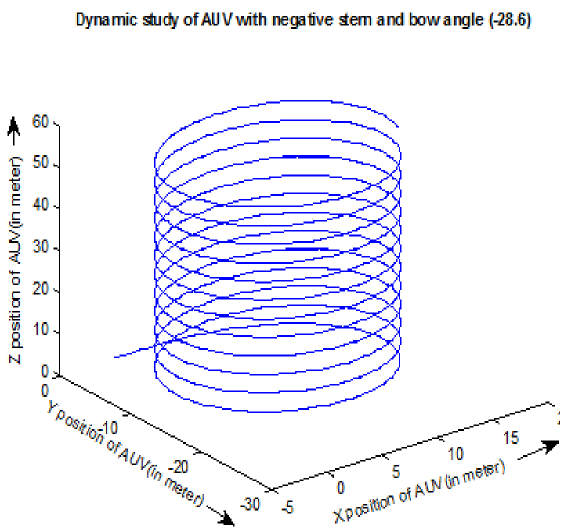


Figure 2.7: Study of AUV with negative Stern angle (-28.6 degree)

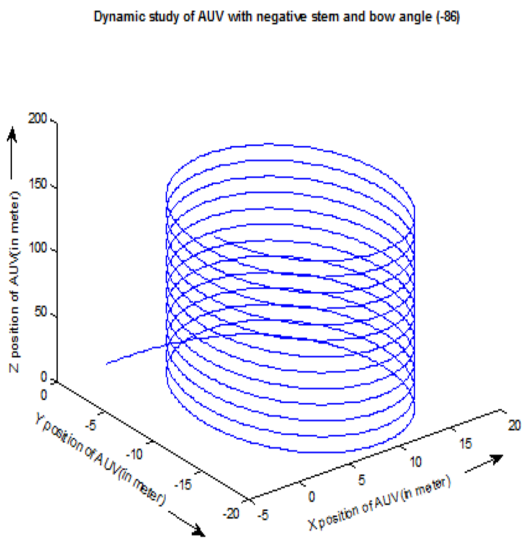


Figure 2.8: Study of AUV with negative Stern angle (-86 degree)

# Chapter 3

# DESIGNING MODEL REFERENCE ADAPTIVE CONTROLLER STRATEGY FOR AN AUV

# Chapter 3
# Designing Model Reference Adaptive Controller Strategy for AUV's Dynamic

## 3.1. Introduction

AUV dynamic is very complex, time varying, non linear and uncertain. Being an underactuated system it makes the controller design for AUV to be very difficult. So usual controllers may not be able to handle these issues. For this reason an adaptive control scheme is being followed as shown in the Fig. 3.1 which will ensure robustness with regards to the uncertainties and external factor like ocean currents, wave disturbances.

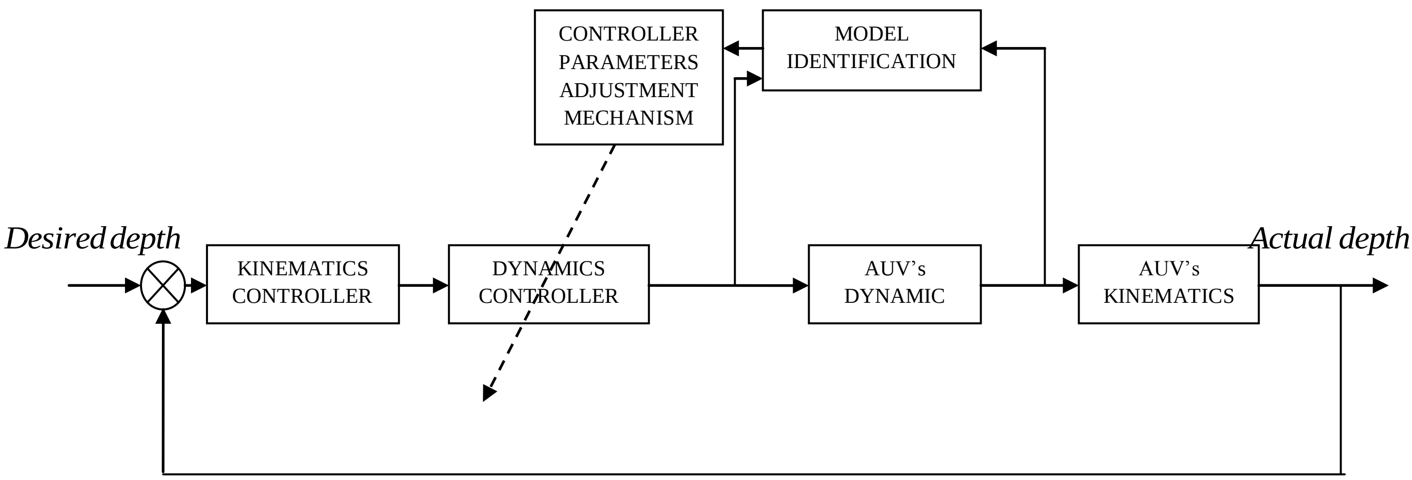


Figure 3.1: An adaptive control structure for an AUV

The Model Reference Adaptive Controller (MRAC) is an adaptive controller where the desired performance is expressed in terms of a reference model [21]. In MRAC, controller parameters are adjusted basically in two ways: by using gradient descent method or by applying stability theory, based on the error, which is the difference between the output from AUV and the output of the reference model as shown Fig.3 [22].

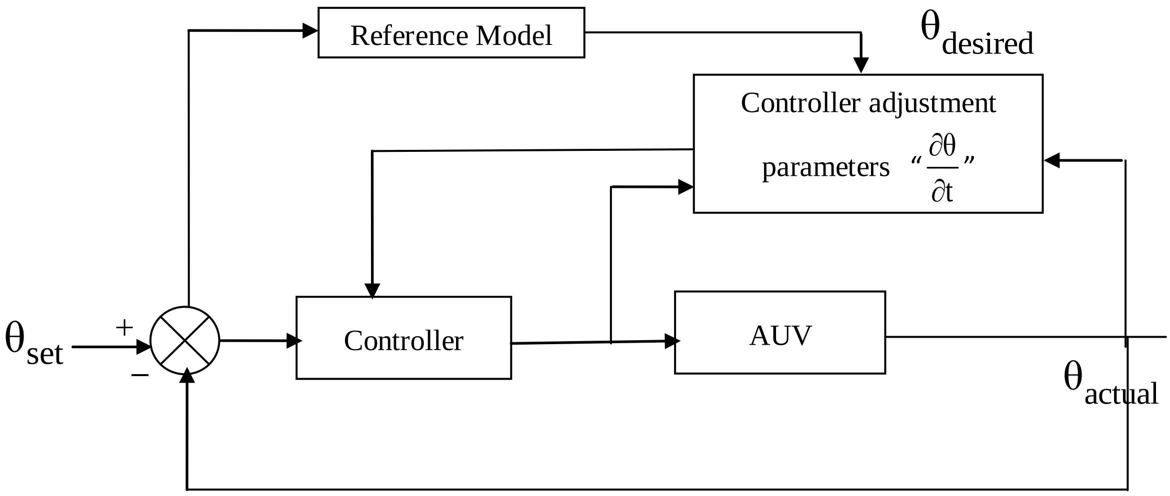


Figure 3.2: Block diagram of the MRAC structure

## 3.2 Linearized Dive Plane Model and Controller of an AUV

The nonlinear equation can be linearise at a point by using Taylor series So linearizing the equation (3) by considering small perturbations around a steady point in the motions of vehicle[20].i.e.

