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Design and Implementation of Fuzzy Logic Controller for Autonomous Underwater Vehicle

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Abstract: The objective of this study is to design a fuzzy logic controller (FLC) for Autonomous Underwater Vehicle (AUV) model for controlling the Pitch and Depth. In this process, fuzzy controllers are designed and implemented for controlling the AUV in the depth plane. Subsequently the controller performance is evaluated in the presence of dynamics of complete model maneuverings. AUV dynamics have been derived under various assumptions on the motion of the vehicle. Plant transfer function is extracted from the hydrodynamic coefficients. Fuzzy logic controller (FLC) using Sugeno type fuzzy inference system is employed with minimal number of rules for Pitch and Depth control. The FLC based on fuzzy logic provides a means of converting a linguistic control strategy based on expert knowledge into an automatic control strategy. In Pitch control FLC inputs are error and error rate, in depth control FLC inputs are error, pitch rate and pitch. This study also involves the design of conventional P and PD controller for comparing performance of FLC. The simulation results show the better performance by applying proposed control strategy. MATLAB control tool box is used for design, implementation and simulation.

Keywords: Autonomous underwater vehicles, Six Degrees of Freedom, Conventional controller, Fuzzy Logic Controller, Depth control.

Nomenclature:

z_w force derivative due to angle of attack
z_q force derivative due to unit pitch rate
z_δ force derivative due to rudder deflection
m_w moment derivative due to angle of attack
m_q moment damping derivative due to pitch rate
m_δ moment derivative due rudder deflection
δ rudder deflection in pitch plane
m mass of the body
U Surge velocity along X Direction in m/s
v Sway velocity along Y Direction in m/s
w Heave velocity along Z Direction in m/s
p Roll velocity about X axis in rad/s
q Pitch velocity about Y axis in rad/s
r Yaw velocity about Z axis in rad/s

I. INTRODUCTION

“AUV” stands for Autonomous Underwater Vehicle. AUV is driven through water by electric propulsion system, controlled and piloted by an on-board computer with six degrees of freedom (6-DOF) maneuverability. Underwater vehicles are classified as manned and unmanned underwater vehicles, AUVs comes under second category. Securing the waters pertaining to navy interest is set to acquire a whole new dimension, with the entry of AUV as force multipliers. The first AUV was developed at the Applied Physics Laboratory (APL) at the University of Washington in the late 1950s by Stan Murphy & Bobfrancois due to the need to obtain oceanographic data along precise trajectories

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[3]. AUV launching is sophisticated example of naval applications, it can be launched either air or from a ship [2] and finds extensive applications in defence organizations such as anti-submarine warfare and air crash investigation, locating ship wrecks on or below the sea floor, help in finding & retrieving black box of a flight & they sense dangerous hazards like live underwater mines. AUVs can help us to better understand of marine and other environmental issues [3], protect the ocean resources and efficiently utilize them for further development. Industries with underwater infrastructure, like pipes and cables, can use AUVs to identify areas that need repair. AUVs must settle predefined depth to complete the above mentioned any tasks set out in its mission. AUV fins plays vital role in stabilizing the vehicle in roll, pitch and yaw motions by changing the deflection of fins and then the forces and moments on the vehicle will be changed accordingly.
The underwater vehicle response is slow compared to air scenario because of low speeds & due to constraints like higher density of water. The precise control of the AUV is a challenging problem due to the influence of uncertain and un-modelled disturbances such as hydrodynamic forces [2]. It is necessary to develop robust, stable and high performance coordinated control techniques to improve static and dynamic behaviour of the system. There are several methods available to design controllers for improvement in their performance. Traditional controllers such as PID controllers are widely used to design an effective control scheme for improving static & dynamic characteristics. However, the conventional PID controller design usually involves tuning the parameters manually by skilled operator. These available methods are more effective and easily be applied if the system mathematical model is known & the objective function formulated in precise terms. So, based on the above facts it is felt that a Fuzzy Logic Controller (FLC) is to be designed for the AUV, which excels in dealing with imprecision. FLC has ability to use simple linguistic variables rather than numerical variables, which does not require well-defined mathematical model [2]. During the past, several years' Fuzzy logic techniques have been successfully utilized in complex or ill-defined processes. Fuzzy logic controller is an important tool in controlling nonlinear, complex and poorly defined systems. The objective of this paper is to design conventional & fuzzy logic controller for pitch and depth system of an AUV, considering pitch, pitch rate & depth as control inputs and horizontal rudder commands as out puts which will dive the AUV into desired path.

