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A New Controller for an Underwater Vehicle Model

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Abstract:
The objective of this study is to evaluate the underwater vehicle model dynamics under various assumptions on the motion of the vehicle and also to design a fuzzy logic controller (FLC) for the model to control the Heading and Depth. The plant transfer functions for yaw rate and pitch rate are extracted from the six degrees of freedom motion equations using hydrodynamic coefficients. Fuzzy logic controller (FLC) using Mamadani type fuzzy inference system is employed with necessary rules for Heading and Depth control. This study also involves the design of conventional PD controller for comparing the performance of FLC. The plant performance is also evaluated with the FUZZY-PD controller.

I. INTRODUCTION

Underwater vehicles, in the broadest sense, cover manned and unmanned vehicles, with the unmanned vehicles being divided into autonomous underwater vehicles (AUVs) which are non-tethered, and remotely operated vehicles (ROVs) which are tethered. The manned versions include submarines and passenger carrying submersibles. The roles of the unmanned vehicles include the use of AUVs by oceanographers to map the features of the ocean and operators such as the oil and gas industry to map the seabed. ROVs are used for many purposes including underwater observation, exploration of the seabed, underwater construction and maintenance of subsea projects and underwater inspection and cleaning of ships' hulls. The Underwater Vehicle is shown in Fig.1

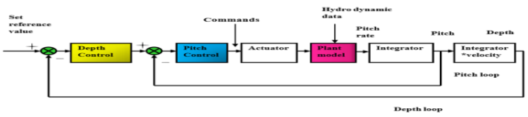

Fig. 1 Block diagram of underwater vehicle

The hydrodynamics involved in underwater vehicle steering and depth systems are highly nonlinear, there are many controllers have been designed and implemented in order to achieve the desired output. Traditional control techniques as PID have encountered difficulties in this non-linear system. PID controllers lack the adaptability to the change of the working state and environment of the underwater vehicle. In order to overcome this problem, intelligent control was gradually used in the course and depth control due to non-linearity control and good robustness.

During the past few years, Fuzzy controller has been successfully applied in many practical areas and fuzzy systems have proven to be superior in performance to some conventional systems especially where the plants are poorly modeled or have nonlinear dynamics. The heading and depth control of an underwater vehicle based on the Fuzzy logic control (FLC) has been proposed that has the advantages: easy of construction and adaptively to parameter variation and strong environmental effects. Specially, in this study presents investigation into the development of Heading and depth control schemes of an underwater vehicle by using a Fuzzy controller [3].

II. MATHMATICAL MODELING OF UNDERWATER VEHICLE:

The mathematical model of an underwater vehicle is so important that it determines the accuracy of the simulation [2]. Underwater vehicle has the inputs from the Propulsion model as thrust, sea disturbances, and

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hydrodynamic data. 6-DOF equations are derived from force and moment equations. There are various forces like gravitational, thrust, drag, disturbance etc. and various moments due to deflections in rudders, thrust misalignments & cross coupling effects. From these force equations, linear (body) accelerations and velocities are derived. Moreover, from the moment equations angular (body) accelerations are derived. These body accelerations are integrated to get the body rates and body positions (like Roll, Pitch & Yaw). The dynamics of the vehicle model obtained from Newton's laws [4].

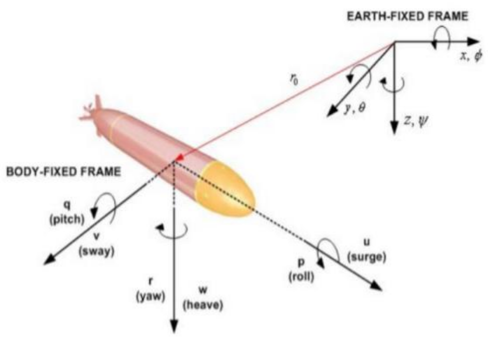

Fig. 2 Body-Fixed and Earth-Fixed Coordinate Systems

The two coordinate frames body fixed and earth fixed are used to model the underwater vehicle motion. The position (*x*, *y*, *z*) and orientation (ϕ, θ, ψ) of the vehicle are described with respect to the Earth fixed frame. The linear/translational and angular/rotational velocities of the vehicle are *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 [1][7].