$u = U + \Delta u$ :Linearised around a steady state forward velocity of the vehicle

$w = \Delta w$ :Linearised about zero

$q = \Delta q$ :Linearised about zero

The dynamics equations governing the AUV becomes

$$\begin{pmatrix} [M - z_{\dot{w}}] & 0 \\ 0 & [I_y - M_{\dot{q}}] \\ & \end{pmatrix} \begin{pmatrix} \dot{w} \\ \dot{q} \\ \end{pmatrix} = \begin{pmatrix} z_w & [z_{uq} + M_{uq}]U \\ M_{wu}U & M_q \\ & \end{pmatrix} \begin{pmatrix} w \\ q \\ \end{pmatrix} + \begin{pmatrix} 0 \\ u^2 M_{\delta s} \\ \end{pmatrix} \delta s \qquad (3.1\ )$$

Using above equations

$$\dot{w} = \frac{z_w}{M - z_{\dot{w}}} w + \frac{z_{uq} + M_{uq}}{M - z_{\dot{w}}} Uq \qquad (3.2)$$

Taking Laplace Transform

$$w(s) = \frac{k_2}{s - k_1} q(s) \qquad (3.3)$$

where $k_2 = \frac{z_{uq} + M_{uq}}{M - z_{\dot{w}}}$ and $k_1 = \frac{z_w}{M - z_{\dot{w}}}$

Similarly,

$$\dot{q} = \frac{M_{wu}}{I_y - M_{\dot{q}}} U\, w + \frac{M_q}{I_y - M_{\dot{q}}} q + U^2 M_{\delta s} \delta s \qquad (3.4)$$

Taking Laplace transform and using eqn.(3.3)

$$q(s) = \frac{C(s - k_1)}{(s - B)(s - k_2) - Ak_2} \delta s \qquad (3.5)$$

where $A = \frac{M_{wu}}{I_y - M_{\dot{q}}} U, B = \frac{M_q}{I_y - M_{\dot{q}}}\ and\ C = U^2 M_{\delta s}$

Using the hydrodynamic coefficient as given in Table A.1 and A.2 and the surge forward velocity (U) set as 0.5 m /s and using the kinematics eqn. (2.5), the above equation becomes:

$$\frac{s\theta(s)}{\delta s(s)} = \frac{-197.84s - 86.6653}{(s + 0.4996)(s + 1.79664)}$$

Applying partial Fraction:

$$\frac{\theta(s)}{\delta s(s)} = \frac{9.3807}{s(s+0.4996)} - \frac{207.2207}{s(s+1.79664)} \tag{3.6}$$

Taking Laplace inverse

$$\theta(t) = (-18.775e^{-0.4996t} + 115.33e^{-1.79664t} - 96.554)\delta s(t) \tag{3.7}$$

## 3.3 MRAC design using MIT rule

AUV dynamics is uncertain so conventional controller may not be able to give the desired performances online. To overcome the above stated problem, the controller designing for a second order system with Model Reference Adaptive Control (MRAC) scheme using the MIT rule for adaptive mechanism is being proposed. In this rule, a cost function is defined as a function of error between the outputs of AUV and the reference model, and parameters in the controller are being adjusted in such a way that the error is minimized [22]. However the proposed controller gives agreeable results, but is very sensitive to reference signal's amplitude change.

Let the loss function is chosen as:

$$J(\theta) = \frac{1}{2}e^2 \tag{3.8}$$

where e is the error between the outputs of AUV and the reference model, and θ is the adjustable parameter. Parameter θ is adjusted in such a way that the change in the parameter θ is kept in the way of the negative gradient of J, i.e.

$$\frac{\partial \theta}{\partial t} = -\gamma \frac{\partial J}{\partial \theta}$$

$$\frac{\partial \theta}{\partial t} = -\gamma e \frac{\partial e}{\partial \theta} \quad (From\ eqn.(3.8)) \tag{3.9}$$

where the partial derivative term $\frac{\partial e}{\partial \theta}$ is defined as the sensitivity derivative of the system. This term indicates how the error is changing with respect to the parameter $\theta$. Eqn. (3.9) describes the change in the parameter θ with respect to time so that the cost function J *(θ)* can be reduced to zero. Here γ is a positive quantity which indicates the adaptation gain of the controller.

Let controller parameters be $\theta_1$ and $\theta_2$

Let the controller is given as:

$$\delta s = \theta_1 q_d(t) - \theta_2 q_a(t) \tag{3.10}$$

So the eqn. (3.8) becomes:

$$\theta_a(t) = (-18.775e^{-0.4996t} + 115.33e^{-1.79664t} - 96.554)(\theta_1 q_d(t) - \theta_2 q_a(t))$$

$$\Rightarrow \theta_a(t) = \frac{[-18.775e^{-0.4996t} + 115.33e^{-1.79664t} - 96.554]\theta_1}{1 + [-18.775e^{-0.4996t} + 115.33e^{-1.79664t} - 96.554]\theta_2}\theta_d \tag{3.11}$$

where $\theta_a(t)$ is the dynamics of an autonomous underwater vehicle.

Let a reference model is chosen to be a second order system which is linear and critically damped in such a fashion that it will make the linearized plant onto desired performance. Let the natural frequency and damping ratio for the model be set at 2.7 rad /min and 1.0 respectively [23].

$$\frac{\theta_{desired}}{\theta_{set}} = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2}$$

$$\theta_{desired}(s) = \frac{7.29}{(s-2.7)^2}\theta_{set}(s)$$

<u>Taking Laplace inverse transform</u>

$$\theta_{desired}(t) = 7.29te^{2.7t}\theta_{set}(t) \tag{3.12}$$

Where $\theta_{desired}$ is the dynamics of the reference model

- Our objective is to design a controller so that AUV could track the model.

The error *(e)* between the output of the reference model and the output of AUV is given as:

$$e=\theta_{desired} - \theta_{actual} \tag{3.13}$$

Taking partial derivatives, the sensitivity parameters are given as:

$$\frac{\partial e}{\partial \theta_1} = \frac{[-18.775e^{-0.4996t} + 115.33e^{-1.79664t} - 96.554]}{1+[-18.775e^{-0.4996t} + 115.33e^{-1.79664t} - 96.554]\theta_2}\theta_{set}(t) \tag{3.14}$$

$$\frac{\partial e}{\partial \theta_2} = \frac{[-18.775e^{-0.4996t} + 115.33e^{-1.79664t} - 96.554]}{1+[-18.775e^{-0.4996t} + 115.33e^{-1.79664t} - 96.554]\theta_2}\theta_a(t) \tag{3.15}$$

From equation (), the updating parameters is given as:

Let, $F = \frac{[-18.775e^{-0.4996t} + 115.33e^{-1.79664t} - 96.554]}{1+[-18.775e^{-0.4996t} + 115.33e^{-1.79664t} - 96.554]\theta_2}$

Using eqn (3.14) and eqn.(3.15) in eqn . (3.9)

$$\frac{\partial \theta_1}{\partial t} = -\gamma F e q_d(t)$$
$$\frac{\partial \theta_2}{\partial t} = \gamma F e q_a(t) \tag{3.16}$$

where, $\gamma$ = adaptation gain

## 3.4 Results and Discussions

Simulations are performed using MATLAB .Adaptation gain so considered is set at 1. The INFANTE AUV parameters [21] are selected for AUV dynamics as given in Table A.1 and Table A.2. The surge velocity was set at 0.5 m/sec and other terms are set at zero. Fig 3.3 and Fig 3.4 shows how MRAC approach can be useful in obtaining the desired value.