II. AUTONOMOUS UNDER WATER VEHICLE MODELING

Two coordinate frames are used to model the AUV motion. The position (x, y, z) and orientation (ϕ, θ, ψ) of an AUV are described with respect to the Earth-fixed frame. The linear and angular velocities of an AUVs are described by u, v, w, p, q, r in the body-fixed frame. X, Y, Z, K, M, N describes the total forces and moments acting on the vehicle with respect to body fixed reference frame [11] [3]. To describe position and translation motion first three sets of coordinates and their time derivatives are required. While for orientation and rotational motion last three sets of coordinates and their time derivatives are required.

TABLE I STANDARD NOTATION FOR AUV

DOF	Motions	Forces and Moments	Linear and Angular velocities	Positions and Euler angles
1	Surge	X	U	x
2	Sway	Y	v	y
3	Heave	Z	w	z
4	Roll	K	p	ϕ
5	Pitch	M	q	θ
6	Yaw	N	r	ψ

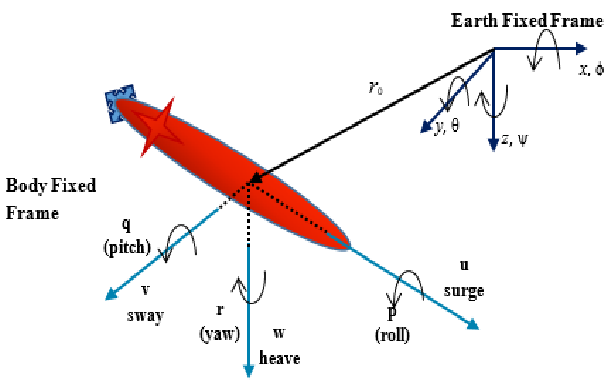

Fig. 1 Body-Fixed and Earth-Fixed Coordinate Systems

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A. Coordinate Transformations
Earth axis to Body axis Transformation
Transforming a vector from the Earth axis system to the body axis system requires three consecutive rotations about the z axis, y axis, and x axis, respectively. The Euler angles are used to rotate the Earth axis system into coincidence with the body axis system. The Euler angles are expressed as yaw (ψ), pitch (θ), and roll (ϕ).

$$[R] = [R]_{z_1\,\psi}[R]_{y_1\theta}[R]_{x_1\phi} \qquad (1)$$

If the above equation is expanded, it takes the form

$$[R] = \begin{bmatrix} c\theta\, c\psi & -c\phi\, s\psi + s\phi\, s\theta\, c\psi & s\phi\, s\psi + c\phi\, s\theta\, c\psi \\ c\theta\, s\psi & c\phi\, c\psi + s\phi\, s\theta\, s\psi & -s\phi\, c\psi + c\phi\, s\theta\, s\psi \\ -s\theta & s\phi\, c\theta & c\phi\, c\theta \end{bmatrix} \qquad (2)$$

It can be said that any position vector in a rotated reference frame may be expressed in terms of the coordinates of original reference frame given by the operation [11].

$$r_{ijk} = [R]^{-1} r_{IJK} \qquad (3)$$

Body fixed frame velocities can be determined from earth fixed frame velocities are

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = [DCM]^T \begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{Z} \end{bmatrix} \qquad (4)$$

Similarly, body angular rates from Euler angle rates are

$$\begin{bmatrix} p \\ q \\ r \end{bmatrix} = [T]^{-1} \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} \qquad (5)$$

$$[T]^{-1} = \begin{bmatrix} 1 & 0 & -s\,\theta \\ 0 & c\,\phi & s\phi\, c\,\theta \\ 0 & -s\,\phi & c\,\phi\;\, c\,\theta \end{bmatrix}$$