DOF		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

Table 1: Notation used for marine vehicles

Force equations (Surge, Sway and Heave) of generalized rigid body are [6]

$$m(\dot u + qw - rv) = X$$
$$m(\dot v + rU - pw) = Y$$
$$m(\dot w + qU + pv) = Z$$

Moment equations (Roll, Pitch and Yaw) of generalized rigid body are

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

A) Yaw rate transfer Function:

Underwater vehicle steering or heading control can be done by means of a rudder or a pair of thrusters. The heading of the vehicle is obtained by the integration of the yaw rate. Hydrodynamic force and moments are related to the body velocities and the control surface deflections. The control design using complex 6 DOF equations are very difficult to obtain the transfer function; these equations are linearized by removing cross coupling effects.

Linearized Steering Equations of Motion are given by

$$Y_v v + Y_{\dot v}\dot v + Y_r r + Y_{\dot r}\dot r + Y_\delta \delta = m\dot v + mur \quad (1)$$
$$N_v v + N_{\dot v}\dot v + N_r r + N_{\dot r}\dot r + N_\delta \delta = I_z\dot r \quad (2)$$

Where

Y_v ,$Y_{\dot v}$, Y_r, $Y_{\dot r}$, Y_δ , N_v,$N_{\dot v}$,N_r , $N_{\dot r}$, N_δ are hydrodynamic coefficients and δ :Rudder deflection in Yaw plane and m:mass of the body.

Applying Laplace Transform on both sides of the equation (1) and (2) and after simplification, the yaw rate transfer function is obtained as

$$\frac{R(s)}{\delta(s)} = -\frac{[A_1B_3 - A_3B_1]}{[A_1B_2 - A_2B_1]}$$

Where

$A_1 = Y_v + sY_{\dot v} - ms$, $A_2 = mu + Y_r - sY_{\dot r}$, $A_3 = -Y_\delta$

And $B_1 = N_v + sN_{\dot v}$, $B_2 = sI_r - N_r - N_{\dot r}s$, $B_3 = -N_\delta$

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The linear steering equations of motion can also be expressed in a compact form as [1]:

$$\begin{bmatrix} m - Y_{\dot{v}} & -Y_{\dot{r}} & 0 \\ -N_{v} & I_Z - N_{\dot{r}} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{v} \\ \dot{r} \\ \dot{\psi} \end{bmatrix} + \begin{bmatrix} -Y_v & mu - Y_r & 0 \\ -N_v & -N_r & 0 \\ 0 & -1 & 0 \end{bmatrix} \begin{bmatrix} v \\ r \\ \psi \end{bmatrix} = \begin{bmatrix} Y_\delta \\ N_\delta \\ 0 \end{bmatrix} \delta$$

where v is the sway velocity, r is the angular velocity in yaw, ψ is the heading angle and δ is the rudder deflection. Rearranging this expression into state-space for, yields:

$\dot{x} = Ax + b\delta$ and $y = c^T x$

Where $x = [v, r, \psi]^T$ and y =ψ. Moreover,

$$\begin{bmatrix} \dot{v} \\ \dot{r} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & 0 \\ a_{21} & a_{22} & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} v \\ r \\ \psi \end{bmatrix} + \begin{bmatrix} b_1 \\ b_2 \\ 0 \end{bmatrix} \delta$$

where the choices of a_{ij} and b_i should be quite obvious. Consequently, the transfers function between ψ and δ_R is obtained as:

$$\frac{\psi}{\delta}(s) = c^T (sI - A)^{-1} b$$
$$= \frac{(a_{21}b_1 - a_{11}b_2) + b_2 s}{s[s^2 - (a_{11} + a_{22})s + a_{11}a_{22} - a_{12}a_{21}]}$$

B) Pitch rate transfer function:

Here, the focus is on the depth control system of the underwater vehicle model. Suppose the vehicle is a rigid body, and assume that the forward speed 'u' is constant and that the sway and yaw modes can be neglected, then the following equations are used to find pitch rate transfer function. Integration of pitch rate produces pitch. Depth is obtained from integration of pitch multiplying with constant velocity of system.