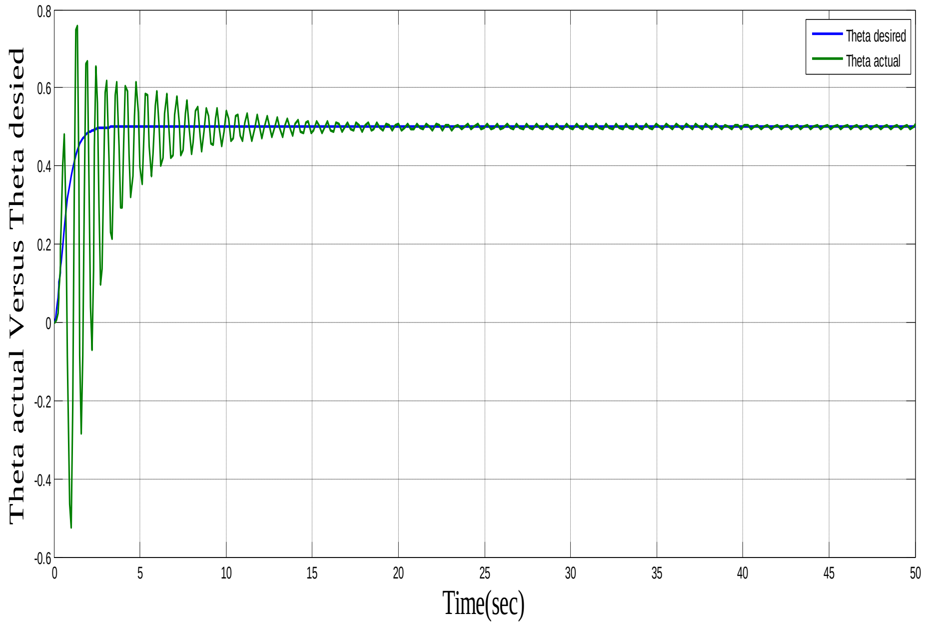


Figure 3.3: Comparison plot between actual theta and desired theta (0.5 radian) using MRAC.

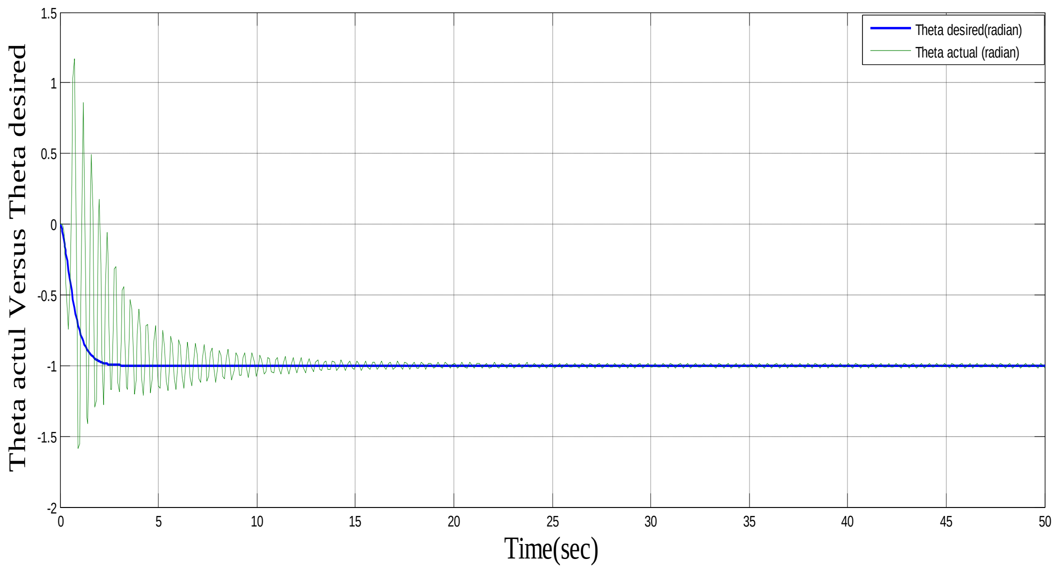


Figure 3.4: Comparison plot between actual theta and desired theta (-1 radian) using MRAC.

## 3.5 Fuzzy Logic Controller

The Fuzzy Logic Controllers (FLCs) in an important tool in controlling nonlinear, complex, and poorly defined systems which incited into the use of fuzzy logic techniques for the kinematics controller of an AUV. As shown in Fig 3.1 the FLC is being proposed for the kinematic controller of an AUV assuming there exists another controller (MRAC) which control the inner loop i.e. the dynamics of an AUV .Structure of the designed FLC for the AUV is shown in Fig. 3.5.The error block in the Fig 3.5 calculates the error derivative and the error between the current states of the AUV and the desired state of the AUV.

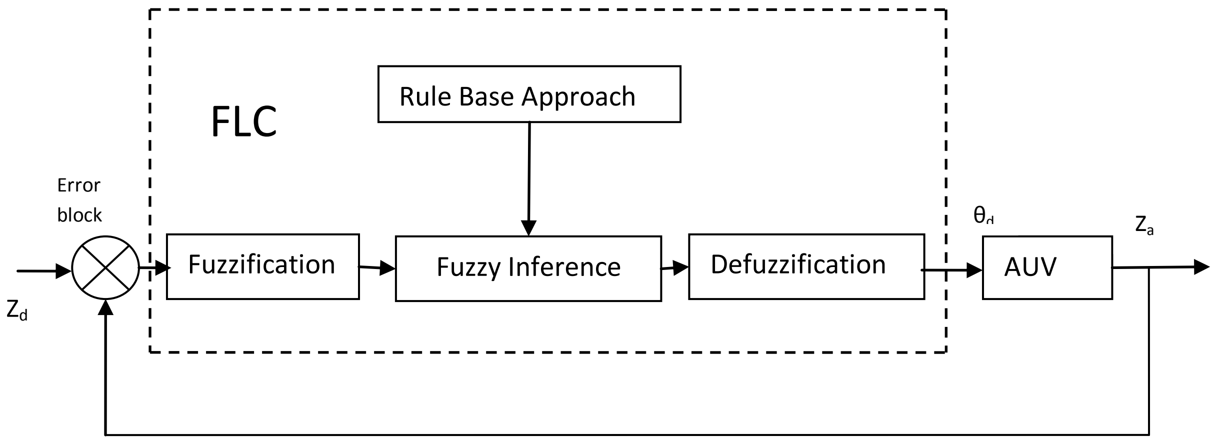


Fig 3.5: Structure of the designed FLC for the AUV

## 3.6. Designing of FLC

For the designing of FLC the error input so considered is the desired depth of the AUV. Considering the eqn. (2.5) as AUV kinematics, the FLC is being proposed to produce the suitable control input i.e. the pitch angle which will drive the AUV to the desired path.

## Linguistic Variables

The input or output variables of the fuzzy logic system are defined using linguistic variables. Linguistic variables associate a linguistic condition with a crisp variable [24]. There are two I/O parameters which are being used to develop the fuzzy logic controller for kinematic controller of AUV for the purpose of controlling the depth motion and the linguistic values that these variables takes for its description of its states are defined in Table 3.1.