Where c=cos and s=sin

B. Rigid body dynamics
Force equations
Surge, sway, heave equations of motion [10]

$$m(\dot{U} + qw - rv) = X \qquad (6)$$

$$m(\dot{v} + rU - pw) = Y \qquad (7)$$

$$m(\dot{w} - qU + pv) = Z \qquad (8)$$

Moment equations
Roll, pitch, yaw equation of motion

$$I_x\dot{p} - (I_y - I_z)qr + I_{yz}(r^2 - q^2) - I_{xz}(pq + \dot{r}) + I_{xy}(rp - \dot{q}) = K \qquad (9)$$

$$I_y\dot{q} - (I_z - I_x)rp + I_{xz}(p^2 - r^2) - I_{xy}(qr + \dot{p}) + I_{yz}(pq - \dot{r}) = M \qquad (10)$$

$$I_z\dot{r} - (I_x - I_y)pq + I_{xy}(q^2 - p^2) - I_{yz}(rp + \dot{q}) + I_{xz}(qr - \dot{p}) = N \qquad (11)$$

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It is difficult to design the controller directly from the above 3 force & 3 moment equations, because the dynamic equations of an AUV are nonlinear and coupled [1]. Therefore, it is necessary to simplify them at the operating point based on assumptions. After several steps of linearization transfer function for pith rate is given below.

C. Extraction of Transfer Function

Hydro dynamic force and moments related to the body velocities and the control surface deflections. These forces and moments are equated to Equations (9) & (11) to get the full dynamics equations of motion used in the simulation[1].

$$\dot{w} - qU = z_w w + z_q q + z_\delta \delta \quad (12)$$

$$\dot{q} = m_w w + m_q q + m_\delta \delta \quad (13)$$

$$\frac{q(s)}{\delta(s)} = \frac{s m_\delta + m_w z_\delta - z_w m_\delta}{s^2 - s(z_w + m_q) + (z_w m_q - m_w (U + z_q))} \quad (14)$$

III. FUZZY LOGIC CONTROLLER DESIGN

Fuzzy logic control is multi valued logic. It is the range of allowable values. Membership values goes from 0 to 1 through intermediate values. FL control is works on fuzzy set theory [I.J. Nagrath & M. Gopal]. A fuzzy set is a set without a clear or well-defined boundary unlike binary logic i.e. all elements of the fuzzy set belong to certain degree given by the MF. A MF maps crisp input onto a normalized domain or fuzzy domain in the interval [0, 1].

A. The Principle Structure of Fuzzy Logic Control

Fuzzy system elements:

Input variables x_1, x_2……x_n are crisp [RC Chakraborty].

Output variables $y=y_1$, y_2, y_m are crisp

Fuzzification: a process of transforming crisp values into grades of membership for linguistic terms, “negative”, “zero”, “positive” of fuzzy sets.

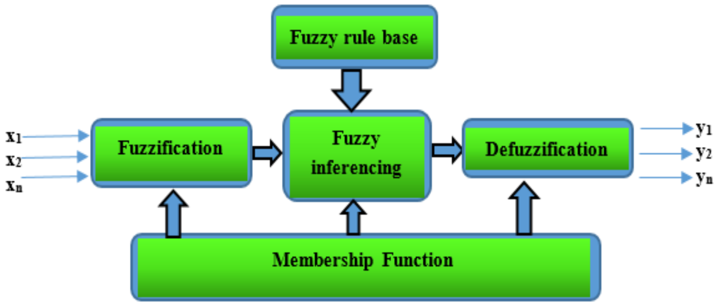

Fig. 2 Structure of fuzzy logic control (FLC)

- **Fuzzy rule base:** a collections propositions containing linguistic variables: the rules are expressed in the form:

If (x is A) AND (y is B) . . . . THEN (z is C)

Where x, y, z represents variables (e.g. degrees, degrees/sec, meters) and A, B, and Z are linguistic variables (e.g. ‘negative’, ‘zero’, ‘positive’)

- **Membership function:** Membership function (MF) specifies the degree to which a given input belongs to a set**.**
- **Fuzzy inferencing:** combines the facts obtained from the fuzzification with the rule base and conducts the fuzzy reasoning process.
- **Defuzzification:** is the reverse process of fuzzification.