The expression for the transverse (heave) force is

$Z_w w + Z_{\dot{w}} \dot{w} + Z_q q + Z_{\dot{q}} \dot{q} + Z_\delta \delta = m\dot{w} - muq$ (3)

and the expression for the rotational (pitch) force is

$M_w w + M_{\dot{w}} \dot{w} + M_q q + M_{\dot{q}} \dot{q} + M_\delta \delta + M_\theta \theta = I_y \dot{q}$ (4)

Where Z_w, $Z_{\dot{w}}$, Z_q, $Z_{\dot{q}}$, Z_δ, M_w, $M_{\dot{w}}$, M_q, $M_{\dot{q}}$, M_δ, M_θ are hydrodynamic coefficients and δ:Rudder deflection in pitch plane and m : mass of the body.

Applying Laplace Transform on both sides of equation (3) and (4) and after simplification

The pitch rate transfer funtion is obtained as

$$\frac{Q(s)}{\delta(s)} = -\frac{[C_1 D_3 - C_3 D_1]}{[C_1 D_2 - C_2 D_1]}$$

Where $C_1 = Z_w + sZ_{\dot{w}} - ms$, $C_2 = mu + Z_q + sZ_{\dot{q}}$, $C_3 = Z_\delta$ and $D_1 = sM_w + s^2 M_{\dot{w}}$, $D_2 = M_q s + M_{\dot{q}} s^2 + M_\theta - I_y s^2$, $D_3 = sM_\delta$

The matrix representation of the equations is given by

$$\begin{bmatrix} m - Z_{\dot{w}} & -Z_{\dot{q}} & 0 & 0 \\ -m_{\dot{w}} & I_y - M_{\dot{q}} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{w} \\ \dot{q} \\ \dot{\theta} \\ \dot{z} \end{bmatrix} + \begin{bmatrix} -Z_w & mu & 0 & 0 \\ -M_w & -M_q & M_\theta & 0 \\ 0 & -1 & 0 & 0 \\ -1 & 0 & u & 0 \end{bmatrix} \begin{bmatrix} w \\ q \\ \theta \\ z \end{bmatrix} = \begin{bmatrix} Z_\delta \\ M_\delta \\ 0 \\ 0 \end{bmatrix} \delta$$

Where w is the Heave velocity, q is the angular velocity in pitch; θ is the pitch angle and δ is the rudder deflection.

Consider

$$A11 = \begin{bmatrix} m - Z_{\dot{w}} & mx_G - Z_{\dot{q}} & 0 & 0 \\ mx_G - m_{\dot{w}} & I_y - M_{\dot{q}} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$$A12 = \begin{bmatrix} -Z_w & mu_0 & 0 & 0 \\ -M_w & mx_G u_0 - M_q & \overline{BG_z W} & 0 \\ 0 & -1 & 0 & 0 \\ -1 & 0 & u_0 & 0 \end{bmatrix} \ \& \ B1 = \begin{bmatrix} Z_\delta \\ M_\delta \\ 0 \\ 0 \end{bmatrix}$$

Rearranging this expression into state-space for, yields:

$$\dot{x} = Ax + b\delta \qquad (2.56)$$
$$y = c^T x$$

Where $x = [w, q, \theta, z]^T$ and y = q and also $A = A_{11}^{-1} * A_{12}$ and $b = A_{11}^{-1} * B_1$

Consequently, the transfers function between q and δ i.e. pitch rate is obtained as:

$$\frac{Q}{\delta}(s) = c^T (sI - A)^{-1} b$$

The transfer functions for yaw rate and pitch rate are obtained with the help of the hydrodynamic coefficients

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and mathematical modelling as given below using MATLAB code.

Yaw rate transfer function:

$$\frac{q(s)}{\delta(s)} = \frac{0.4556s + 0.41}{s^2 + 1.358s + 0.1645}$$

Pitch rate transfer function:

$$\frac{q(s)}{\delta(s)} = \frac{0.4607s^2 + 0.1868s}{s^3 + 1.276s^2 + 0.8593s + 0.01651}$$

III. CONTROLLER DESIGN

A) P-I-D Controller:

P-I-D controller has the optimum control dynamics including zero steady state error, fast response, no oscillations and higher stability. One of the main advantages of the P-I-D controller is that it can be used with higher order processes. A PID controller contains three independent control terms: a proportional, an integral and a derivative term. It uses current and recent error values and error changing rates as input parameters.