## Membership Function

Membership Functions (MF) are used to map the crisp input values to fuzzy linguistic terms and vice versa .Various types of MF exists. Some of them are triangular MF, gaussian distribution function, trapezoidal MF, Pi function, sigmoid MFs, etc. [24]. However in this thesis the trapezoid membership functions are being chosen to define the fuzzy variables. Mathematically a trapezoid MF is defined as follows:

$$\mu_F(x, a, b, c, d) = \begin{cases} 0, & \text{if } x < a \\ (x-a)/(b-a), & \text{if } a \leq x \leq b \\ 1, & \text{if } b < x < c \\ (d-x)/(d-c), & \text{if } c \leq x \leq d \\ 0, & \text{if } d < x \end{cases}$$

## Defuzzification

Once the fuzzy output is obtained then it is converted into a crisp value so that proper action can be taken by the system to obtained desired performed. The process of doing it is referred as defuzzification. Several methods are being used for this purpose [18].

However the approach that is being used in the thesis is the centroid method. Mathematically it is defined as [24]

$$x' = \frac{\int \mu_i(x)\, x\, dx}{\int \mu_i(x)\, dx}$$

where x' is the fuzzy output, $\mu_i(x)$ is the MF and x is the output variable

- A rule base is to be designed which will drive the AUV to steer onto a desired depth. These rule base are knowledge base and these are implemented using IF-THEN rules [24] .The rule base as shown in Table 3.2 explains the relationship between i/o fuzzy variables so defined as membership function. Table 3.2 is designed for the depth control motion of an AUV. Considering the error and the error derivative, a fuzzy rule base is being designed which replica the Proportional - Derivative controller's properties.

| | |
|---|---|
| NB | Negative Big |
| NM | Negative Medium |
| NS | Negative Small |
| ZO | Zero |
| PS | Positive Small |
| PM | Positive Medium |
| PB | Positive Big |

Table 3.1: Linguistic variables

| ė \ e | NB | NM | NS | ZO | PS | PM | PB |
|---|---|---|---|---|---|---|---|
| NB | NB | NB | NB | NB | NM | NS | ZO |
| NM | NB | NB | NB | NM | NS | ZO | PS |
| NS | NB | NB | NM | NS | ZO | PS | PM |
| ZO | NB | NM | NS | ZO | PS | PM | PB |
| PS | NM | NS | ZO | PS | PM | PB | PB |
| PM | NS | ZO | PS | PM | PB | PB | PB |
| PB | ZO | PS | PM | PB | PB | PB | PB |

Table 3.2: Fuzzy Rule Base for depth motion control

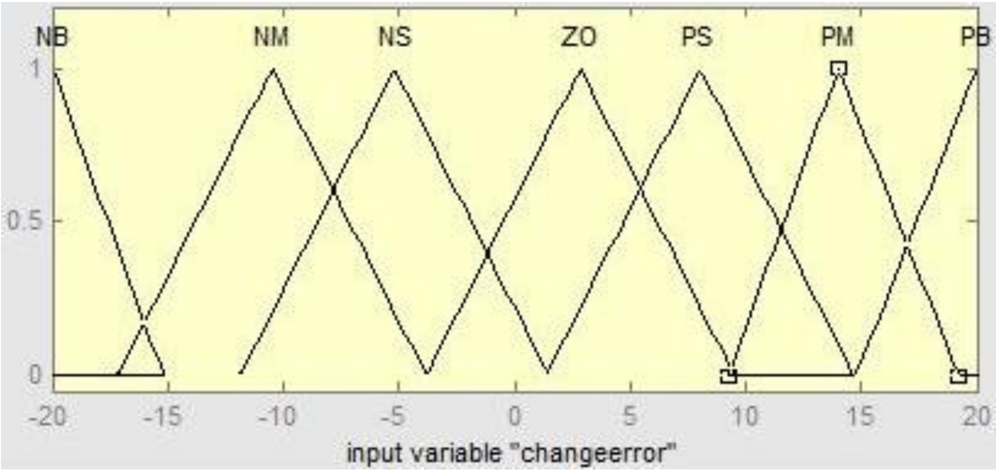


Figure 3.6: Membership function for the input variable “change in error”

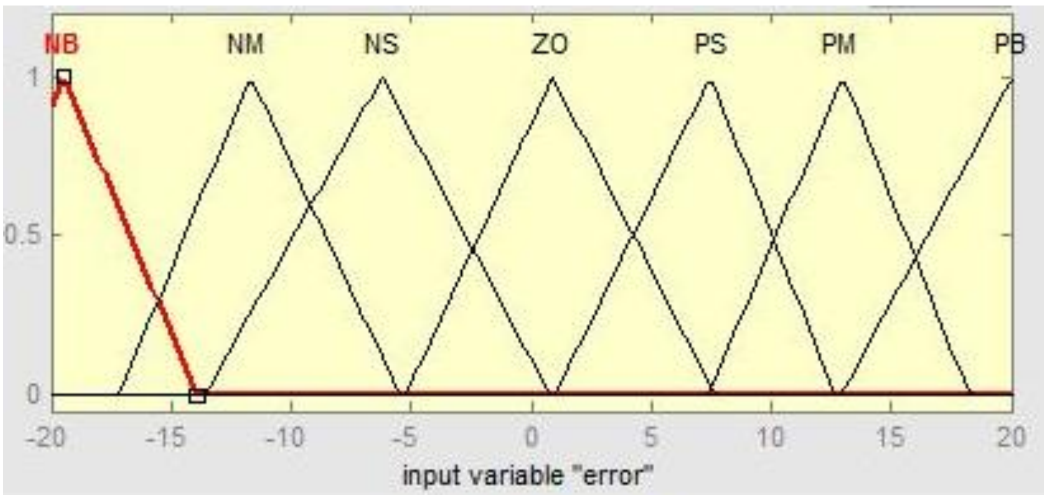


Figure 3.7: Membership function for the input variable “error”

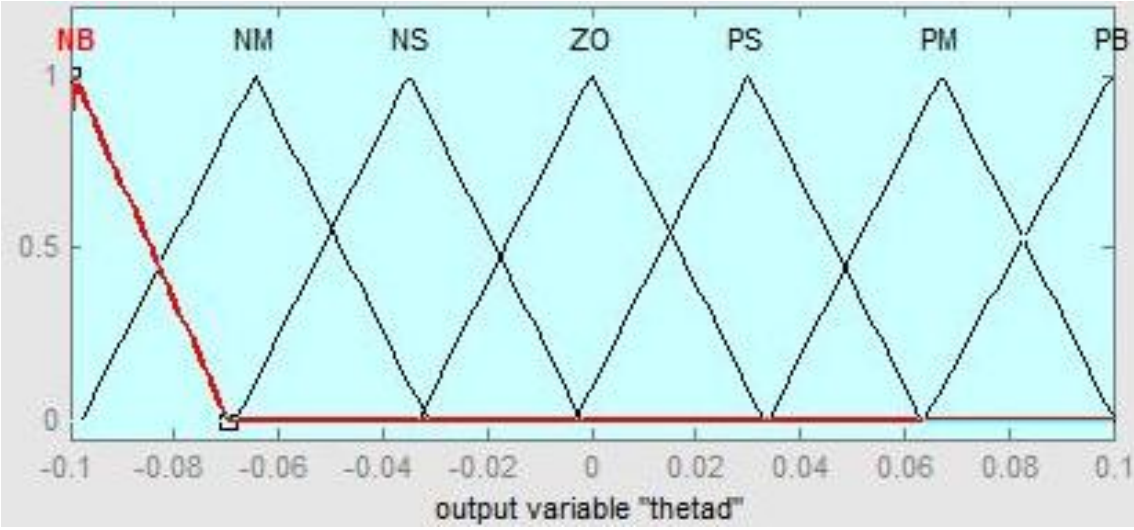


Figure 3.8: Membership function for the output variable “thetad”

## 3.7. Results and Discussions

To verify the controller developed in this chapter, MATLAB/SIMULINK environment is chosen. The INFANTE AUV [21] parameters are selected for AUV dynamics as given in Table A.1 and Table A.2. The surge velocity is set at 0.5 m/sec and other terms are set to zero.