B. Fuzzy pitch control design

The membership functions of variables of Pitch loop for Sugeno type are shown in Figure 3 with two input variables and one output variable. Error and error rate variables in pitch loop have been assigned to negative(N), zero(Z) and positive(P) membership functions and horizontal rudder command variable assigned to large negative (ln), small negative (sn), zero (z), small positive (sp), large positive (lp) membership functions. The rules in the pitch loop are as follows

(1) If (pitch error) is (N) AND (pitch rate) is (N) ⇒ Then (HorRudCom) is (ln)

(2) If (pitch error) is (N) AND (pitch rate) is (Z) ⇒ Then (HorRudCom) is (sn)

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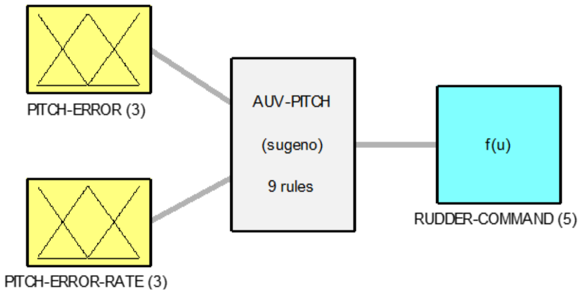
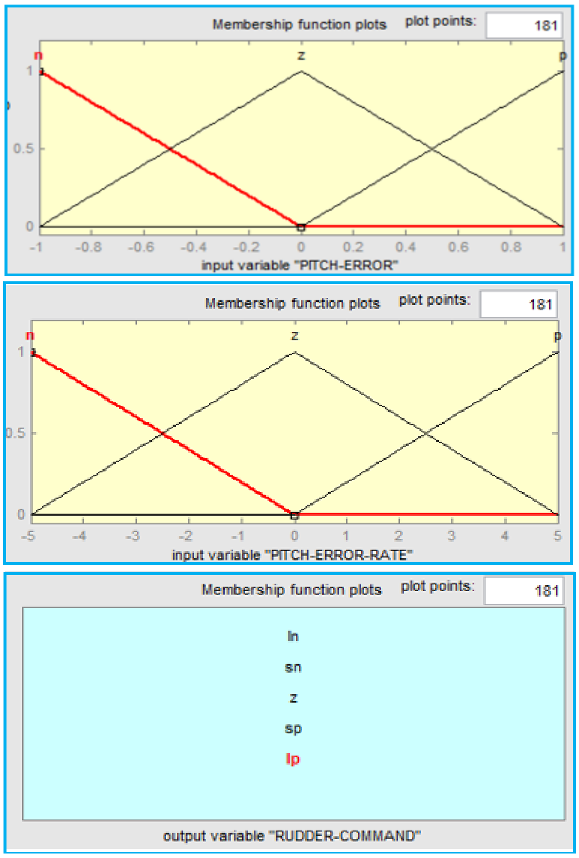


(a) Pitch loop fuzzy control block diagram



(b) Membership functions

Fig. 3 Pitch Loop Variables and Membership Functions

(3) If (pitch error) is (N) AND (pitch rate) is (P) ⇒ Then (HorRudCom) is (z)
(4) If (pitch error) is (Z) AND (pitch rate) is (N) ⇒ Then (HorRudCom) is (sn)
(5) If (pitch error) is (Z) AND (pitch rate) is (Z) ⇒ Then (HorRudCom) is (z)
(6) If (pitch error) is (Z) AND (pitch rate) is (P) ⇒ Then (HorHorRudCom) is (sp)
(7) If (pitch error) is (P) AND (pitch rate) is (N) ⇒ Then (HorRudCom) is (z)
(8) If (pitch error) is (P) AND (pitch rate) is (Z) ⇒ Then (HorRudCom) is (sp)
(9) If (pitch error) is (P) AND (pitch rate) is (P) ⇒ Then (HorRudCom) is (lp)
Output MF's are constants, they must be tuned to reach good performance

C. Fuzzy Depth Control Design

Before any changes appear in the depth, the pitch angle begins to change. Therefore, by controlling the pitch angle, one can in fact control the depth and this result in the stabilization of the depth variables. Based on this observation, three fuzzy variables are selected to control the depth loop. The depth loop variables and membership functions of the fuzzy control system are shown in Fig. 4(a) and Fig. 4(b). The following rules are chosen to have a good performance of Depth control. The rules in the depth loop are as follows
If depth error is (N) ⇒horizontal rudder command is (LN)