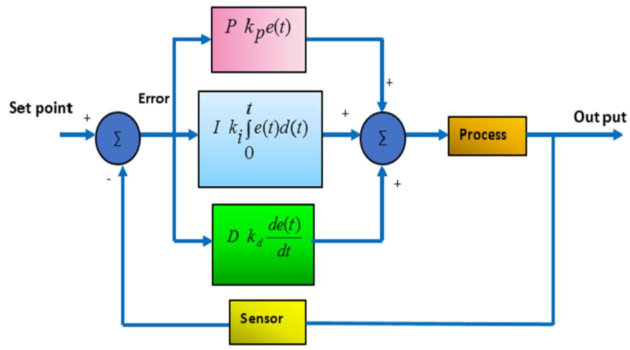

Fig. 3 Block diagram of a PID Controller.

The controller gains Kp, Ki, Kd are constant factors. Fig. 3 shows the 3 terms of a PID controller. The controller output is given by

$$u_{out} = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt}$$

Effects of each of controllers Kp, Ki and Kd on a closed-loop system are summarized in the table shown in table 2.

Closed loop Response	Rise time	Over shoot	Settling time	Steady state error
Kp	Decrease	Increase	Small change	Decrease
Ki	Decrease	Increase	Increase	Eliminate
Kd	Small change	Decrease	Decrease	Small change

Table 2 Effects of each controller in closed loop system

Conventional PID controllers have been a wide range of use in industry because of its simple structure and acceptable performance. This controller deals with both time response and frequency response improvements if they are properly tuned. However, the conventional PID controller design usually involves tuning the parameters manually by skilled operator. Also, the conventional PID controllers could not satisfy the control requirements of much more complicated systems of today. 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.

B) Fuzzy Logic Controller:

In conventional control there exists a binary logic about the membership of an element in a universe of discourse however in a fuzzy control method there does not exist the sharp boundary and membership value is assigned to an element who claims to be the member of a universe of discourse. Fuzzy logic evaluates conditions with relaxed boundaries and operates on the basis of certain rules and definitions which have been defined in the rule and data base of the system and is preferred in those systems where mathematical modelling is a difficult task or lot of computational force is required to evaluate a parameter. Fuzzy inference system evaluates the parameters using rules defined by the experience of the plant or by observation gathered working over the plant.

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. 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 Membership Function (MF). A MF maps crisp input onto a normalized domain or fuzzy domain in the interval [0, 1]. In recent years, FL systems have gained a lot of attention due to their ability to incorporate expert (human originated) knowledge into the system design which can be very useful in making correct decisions and carrying out appropriate control actions and

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effectively handle imprecise, ambiguous and incomplete information. The structure of FLC is given in Fig.4.

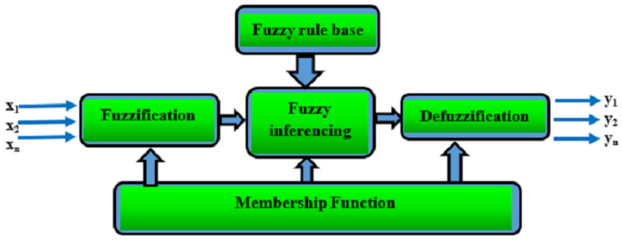


Fig. 4 Structure of fuzzy logic control (FLC)

As a first step, interests of the control objective are specified for optimized operation of the plant and variables of interest are selected which are fuzzified i.e., they are assigned a value of membership in the universe of discourse. Different membership functions are used to assign membership value to the actual value of the input parameter. A relationship is defined between the selected input and output variables using the expert system i.e. the experience of the plant, observations of the plant and desired operation of the plant. A rule base is then developed for different conditions of the plant which relates input and output variables using the principles of expert system. Every input and output is mapped using the membership function over a universe of discourse or the values of the linguistic variables. The fuzzified data is then passed through the developed rule base of the fuzzy system and an inference is made based upon the selected rules defining the conditions more appropriately.

All or selected rules are used to make an inference, it depends upon the complexity and requirement of the situation in the control of plant. The fuzzified inference is then defuzzified using the membership functions defining the output variables and selecting a fuzzy defuzzification method. Generally used methods for defuzzification are Mamdani, Lusi-Lorson, Sugeno and Takagi-Sugeno. Then in final stage a center of gravity method is used commonly to calculate the value of the control parameter. When using fuzzy logic controller the variables of interest are the 'error' and 'change in error'. The target is to generate a command to minimize the error looking at the trend of the error which is specified by the variable 'change in error'.

