Fuzzy Logic Based Depth Control of an Autonomous Underwater Vehicle

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Abstract: **This paper presents an adaptive fuzzy logic based controller for the depth control of an Autonomous Underwater Vehicle(AUV). The kinematic and dynamic motion of an AUV is described using six degree of freedom differential equations of motion using bodyand earth-fixed frame of references. Due to hydrodynamic forces, these equations are complex, non-linear and highly coupled therefore are impractical for use in controller design. In practice, system is commonly decomposed into three non-interactive systems such as diving subsystem, steering subsystem and speed subsystem. In this study a reduced order model was derived for diving system using depth plane dynamics and a suitable dual loop control strategy is formulated by synthesizing fuzzy logic based control in series with a phase lead dynamic compensator to achieve the desired set point tracking and reasonably good performance objectives under variety of disturbances encountered in oceanic environments.The obvious benefits of this type of approach lies in the simplicity of the scheme compared to the conventional deterministic systems and easy implementation for real time control of the Autonomous Underwater Vehicles. The proposed fuzzy logic based controller accepts deterministic information, the depth of the vehicle as input and achieves imprecise reasoning and de-fuzzification to generate a deterministic control output which manipulates the pitch angle and hence the depth of the vehicle. The simulated results clearly demonstrate the efficacy of this approach as compared to the conventional PID controller designed and tuned using Ziegler-Nichols scheme.**

Keywords : Autonomous Underwater Vehicle, Six Degrees of Freedom, Proportional-Integral-Derivative (PID) controller, Fuzzy Logic Controller, depth control, Center of mass(COM),Phase Lead Compensator.

1. INTRODUCTION

The interest in underwater vehicles dates back to the 1950s.The first underwater vehicle was developed in Washington University in the year 1957.Since then interest in underwater vehicles have increased and with the advancement of electronics and control engineering techniques it has been possible to make underwater vehicles autonomous. It has been revealed through research that ocean floors contain vast amounts of untapped resources in the form of petroleum, minerals and natural gas. Since these areas are extremely hazardous for human beings to go and explore,the only feasible solution is to send some robotic vehicles to these areas. These vehicles have to be autonomous for effective functioning. One of the main applications of these underwater vehicles is the ocean floor mapping. It also providesan important means of research in deep sea marine life.

With the advancement of control engineering many techniques have been applied to control the dynamics of underwater vehicles. Due to the inherent non-linearities in the dynamic model,non-linear techniques like sliding mode control[9],adaptive control[8] and back stepping control based on Lyapunov stability theory have been applied[7]. Recently modern control approaches like Fuzzy logic have been proposed in [3] and [4], as this technique offers high degree of robustness and resistance to disturbance.

The major challenge in designing a control technique for underwater vehicle is to find an accurate mathematical model of the vehicle itself. The difficulties lies in the fact that the dynamics are highly non-linear and coupled and secondly it is extremely difficult to find all hydrodynamic parameters affecting the vehicle dynamics with reasonable accuracy, also a lot of environmental disturbances may arise and affect the system which are difficult to predict while designing.

Keeping these challenges in mind an adaptive fuzzy logic based controller coupled with a dynamic compensator has been designed whose performance may not depend heavily on the accuracy of the system model.The results of the simulation are compared with a conventionalPID controller, since PID controllers are easy to implement and are still widely used.

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The paper is arranged as follows. In Section 2 we present the modeling of an AUV and discuss both the kinematics and dynamics part.Adual loop PID control scheme is developed in the Section 3. Section 4 briefly covers the structure and implementation of fuzzy logic control scheme. In the conclusive part we present the simulation graphs and provide a comparative study between the PID and the fuzzy logic control schemes. The system parameters used in this paper are obtained from [2]. All the simulations have been done in Matlab/Simulink environment.