The FLC controller is employed to control the AUV kinematics and the AUV dynamics is being controlled by MRAC. A reference depth of 10 meter is considered and it is required that the AUV should follow this depth profile. From Fig.3.9, the effectiveness of the FLC controller is verified. From the figure, AUV approaches the desired path within 500 seconds with a steady state error of ± 0.26, which is trivial.

The MRAC controller is utilized for controlling the AUV dynamics. The FLC controller for AUV kinematics provides a desired pitch angle which is to be followed by the dynamic controller i.e. MRAC as shown in Fig. 3.10.

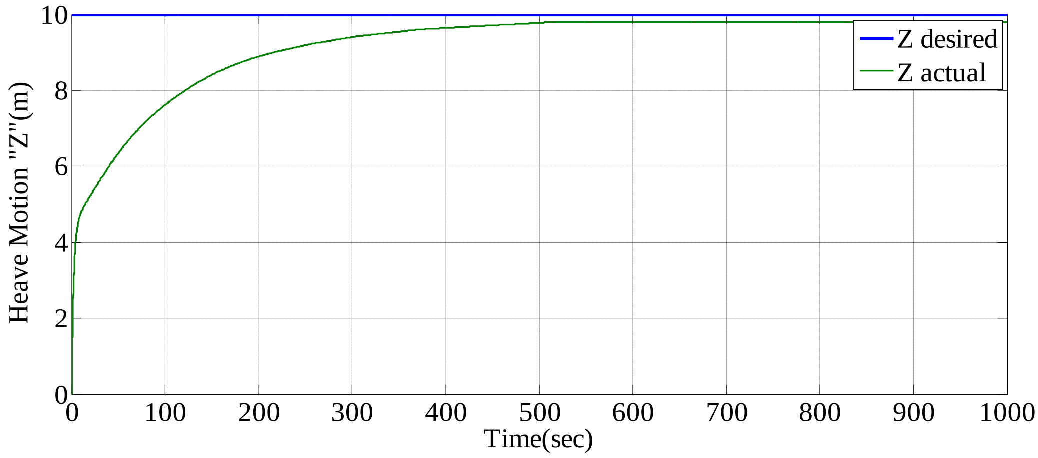


Figure 3.9: Comparison plot between actual depth "Z" to that of desired depth "Z"(10 m)

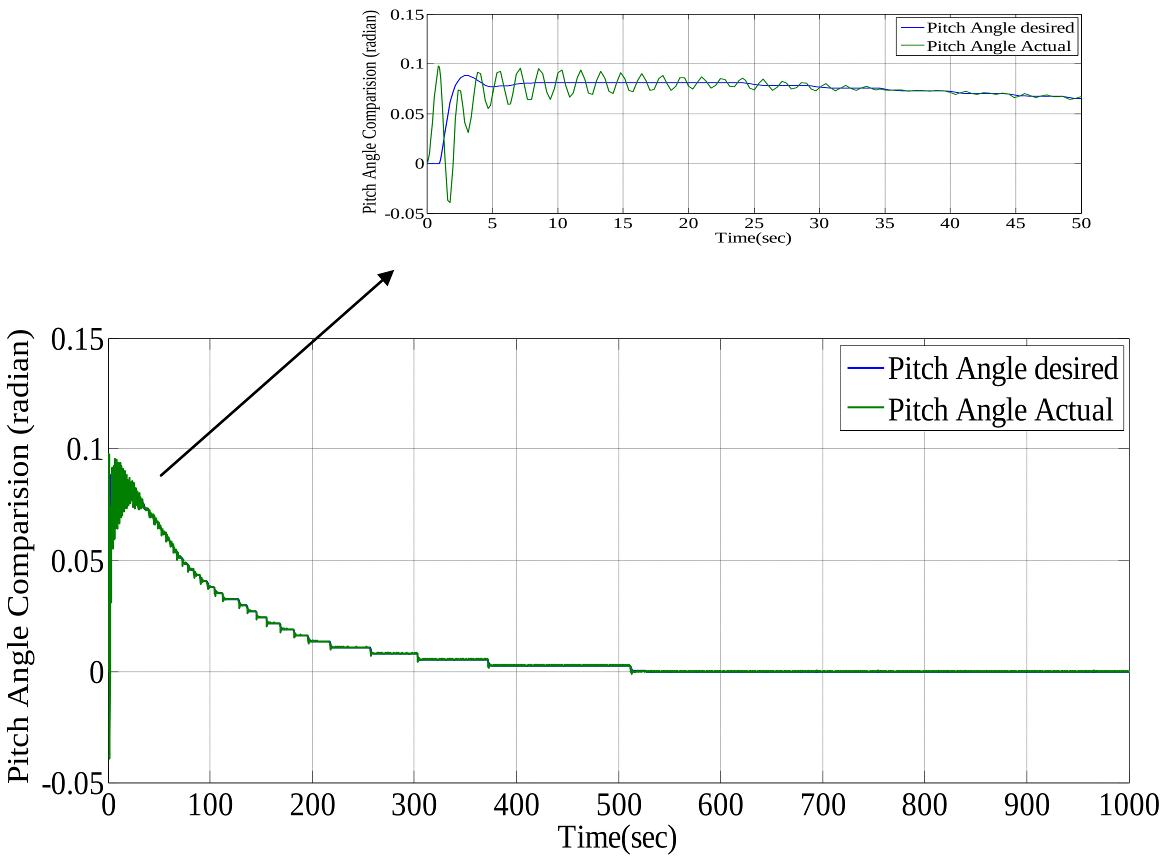


Figure 3.10: Comparison plot between the actual pitch angles to that of desired one