C) Design of A Fuzzy Logic Controller:

The Fuzzy logic controller has two inputs: error and derivative of error, and one output: rudder angle and the output of fuzzy controller i.e rudder command is an actuating signal for vehicle steering system.

The fuzzy sets for each input and output variables consisting of seven linguistic variables:

e = {NB, NM, NS, ZO, PS, PM, PB}

de = {NB, NM, NS, ZO, PS, PM, PB}

Rudder angle = {NB, NM, NS, ZO, PS, PM, PB}

Where NB:Negative Big, NM:Negative Medium, NS Negative Small, ZO:Zero, PS:Positive Small, PM:Positive Medium, PB:Positive Big. The Fuzzy inference system of simulink is shown in Fig.5.

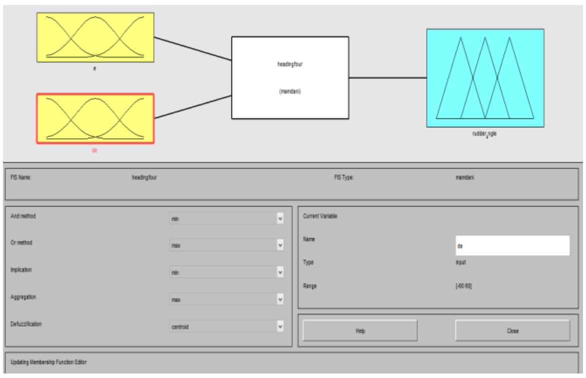
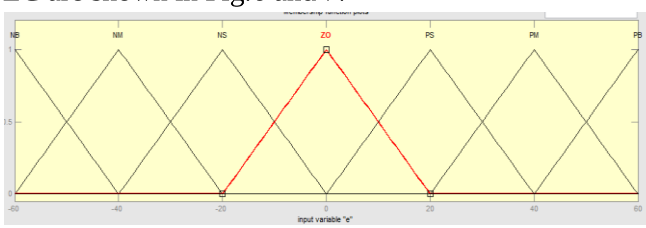


Fig.5 Fuzzy inference system

For the implementation of Heading controller triangular membership functions are used. Input error range is from [-60, 60] and error rate range is from [-30, 30] whereas output variable lies in the range of [-60, 60]. The membership functions of these inputs and output of the FLC are shown in Fig.6 and 7.



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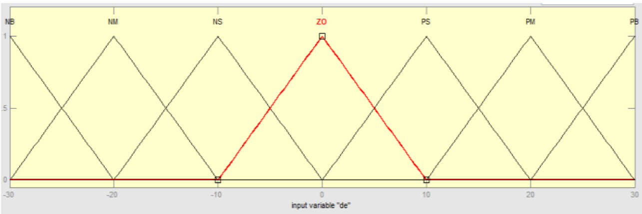

Fig.6 Membership functions of input variables

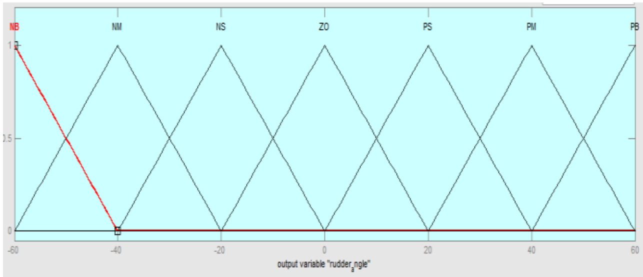

Fig.7 Membership functions of output variable

Generally, Fuzzy rules are depended on response characteristics of the Heading angle and the summary of designer's knowledge and experience. These are fundamental rules for rudder command in accord to errors (e) and changes-in-error (de). These are some basic rules for example[3].

- If the vessel is deflected to the right with a small angle and has a small rate of change to the right, turn the rudder a small amount to the right.
- If the vessel a deflected to the right with a small angle and has a small rate of change to the left, turn the rudder to zero.
- If the vessel is deflected to the right with a small angle and has an average rate of change to the right turn the rudder an average amount to the right…

According to the above fuzzy inputs, outputs variables and these fundamental rules, the fuzzy control rules [6] of Rudder command (δ) are shown in Table 3.

ec / e	NB	NM	NS	ZO	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NS	NB	NB	NB	NM	NS	ZE	PS
NM	NB	NB	NM	NS	ZE	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	ZE	PS	PM	PB	PB	PB	PB

Table 3: Fuzzy Rule Base for the system

SURFACE VIEW:

The fuzzy variable can be plotted on a three dimensional plot to explain the relationship between input variables and output variables. The plot is shown in the Fig.8

Mamadani type fuzzy inference system is used for the design of Fuzzy logic controller for heading and depth control of underwater vehicle model. The defuzzification method used in this system is cenroid method.