2. AUV MODELING

The notation used in this paper is in accordance to SNAME 1950 [11].The six degree of freedom modeling is based on the Newton Euler equations as described in [1].Two coordinate frames are considered in the modeling of the AUV.The body fixed frame which is assumed to be located in the body of the robotic vehicle, these coordinates are measured with respect to another reference frame which is assumed to be fixed and is known as the Inertial frame or earth fixed frame.The body fixed frame contains six velocity coordinates representing three translational and three rotational velocities along X,Y and Z direction respectively.The body fixed frame is represented by the vector $\nu=[uvwpqr]^T$,where $\nu_1=[uvw]^T$ are the translational velocities and are known as surge, sway and heave velocities and $\nu_2=[pqr]^T$ are the rotational velocities and are known as roll,pitch and yaw motions.The earth fixed frame consists of six coordinates which represents the position and orientation of the vehicle. The earth fixed frame is represented by the vector $\boldsymbol{\eta}=[xyz\phi\theta\psi]^T$ where $\boldsymbol{\eta}_1=[xyz]^T$ are the position coordinates and $\boldsymbol{\eta}_2=[\phi\theta\psi]^T$ are the rotational coordinates.

The mapping between the two coordinate frames is given by the Euler angle transformation $\dot{\eta}=J(\boldsymbol{\eta}_2)\nu$, where $J(\boldsymbol{\eta}_2)$ is the Jacobian matrix.

The origin of the body fixed coordinate frame is considered at the center of mass of the vehicle.The translational motion is described by Newton's second law

$$F = ma \qquad (1)$$

Where$m$is the mass of the vehicle and$a$is acceleration of the center of mass of the vehicle.The rotational motion of the vehicle is governed by Euler's equation:

$$M_c = I_c\dot{\omega} + \omega \times I_c. \qquad (2)$$

F and M_c are external forces and moments which include gravitational,buoyancy,propulsive,control and hydrodynamic forces and moments.

Based on the Newton's and Euler's equation the six degrees of freedom equation of motion for the AUV can be written in terms of body fixed coordinates:

$$\begin{aligned}
&m[\dot{u} - vr + wq - x_g(q^2 + r^2) + y_g(pq - \dot{r}) \\
&\qquad + z_g(pr + \dot{q}) = \sum X_{ext} \\
&m[\dot{v} - wp + ur - y_g(r^2 + p^2) + z_g(qr - \dot{p}) \\
&\qquad + x_g(qp + \dot{r}) = \sum Y_{ext} \\
&m[\dot{w} - uq + vp - z_g(p^2 + q^2) + x_g(rp - \dot{q}) \\
&\qquad + y_g(rq + \dot{p}) = \sum Z_{ext} \\
&I_{xx}\dot{p} + (I_{zz} - I_{yy})qr + m[y_g(\dot{w} - uq + vp) \\
&\qquad - z_g(\dot{v} - wp + ur)] = \sum K_{ext} \\
&I_{yy}\dot{q} + (I_{xx} - I_{zz})rp + m[z_g(\dot{u} - vr + wq) \\
&\qquad - x_g(\dot{w} - uq + vp)] = \sum M_{ext} \\
&I_{zz}\dot{r} + (I_{yy} - I_{xx})pq + m[x_g(\dot{v} - wp + ur) \\
&\qquad - y_g(\dot{u} - vr + wq)] = \sum N_{ext}
\end{aligned} \qquad (3)$$

Model reduction: In this study we consider the depth plane dynamics. For depth plane maneuvering, the pitch angle of the vehicle has to be controlled. As shown in Figure 1, when a rotation of angle θ is given along the Y axis, the X and Z axes are shifted to X1 and Z1. Therefore we can neglect the out of plane terms to derive the following three term state vector as given in [2].Values of the various parameters are tabulated in TABLE 1.