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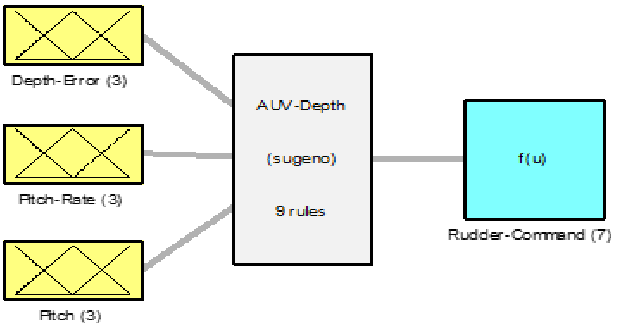
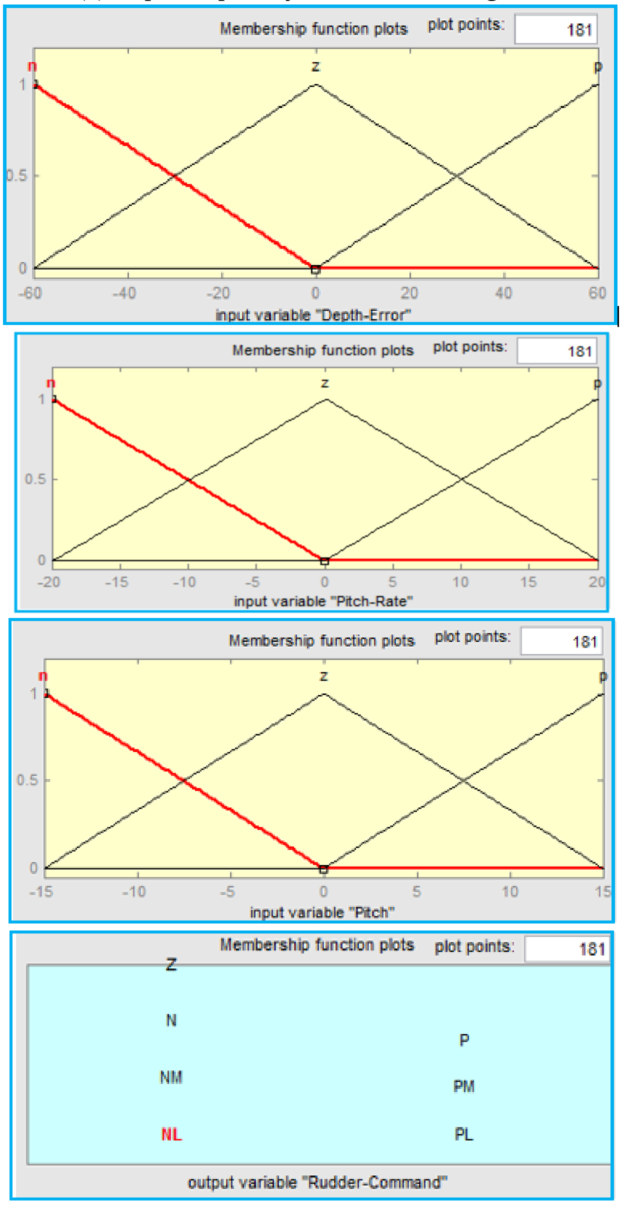


(a) Depth loop fuzzy control block diagram



(b) Membership functions

Fig. 4 Depth Loop Variables and Membership Functions

If depth error is (Z) ⇒horizontal rudder command is (Z)
If depth error is (P) ⇒horizontal rudder command is (LP)
If pitch rate is (N) ⇒horizontal rudder command is (MP)
If pitch rate is (Z) ⇒horizontal rudder command is (Z)

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If pitch rate is (P) ⇒horizontal rudder command is (MN)
If pitch is (N) ⇒horizontal rudder command is (N)
If pitch is (Z) ⇒horizontal rudder command is (Z)
If pitch is (P) ⇒horizontal rudder command is (P)
Output membership functions are constants; they must be tuned to reach good performance.

IV. HYDRO DYNAMIC COEFFICIENT PARAMETERS& SPECIFICATIONS

TABLE II HYDRO DYNAMIC COEFFICIENT PARAMETERS

Parameter	**Value**	**Units**	**Description**
M_δ	-1.46E1	kg/rad	Fin lift moment
Z_W	-1.16E1	kg/m	Body lift force & fin lift
Z_δ	2.13E1	kg/(m*rad)	Fin lift force
M_W	-5.48E-1	kg	Body & fin lift & munk moment
Mq	-4.16E0	kg*m/rad	Added mass cross term & fin lift
m_{22}	-7.78E1	kg	Added mass
Zq	8.84E-1	kg/rad	Added mass cross term & fin lift
m	66.0399	kg	Mass
U	3	m/s	Forward Speed

The transfer function for pitch rate is given below from the equation 15

$$\frac{q(s)}{\delta(s)} = \frac{14.6s + 181}{s^2 + 15.76s + 39.51} \qquad (15)$$

The response of control system must satisfy the transient and steady state requirements. The design requirements for Pitch and Depth control systems are formulated in the table given below.