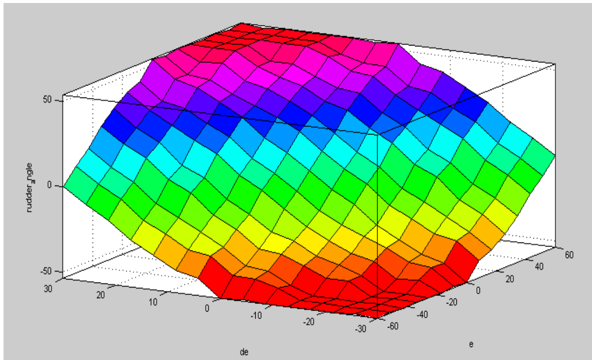

Fig.8 Surface view of fuzzy rules

IV SIMULATION:

Matlab / Simulink is used for the simulation of step responses of plant without controller, plant with PD , Plant with Fuzzy and Plant with Fuzzy-PD controllers for the control of heading and depth of underwater vehicle model. The simulink block diagrams are given below.

A) Plant without controller:

The simulink block diagram of the closed loop system for heading and depth are given below.

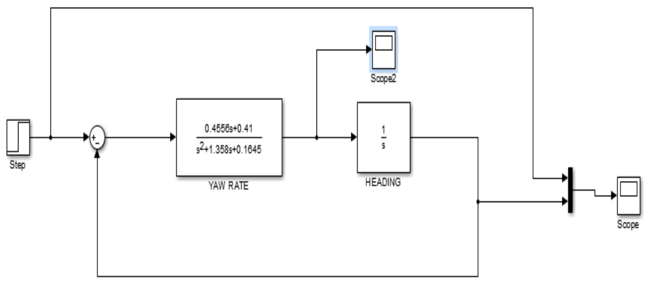

Fig. 9 Simulink block diagram for heading of underwater vehicle model

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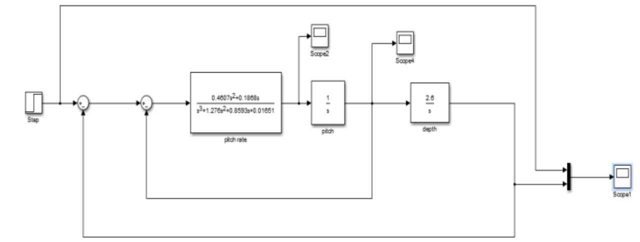

Fig.10 Simulink block diagram for depth of underwater vehicle model

B) Plant with PD Controller

Simulink is used to develop the controller. For the control of heading and depth of underwater vehicle model, PD type controllers are used in order to achieve the desired output. Each controller is described below.

To control Heading angle of the underwater vehicle control input can be defined as

$$U = K_p(\psi_d - \psi) + K_d(\dot{\psi}_d - \dot{\psi})$$

The equation above can be implemented in Simulink as shown in Fig. 11 below. In order to get the desired output, the gains of the PD controller are Kp=1.7 and Kd=6.

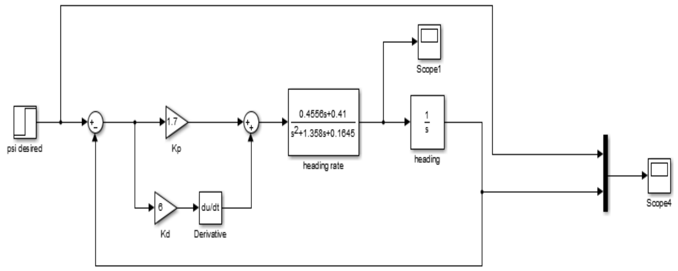

Fig.11 Simulink block diagram PD Heading Controller for the vehicle model

To control the depth of an underwater vehicle the control input for Pitch angle can be defined as equation below. Depth is obtained from integration of pitch multiplying with constant velocity.

$$U = K_p(\theta_d - \theta) + K_d(\dot{\theta}_d - \dot{\theta})$$

The above equation can be implemented in Simulink as shown in Fig.12 below. In order to get the desired output, the gains of the PD controller are Kp=1.2 and Kd=4.