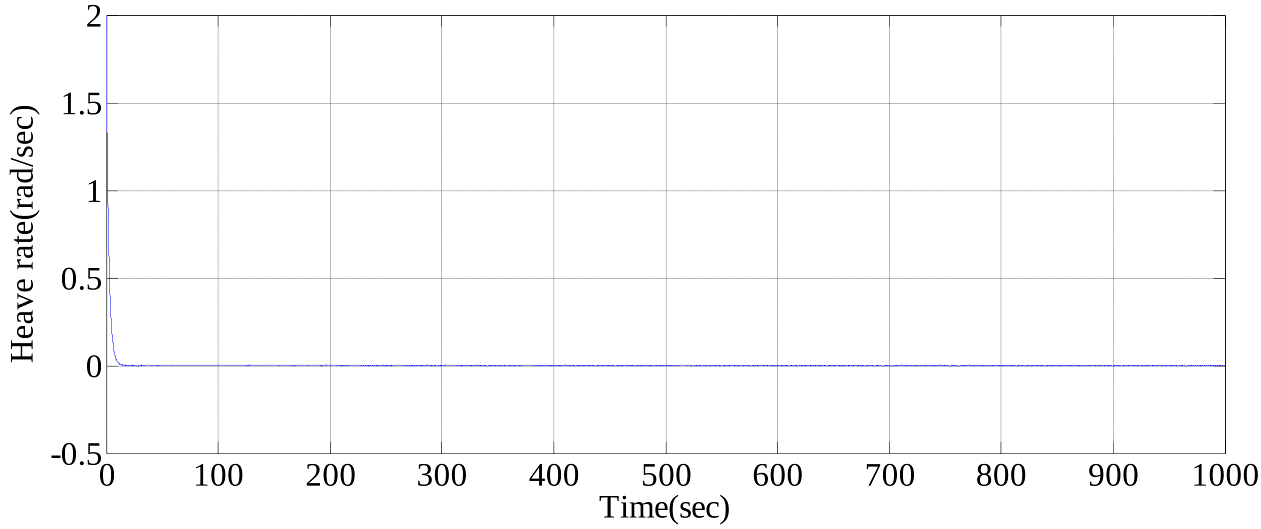


Figure 3.11: Variation of heave rate along the path

# Chapter 4

# LYAPUNOV BASED BACKSTEPPING CONTROLLER FOR DEPTH MOTION OF AN AUV

# Chapter 4

# Lyapunov based Backstepping Controller for depth motion of an AUV

## 4.1 Introduction

For any given control system, it is required to have a stable system since an unstable control system is useless. Lyapunov design has been a important tool for studying the stability of the nonlinear systems [25][26]. Though Lyapunov design is a very powerful tool for control system design, stability and performance analysis, the construction of a Lyapunov function is not easy for general nonlinear systems, and it is usually a trial-and-error basis. Different choices of Lyapunov functions may result in different control structures and control performance. Lyapunov design is used in many contexts, such as adaptive control, dynamic feedback, output-feedback, etc. The Lyapunov stability theory includes two methods. Lyapunov's first method uses the idea of linearization of a system around a given point and with this method it is possible only to achieve local stability results whereas in the second method i.e. Lyapunov's direct method, which is the most important tool for designing and analysis of nonlinear systems, there is no need to go for linearization and we can achieve global stability. The basic idea of Lyapunov's direct method is that if the total energy for any given system is continuously dissipating, then the system will eventually reaches to an equilibrium point and remain at that point until and unless some external perturbation is applied. Lyapunov's direct method basically include following two step:

1. Finding a appropriate scalar function, usually referred to as Lyapunov candidate function,

2. To evaluate its time derivative (first order) along the trajectory of the given system. As time increases if the Lyapunov function derivative decreases along the system trajectory, then the energy of the system is dissipated and thus the system will eventually settle's down.

Let a system is defined as:

$$\dot{x} = f(x,u) \tag{4.1}$$

where $u \in R^m$ is the control input , $x \in R^n$ is the state

Substituting $u = u(x)$ into (4.1), the autonomous closed-loop dynamics becomes:

$$\dot{x} = f(x,u(x)) \tag{4.2}$$

Let V (x) be chosen as a Lyapunov candidate function for analysis the stability of the above system. The objective is to find suitable value for u(x) such that it will guarantee that for all $x \in R^n$, the first order time derivative of the Lyapunov's function along the above system trajectory satisfies:

$$\dot{V}(x) = \frac{\partial V(x)}{\partial x} f(x,u(x)) \leq -Q(x) \tag{4.3}$$

.

where Q(x) is a positive definite function.

## 4.2 Objective

To design a control law such that the output signals i.e. actual depth tracks the reference signal i.e. desired depth despite the presence of parametric uncertainties.

## 4.3 Dynamics of an AUV with regards to dive plane motion

The dynamics and kinematics with respect to depth motion are given by:

$$\begin{pmatrix} \dot{z} \\ \dot{\theta} \end{pmatrix} = \begin{pmatrix} \cos\theta & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} w \\ q \end{pmatrix} - \begin{pmatrix} U\sin\theta \\ 0 \end{pmatrix} = B_1 \begin{pmatrix} w \\ q \end{pmatrix} - B_\theta \tag{4.4a}$$

$$\begin{pmatrix} \dot{w} \\ \dot{q} \end{pmatrix} = \begin{pmatrix} \frac{Z_w}{M - Z_{\dot{w}}} & \frac{[Z_{uq} + M_{uq}]U}{M - Z_{\dot{w}}} \\ \frac{M_{wu}U}{I_y - M_{\dot{q}}} & \frac{M_q}{I_y - M_{\dot{q}}} \end{pmatrix} \begin{pmatrix} w \\ q \end{pmatrix} - \begin{pmatrix} \frac{(w - B)\cos\theta}{M - Z_{\dot{w}}} \\ \frac{X_B B\cos\theta + Z_B \sin\theta}{I_y - M_{\dot{q}}} \end{pmatrix} + \begin{pmatrix} 0 \\ \frac{U^2 M_{\delta s}}{I_y - M_{\dot{q}}} \end{pmatrix} = B_2 \begin{pmatrix} w \\ q \end{pmatrix} + B_{\theta'} + B_3 \delta s \tag{4.4b}$$

<u>From eqn. (4.4a -4.4b)</u>

$$\dot{x} = \begin{pmatrix} 0_{2\times2} & B_1 \\ 0_{2\times2} & B_2 \end{pmatrix} x - \begin{pmatrix} -B_\theta \\ B_{\theta'} \end{pmatrix} + \begin{pmatrix} 0_{2\times1} \\ B_3 \end{pmatrix} \delta s \tag{4.5a}$$

If output vector is defined as

$$y = (z \quad \theta) \in R^{1\times2} \tag{4.5b}$$

Then,

$$y = (z \quad \theta) = C^T x \tag{4.5c}$$

where $C = (I_{2\times2} \quad 0_{2\times2}) \in R^{4\times2}$ and I is the identity matrix.

Let the depth reference and the pitch angle trajectory reference be defined as

$$y_r = (z_r \quad \theta_r) \in R^{1\times2} \tag{4.6}$$

## 4.4 Lyapunov Based Backstepping Controller Design

Let

$$x = (x_1 \quad x_2) \in R^{1\times 4} \tag{4.7}$$

where $x_1 = (z \quad \theta)$ and $x_2 = (w \quad q)$

Let the tracking error be defined as:

$$Z_1 = \begin{pmatrix} z \\ \theta \end{pmatrix} - \begin{pmatrix} z_r \\ \theta_r \end{pmatrix} \tag{4.8}$$

$$Z_1 = x_1 - y_r \tag{4.9}$$

$$\begin{aligned} \dot{Z}_1 &= \dot{x}_1 - \dot{y}_r \\ &= (B_1 x_2 - B_\theta) - \dot{y}_r \quad \text{(From eqn (4.5}a\text{))} \end{aligned} \tag{4.10}$$

Defining the change of coordinates as:

$$Z_2 = x_2 - \beta, \tag{4.11}$$

where $\beta \in R^2$ is the stabilizing signal.

<u>Using eqn.(4.11) in eqn.(4.10)</u>

$$\dot{Z}_1 = B_1 Z_2 + B_1 \beta - B_\theta - \dot{y}_\mathrm{r} \tag{4.12}$$

Let be β chosen in such a way that it will regulate, $Z_1$ to origin i.e.,

$$\beta = B_1^{-1}[B_\theta + \dot{y}_r - \dot{C}_1 Z_1] \tag{4.13}$$

where $C_1$ is a positive real number

<u>Using eqn. (4.13) in eqn. (4.12),</u>

$$\dot{Z}_1 = B_1 Z_2 - C_1 Z_1 \tag{4.14}$$

Let the Lyapunov function be defined as:

$$V_1(Z_1) = \frac{1}{2} Z_1^T Z_1 \tag{4.15}$$

So,

$$\dot{V}_1 = \frac{1}{2}[Z_1^T \dot{Z}_1 + \dot{Z}_1^T Z_1]$$

Using eqn. (4.14)

$$\dot{V}_1 = Z_1^T B_1 Z_2 - C_1 Z_1^T Z_1$$

$$\Rightarrow \dot{V}_1 = -C_1 Z_1^T Z_1, if\ Z_2 = 0 \tag{4.16}$$

However $Z_2$ is not the control input so it cannot be equated to zero. So the term "$Z_1^T B_1 Z_2$" must be compensated by regulating $Z_1$ to zero.