TABLE III DESIGN REQUIREMENTS

S. no	**Attributes**	**Rise time (sec)<**	**Settling time (sec) <**	**Peak overshoot (%)<**	**Steady state error (%)**
1	**Pitch Control**	1.5	2.5	10%	0%
2	**Depth Control**	30	50	10%	0%

V. SIMULINK MODEL AND RESULTS FOR DESIGN OF PITCH & DEPTH CONTROL

A. Pitch Control

The block diagram of a simple Pitch control system with unit feedback is shown in Fig. 5

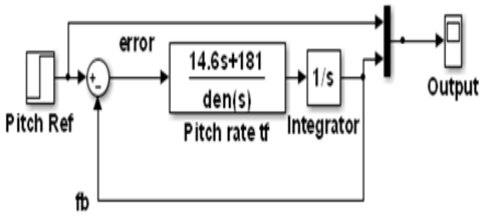

Fig. 5 Pitch control loop

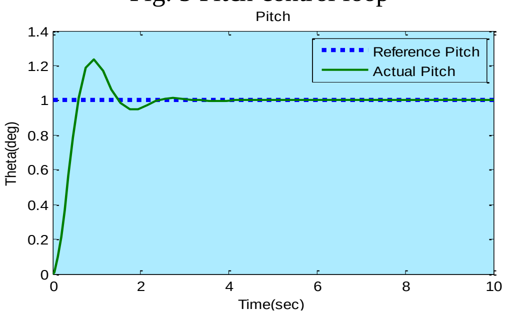

Fig. 6 Step response of Pitch loop

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Integration of pitch rate produces Pitch angle. The open loop transfer function of the pitch loop is type one. Fig. 6 shows the unit step response of the Pitch loop. It is clear that the response is not satisfying the overshoot requirement.

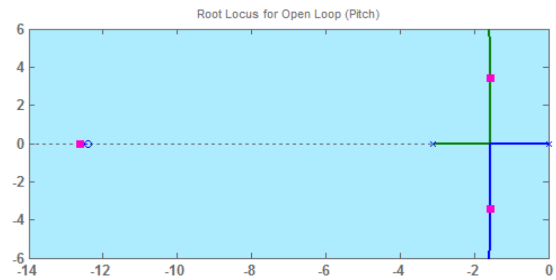

Fig. 7 Poles and zeros location before tuning the controller

A derivative controller helps to reduce the overshoot. PD controller increases the damping ratio and reduces peak overshoot and settling time. Steady state error, type and ω_n of the system remains unchanged. The transfer function of the designed **PD controller** is

$1.5+0.5s$

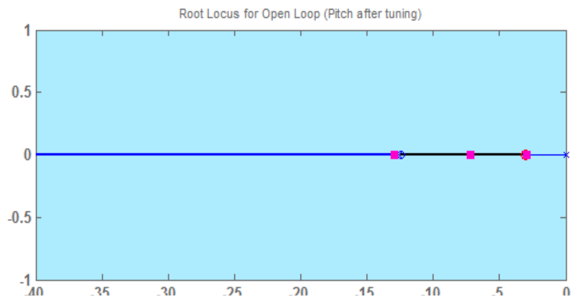

Fig. 8 Root locus after tuning the controller

The root locus of the system after tuning location of zero at -3. After designing PD controller for Pitch according to required specifications open loop poles and zeros location in root locus shown in Fig 8, Simulink model for pitch with PD controller are shown below