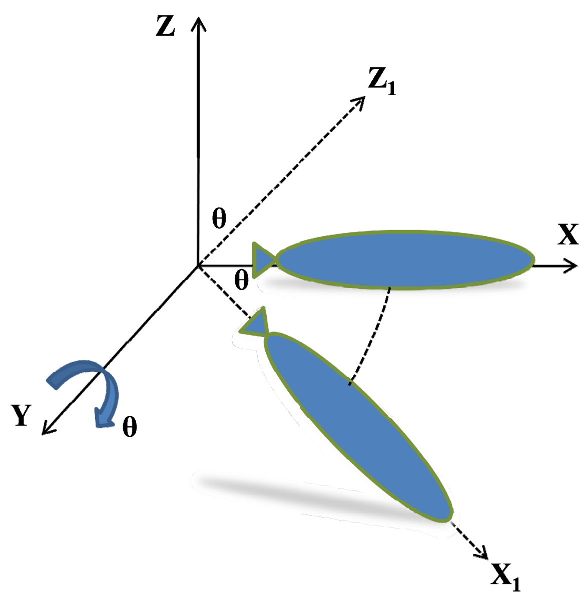


Figure 1: Depth Plane Dynamics

$$\begin{bmatrix} I_{yy} - M_{\dot{q}} & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{q} \\ \dot{z} \\ \dot{\theta} \end{bmatrix} + \begin{bmatrix} -M_q & 0 & -M_\theta \\ 0 & 0 & U \\ -1 & 0 & 0 \end{bmatrix} \begin{bmatrix} q \\ z \\ \theta \end{bmatrix} = \begin{bmatrix} M_{\delta s} \\ 0 \\ 0 \end{bmatrix} \quad (4)$$

In equation (4) I_{yy} is the moment of inertia about Y axis, M_θ,M_q, $M_{\dot{q}}$ are hydrodynamic parameters defined in TABLE 1.
this can be re-arranged as

$$\begin{bmatrix} \dot{q} \\ \dot{z} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \frac{M_q}{I_{yy} - M_{\dot{q}}} & 0 & \frac{M_\theta}{I_{yy} - M_{\dot{q}}} \\ 0 & 0 & -U \\ 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} q \\ z \\ \theta \end{bmatrix} + \begin{bmatrix} \frac{M_{\delta s}}{I_{yy} - M_{\dot{q}}} \\ 0 \\ 0 \end{bmatrix} \delta s \quad (5)$$

δs is the input given to the system which may be step, sinusoidal or any other input.
This is of the form $\dot{x}(t)=Ax(t)+Bu(t)$
Where

$$A = \begin{bmatrix} -0.82 & 0.00 & -0.69 \\ 0.00 & 0.00 & -1.54 \\ 1.00 & 0.00 & 0.00 \end{bmatrix}$$

$$B = \begin{bmatrix} -4.16 \\ 0.00 \\ 0.00 \end{bmatrix} \quad (6)$$

U is the linear velocity of the vehicle (3m/s).
The transfer function for the pitch control is obtained from the above state space equation as

$$\frac{\theta(s)}{\delta s(s)} = \frac{\frac{M_{\delta s}}{Iyy - M_{\dot{q}}}}{s^2 - \frac{M_q}{Iyy - M_{\dot{q}}} s - \frac{M_\theta}{Iyy - M_{\dot{q}}}} \quad (7)$$

From the table (1) we derive the transfer function as

$$\frac{\theta(s)}{\delta s(s)} = \frac{-4.16}{s^2 + 0.82s + 0.69} \quad (8)$$

And the depth loop equation is

$$\frac{z(s)}{\theta(s)} = -\frac{3}{s} \quad (9)$$

TABLE 1.HYDRODYNAMIC PARAMETER FROM [2].

Parameter	Value	Units	Description
Iyy	3.45	kgm²	MI along y axis about COM
$M_{\dot{q}}$	-4.88	kgm²	Added Mass term
M_q	-6.87	kgm²/s	Combined term
M_θ	-5.77	kgm²/s²	Hydrostatic moment (pitch axis)
$M_{\delta s}$	-3.46	kgm²/s²	Fin Lift moment

3. DESIGN AND DEVELOPMENT OF DUAL LOOP PID CONTROL

In the PID control strategy two loops are considered,the inner pitch loop and the outer depth loop.The inner pitch loop transfer function is second order and has a considerably faster response whereas the outer depth loop response is quite slow.In order to get satisfactory results both in terms of response time and regulatory control (set point tracking) PID control schemes are used both in the inner pitch loop and the outer depth loop.