From the eqn. (4.11) it is known

$$Z_2 = x_2 - \beta$$

So, differentiating the above eqn.

$$\dot{Z}_2 = (B_2 x_2 + B_{\theta'} + B_3 \delta s) - \dot{\beta} \tag{4.17}$$

Taking partial differentiation the eqn. (4.13)

$$\dot{\beta} = \frac{\partial \beta}{\partial \theta}\dot{\theta} + \frac{\partial \beta}{\partial Z_1}\dot{Z}_1 + \frac{\partial \beta}{\partial \dot{y}_r}\ddot{y}_r$$

$$= (k_1 + k_2 + k_3 \dot{y}_r - k_3 C_1 Z_1)q + (B_1^{-1} C_1)(-C_1 Z_1 + B_1 Z_2) + B_1^{-1} \ddot{y}_r \tag{4.18}$$

$$\text{where}, k_1 = B_1^{-1}\begin{pmatrix} U\cos\theta \\ 0 \end{pmatrix}; k_2 = \begin{pmatrix} \frac{-1}{\sqrt{1+\theta^2}} & 0 \\ 0 & 0 \end{pmatrix} B_\theta; k_3 = \begin{pmatrix} \frac{-1}{\sqrt{1+\theta^2}} & 0 \\ 0 & 0 \end{pmatrix}$$

So, the eqn. (4.17) becomes:

$$\dot{Z}_2 = (B_2 x_2 + B_{\theta'} + B_3 \delta s) - [(k_1 + k_2 + k_3 \dot{y}_r - k_3 C_1 Z_1)q + (B_1^{-1} C_1)(-C_1 Z_1 + B_1 Z_2) + B_1^{-1} \ddot{y}_r] \tag{4.19}$$

Let the second Lyapunov function be defined as :

$$V_2 = V_1 + \frac{1}{2} Z_1^T Z_1 \tag{4.20}$$

$$\text{So,} \dot{V}_2 = \dot{V}_1 + \frac{1}{2}[Z_2{}^T \dot{Z}_2 + \dot{Z}_2{}^T Z_2]$$

<u>Using eqn. (4.19),</u>

$$\dot{V}_2 = -C_1 Z_1{}^T Z_1 \qquad (4.21)$$

<u>If and only if</u>

$$\delta s = -(Z_2^T B_3)^{-1}[Z_1{}^T B_1 Z_1 + Z_2{}^T B_2 x_2 + Z_2{}^T B_{\theta'} - Z_2{}^T (k_1 + k_2 + k_3 \dot{y}_r - k_3 C_1 Z_1) q - Z_2{}^T (B_1^{-1} C_1^2 Z_1 + C_1 Z_2 - B_1^{-1} \ddot{y}_r)] \qquad (4.22)$$

<u>Calculation of error</u>

$$e = Z_d - Z_a \qquad (4.23)$$

<u>To get a desired pitch angle this will drive the AUV dynamics onto a desired depth as per eqn. (4.22) ,again we have to choose a third Lyapunov function</u>

Let the Lyapunov function be chosen as:

$$V_1 = \frac{1}{2} e^2 \qquad (4.9)$$

Taking derivative and using the condition as discussed in section 4.1,

$$\begin{aligned} \dot{V}_1 &= e\dot{e} \\ &= e(\dot{Z}_d - \dot{Z}_a) \\ &= e(-eK) \qquad [\textit{from eqn.}(4.3)] \\ &= -e^2 K < 0, \qquad (4.10) \end{aligned}$$

<u>If and only if,</u>

$$\begin{aligned} \dot{Z}_d + [U \sin\theta - w \cos\theta] &= -eK \\ \Rightarrow \dot{Z}_d + \sqrt{w^2 + U^2}[\cos(\psi + \theta)] &= -eK \end{aligned}$$

$$\text{where } \psi = \sin^{-1} \frac{U}{\sqrt{w^2 + U^2}}$$

Thus required, $$\theta_d = \arccos[\frac{-eK - \dot{Z}_d}{\sqrt{w^2 + U^2}}] - \psi \qquad (4.11)$$

## 4.5 Results and Discussions

To verify the controller developed in this chapter, MATLAB/SIMULINK environment is chosen. The INFANTE AUV parameters [21] are selected for AUV dynamics as given in Table A.1 and Table A.2. The surge velocity is set at 0.5 m/sec and all other parameters are set at zero. $C_{1,}$ a positive constant is set at 1.61. Using eqn. (4.11) i.e. the kinematic control law as shown in Fig 4, the dynamics of AUV is made to follow its desired depth of 3 meter within 10 sec 1 by using Lyapunov based Backsteeping approach as shown in Fig 4.2 .

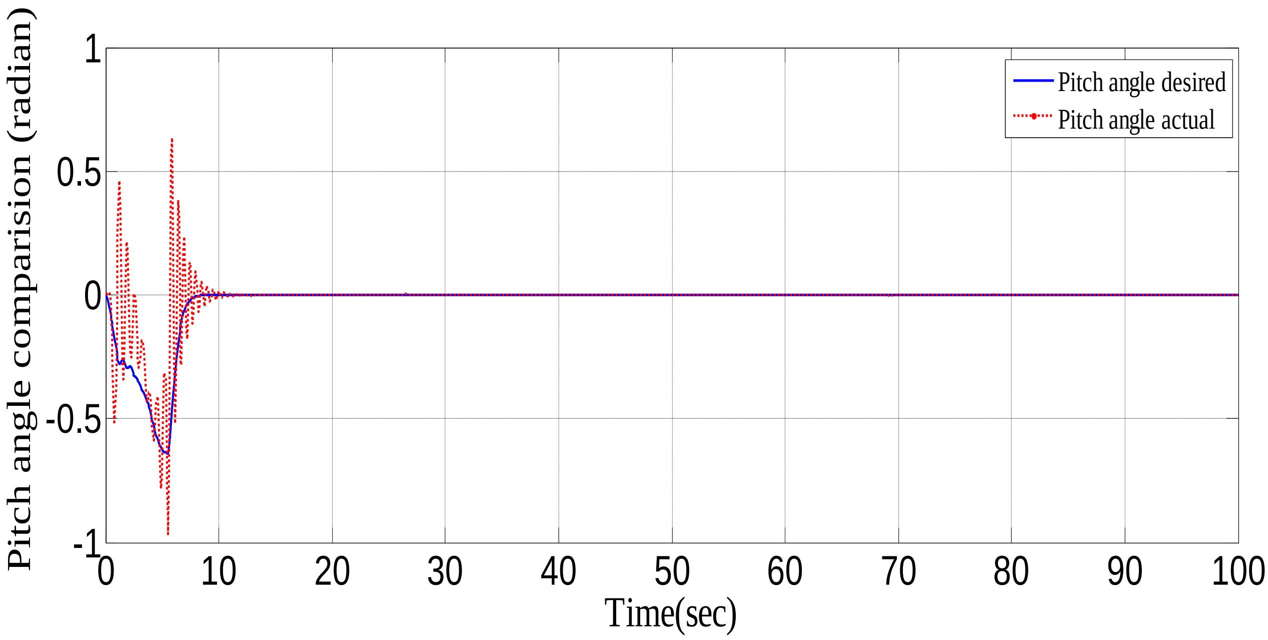


Figure 4.1: Comparison between the desired pitch angle and actual pitch angle using Lyapunov Backstepping approach