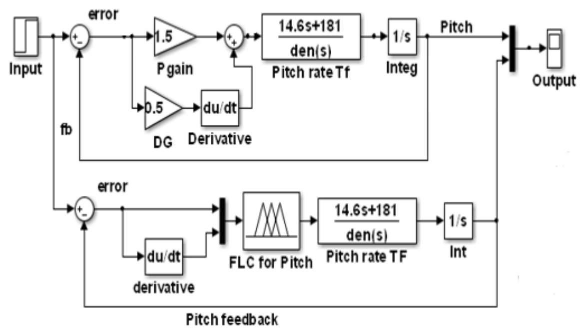

Fig. 9 Pitch control loop with controllers

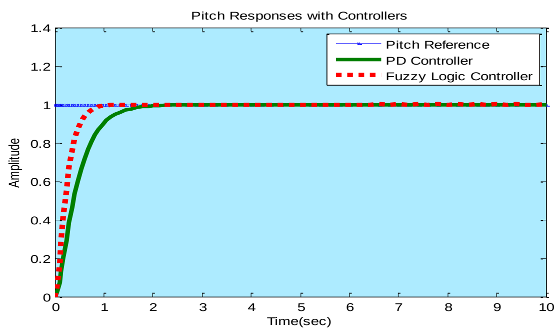

Fig. 10 Simulated performance comparisons of Pitch loop

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Control law: Pitch Command = PD Controller *(Reference – Feedback).
Pitch control system keeps the AUV in pre-defined maneuvers. The unit step response of Pitch with PD controller & with fuzzy logic controller of the system is shown in Fig. 10.

Summary:
After comparing the performance of conventional PD and Fuzzy Logic Controller as shown in TABLE IV it is clear that fuzzy logic has small Rise time, settling time and it is having the fast response as compared to conventional PD Controller.

TABLE IV COMPARING VARIOUS TIME DOMAIN SPECIFICATIONS FOR PITCH CONTROL SYSTEM

S. no.	Controller used	Rise time(sec)	Settling time(sec)	Peak overs-hoot (%)	Steady state error (%)
1	PD Controller	1.2	2.3	negligible	0%
2	Fuzzy Logic Controller	0.6	1.5	negligible	0%

B. Depth Control
A simple proportional controller found to satisfy the design requirements. It is simple regulating type, tuning is easy.

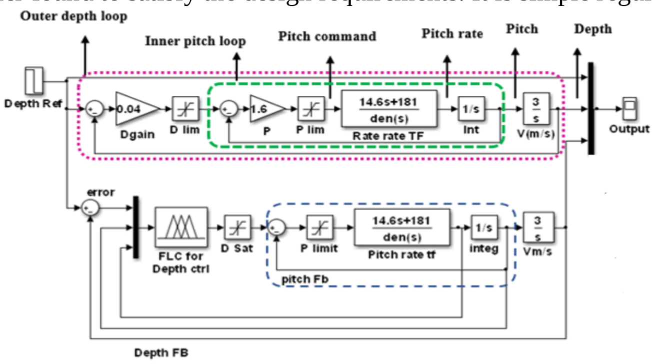

Fig. 11 Depth control loop with controllers

Depth control system helps the vehicle to dive down and settle at predefined set depth. The pitch loop is inner to depth loop. Pitch reference input is provided by the depth controller. A step input of 60 is set as depth reference.

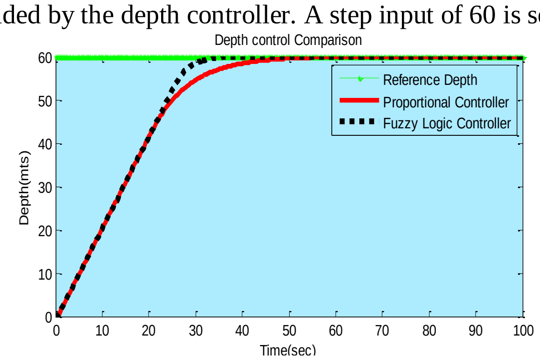

Fig. 12 Simulated performance comparisons of Depth loop

TABLE V COMPARING VARIOUS TIME DOMAIN SPECIFICATIONS FOR DEPTH CONTROL SYSTEM

S. no	Controller used	Rise time (sec)	Settling time (sec)	Peak overshoot (%)	Steady state error (%)
1	PD Controller	25	45	Negligible	0%
2	Fuzzy Logic Controller	20	33	Negligible	0%

Summary:
After comparing the performance of conventional P and Fuzzy Logic Controller as shown in TABLE V it is clear that fuzzy logic has small Rise time, Settling time and it is having the fast response as compared to conventional P Controller.

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Simulation results for the Autonomous underwater vehicle are depicted below for a time of 70 sec.