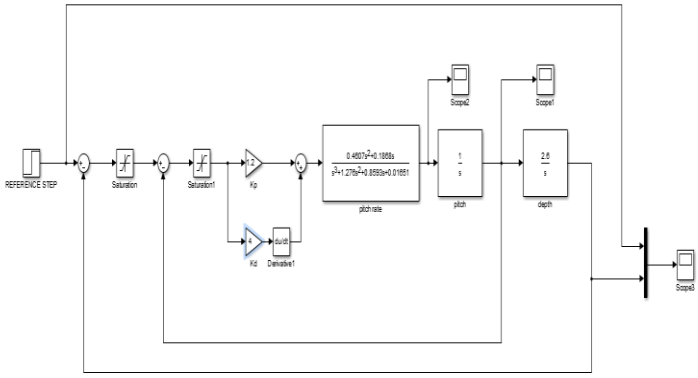

Fig.12 Simulink block diagram of PD pitch controller for depth of the vehicle model

C) Plant with Fuzzy Controller:

The simulink block diagrams of fuzzy controllers for heading and depth control of underwater vehicle model are shown below.

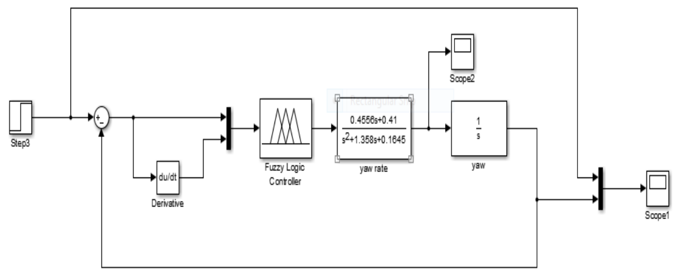

Fig.13 Simulink block diagram of Fuzzy heading controller for underwater model

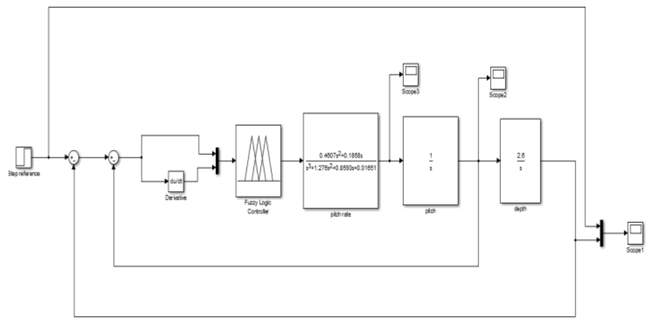

Fig.14 Simulink block diagram of Fuzzy pitch controller for depth of underwater model

D) Plant with FUZZY-PD Controller:

The combination of Fuzzy and PD controllers are used for the heading and depth control of underwater vehicle

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model to get the desired output. The simulink block diagrams are shown below.

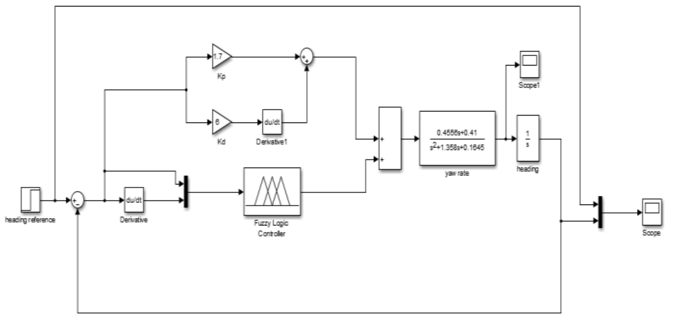

Fig.15 Simulink block diageram Fuzzy-PD heading controller for underwater model

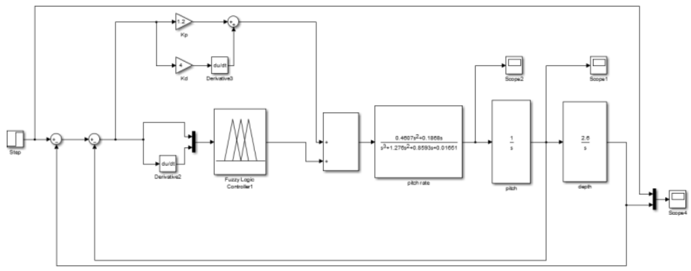

Fig.16 Simulink block diagram of Fuzzy-PD pitch controller for depth of underwater model