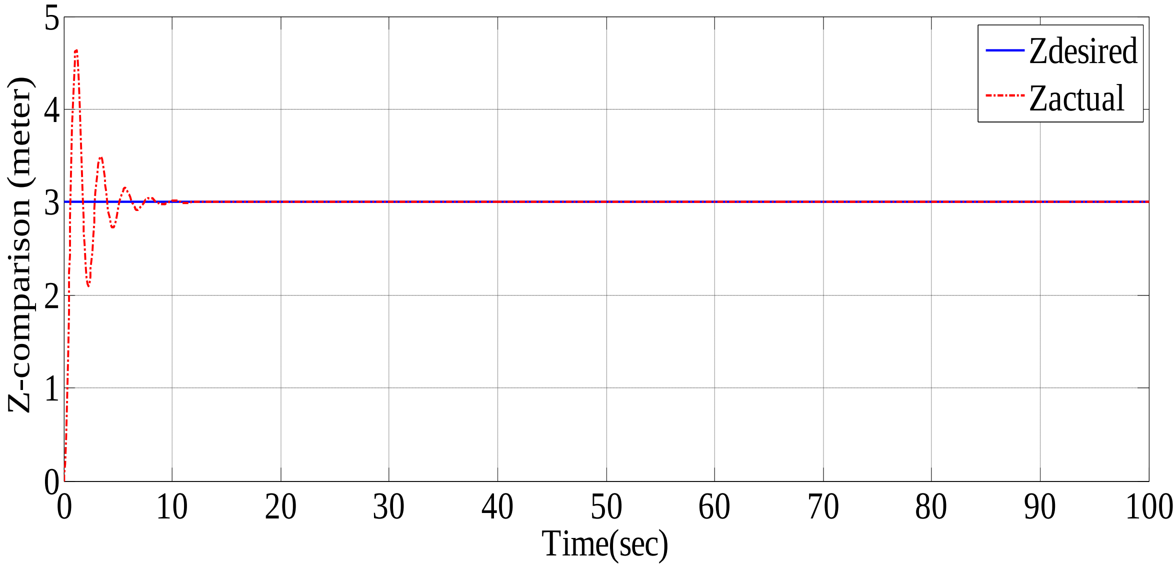


Figure 4.2: Comparison between the actual depth and desired depth (3 meter) using Lyapunov Backstepping approach

# Chapter 5

# CONCLUSION AND SCOPE OF FUTURE WORK

# Chapter 5

# Conclusion and Future Work

## 5.1 Conclusion

This thesis addressed the depth following control problem of an AUV. The development of depth following controller for an AUV has been successfully implemented using MATLAB and SIMULINK considering the fact that the AUV dynamic being very complex, time varying, non linear and uncertain. In the thesis two control algorithms is being proposed to address the dive control of an AUV. First controller is proposed which involves two step processes: First a kinematic controller is designed which will provide the reference for the dynamic controller. The kinematic controller is designed using Fuzzy Logic Controller.  For the design of dynamic controller, MRAC is being used and the second controller is being designed using Lyapunov based Backstepping approach. In this approach desired pitch angle is first obtained using Lyapunov based Backsteeping approach which will drive the AUV dynamics onto a desired depth. In the latter approach the controller is designed without any restriction on pitch angle variations.

## 5.2 Future Work

The effect of underwater currents and wave disturbances has not been considered in the development of control laws for the depth control of the AUV. So the above effect needs to be considered for the designing purpose

# Appendixes A

The INFANE AUV parameters are considered for control of depth motion.

Table A.1: AUV Parameters

| | | | |
|---|---|---|---|
| m | = 2234.5 kg | ; B | = 21898 N |
| L | = 4.215 m | ; $\rho$ | =1030 kg/m$^3$ |
| $I_x$ | $= 700 Nms^2$ | ; $I_y$ | $= 1700 Nms^2$ |
| $I_z$ | $= 2000 Nms^2$ | ; $I_{xy}$ | $= 0$ |
| $I_{yz}$ | $= 0$ | ; $I_{xz}$ | $= 0$ |
| $CB$ | $= (0\ \ 0\ \ -0.041)$ | | |
| $CG$ | $= (0\ \ 0\ \ 0)$ | | |

Table A.2: INFANTE AUV Hydrodynamic coefficient

| | |
|---|---|
| $C_{X_{\dot{u}}} = \frac{\rho}{2} L^3 X_{\dot{u}} = -141.9$ ; | $C_{Y_{\dot{r}}} = \frac{\rho}{2} L^4 Y_{\dot{r}} = 186.9$ ; |
| $C_{Z_{\dot{q}}} = \frac{\rho}{2} L^4 Z_{\dot{q}} = -1701.9$ ; | $C_{K_{\dot{q}}} = \frac{\rho}{2} L^4 K_{\dot{q}} = -40.6$ ; |
| $C_{N_{\dot{v}}} = \frac{\rho}{2} L^4 N_{\dot{v}} = 957$ ; | $C_{N_{\dot{r}}} = \frac{\rho}{2} L^5 N_{\dot{r}} = -1349$ ; |
| $C_{X_{ww}} = \frac{\rho}{2} L^2 X_{ww} = -89.48$ ; | $C_{X_{qq}} = \frac{\rho}{2} L^4 X_{qq} = 9587.4$ ; |
| $C_{Y_{vv}} = \frac{\rho}{2} L^2 Y_{vv} = -667.5$ ; | $C_{N_{vv}} = \frac{\rho}{2} L^3 N_{vv} = 433.8$ ; |
| $C_{X_{w\delta s}} = \frac{\rho}{2} L^2 X_{w\delta s} = -221.7$ ; | $C_{X_{\delta s\delta s}} = \frac{\rho}{2} L^2 X_{\delta s\delta s} = -455$ ; |
| $C_{Y_{\delta r}} = \frac{\rho}{2} L^2 Y_{\delta r} = 117.2$ ; | $C_{Z_{\delta s}} = \frac{\rho}{2} L^2 Z_{\delta s} = -689.7$ ; |
| $C_{Z_{\dot{W}}} = \frac{\rho}{2} L^3 Z_{\dot{W}} = -4617$ ; | $C_{M_{\dot{q}}} = \frac{\rho}{2} L^5 M_{\dot{q}} = -1692.3$ ; |
| $C_{X_{wq}} = \frac{\rho}{2} L^3 X_{wq} = 137$ ; | $C_{X_{q\delta s}} = \frac{\rho}{2} L^3 X_{q\delta s} = -308.9$ ; |
| $C_{Y_{rr}} = \frac{\rho}{2} L^4 Y_{rr} = -32.5$ ; | $C_{N_{\delta r}} = \frac{\rho}{2} L^3 N_{\delta r} = -266$ ; |
| $C_{X_{vv}} = \frac{\rho}{2} L^2 X_{vv} = -128$ ; | $C_{M_{\delta s}} = \frac{\rho}{2} L^3 M_{\delta s} = -791.3$ ; |
| $C_{X_{\delta r\delta r}} = \frac{\rho}{2} L^2 X_{\delta r\delta r} = -80.3$ ; | $C_{N_{rr}} = \frac{\rho}{2} L^5 N_{rr} = -310$ ; |
| $C_{X_{rr}} = \frac{\rho}{2} L^4 X_{rr} = 832$ ; | $C_{X_{uu}} = \frac{\rho}{2} L^2 X_{uu} = -35.4$ ; |
| $C_{M_{\dot{W}}} = \frac{\rho}{2} L^4 M_{\dot{W}} = -2090.4$ ; | $C_{Y_{\dot{v}}} = \frac{\rho}{2} L^3 Y_{\dot{v}} = -1715.4$ ; |

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