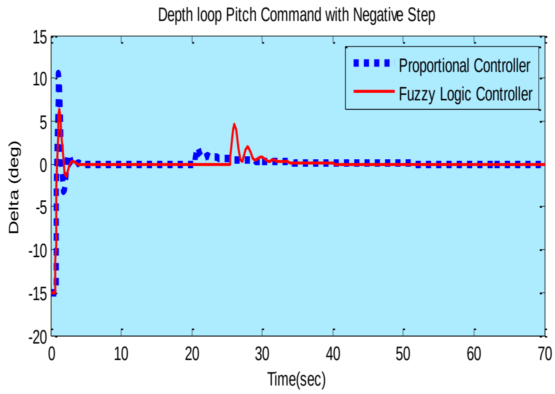

Fig. 13 Surface deflection of Pitch

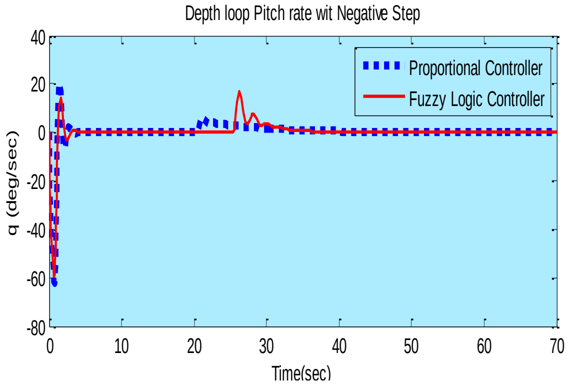

Fig. 14 Pitch rate

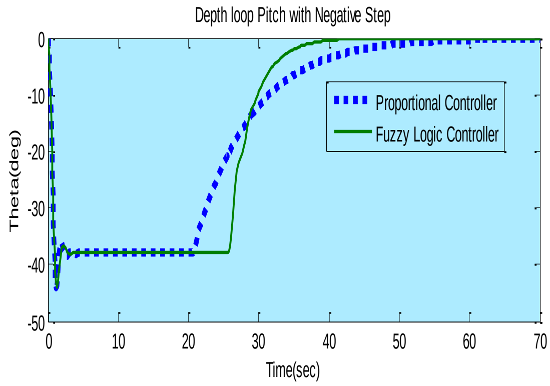

Fig. 15 Pitch motion for the AUV

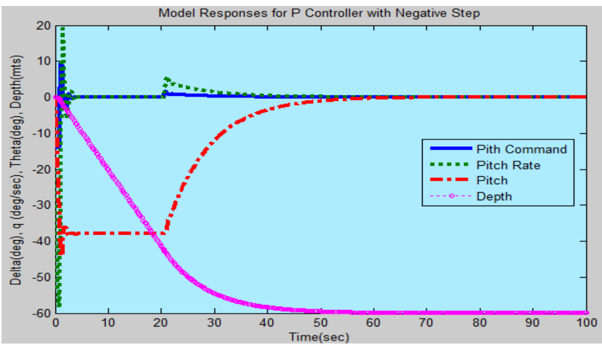

Fig. 16 Depth Control Responses for P controller

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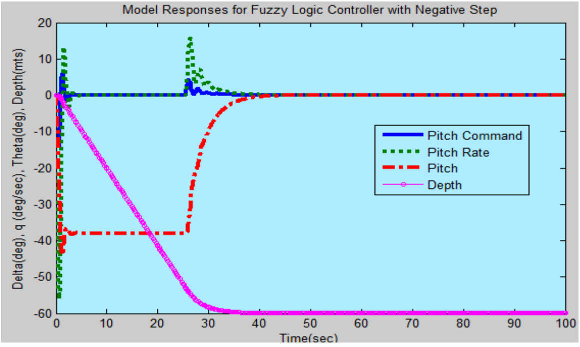

Fig. 17 Depth Control Responses for Fuzzy Logic Controller

VI. CONCLUSION

The aim of this paper is to design controllers for Pitch & Depth control, which is used in application of AUV's in order to reach the intended point under water. The focus of this project is to apply soft computing technique that is fuzzy logic to design Fuzzy logic controller to get better dynamic and static performance at the output. The comparison of simulated responses clearly emphasized the advantages of fuzzy inference systems. FLC have some advantages such as simplicity of implementation, faster response. Some of the possible works to design controllers and implementation for Roll, Pitch and Yaw of the Autonomous under water vehicle are listed below.

- Tuning the PID controller by using Genetic Algorithms Techniques.
- Apply the NN based adaptive control & Sliding mode control.
- Verification and validation of control algorithm through Hardware in Loop Simulation (HILS).

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