E) Simulation Results:

The step responses of the plant without controller and plant with various controllers discussed above for heading and depth are given below

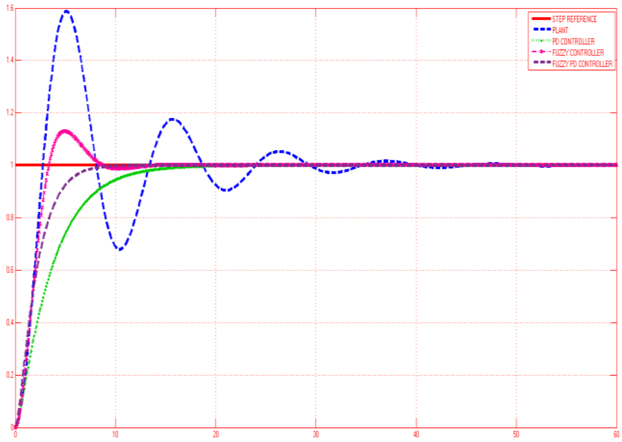

Fig.17 Comparison of Step response of the plant and various controllers for Heading Control

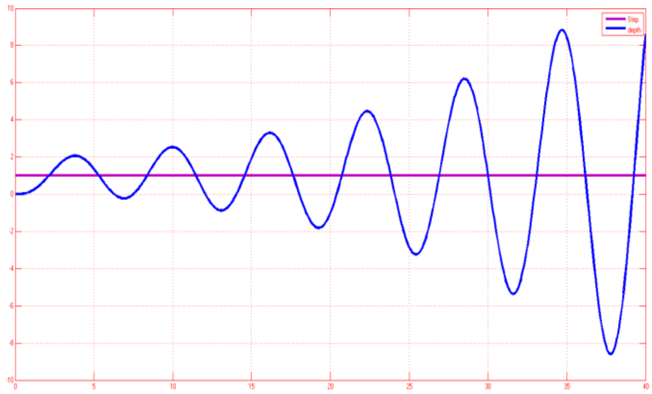

Fig.18 Step response of underwater vehicle model for depth without controller

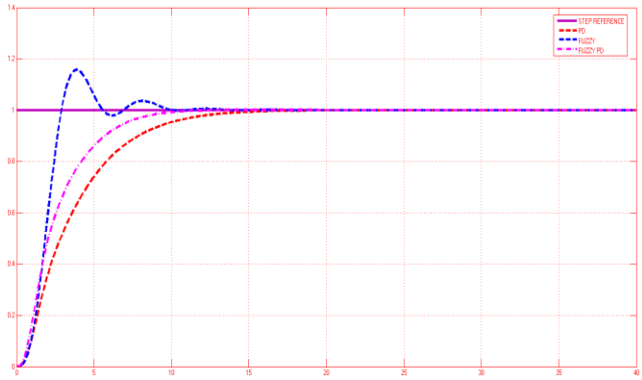

Fig.19 Comparison of Step response of various controllers for depth control of underwater vehicle model

All the data extracted from Fig.17-19 and is displayed in the table 4 below.

	Plant		PD controller		Fuzzy controller		Fuzzy-PD controller	
	Ts (Sec)	A	Ts (Sec)	A	Ts (Sec)	A	Ts (Sec)	A
Heading	48	1	21	1	18	1.12	14	1
Depth	∞	∞	18	1	14	1.15	12	1

Table 4: Comparison of results of various controllers Where Ts settling time and A Amplitude

By looking at table 4 and comparing the results for heading and depth, it is observed that the settling time is better and there is no peak overshoot using Fuzzy-PD controller.

V. CONCLUSION

The aim of this thesis is to design controllers for Heading and Depth control, which is used in application of underwater vehicle model in order to reach the intended point underwater. This study presented the heading and depth control of the underwater vehicle model by approximating the non-linear dynamics of the vehicle.

The main focus of this study 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. FLC have some advantages such as simplicity of implementation, faster response, adapt to different situations. The comparison of simulated responses clearly emphasized the advantages of fuzzy inference systems.

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