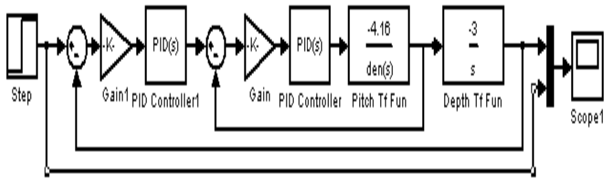


Figure2. PID control scheme

4. STRUCTURE ANDIMPLEMENTATION OF FUZZY LOGIC CONTROLLER

The main advantage of fuzzy controller over other controllers is that it is mathematically less intensive and supports imprecise modeling.Fuzzy controller uses linguistic variables as their inputs and generates a particular crisp value as output after defuzzification. Center of gravity method is used for de-fuzzifying the fuzzy output generated by the controller.Two control variables are used namely error(e) (difference between desired depth and depth achieved by the system on application of input)and change in error(Δe). The basic block diagram of a fuzzy logic controller with error and change in error as inputs and control as output is shown in Figure 3.

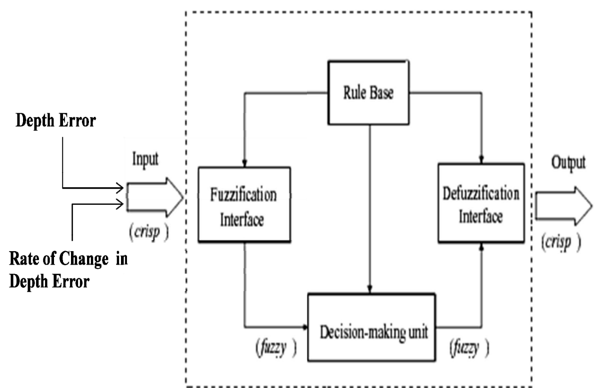
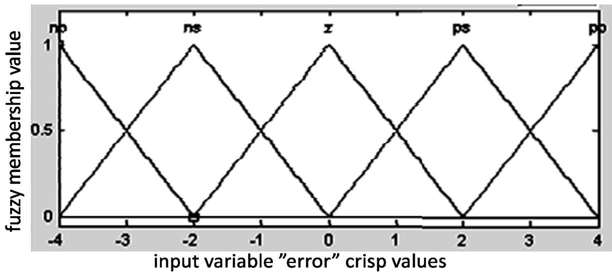


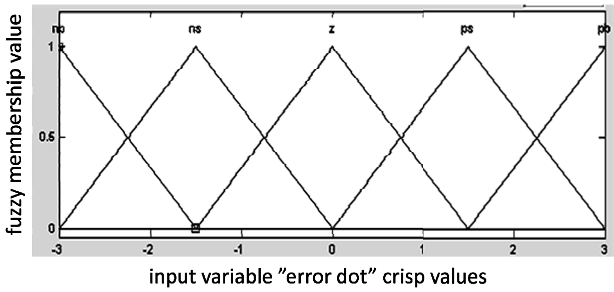
Figure 3: Basic block diagram of a fuzzy controller

Fuzzification

The membership functions for the two input variables change in error(Δe) and error(e) and the control output is shown below . The membership functions represent fuzzy linguistic variables.



(a)



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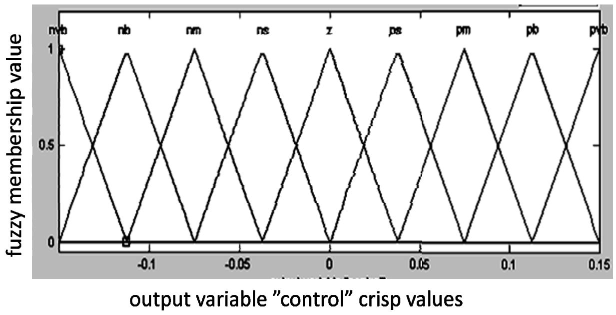


(c)

Figure4. Membership functions for (a)error (b)change in error and (c)control output

Fuzzy Rule Base

The rule base with the two control inputs and the corresponding output generated is shown in TABLE 2.

TABLE 2. RULE TABLE FOR FUZZY CONTROLLER

Δe / e	NB	NS	Z	PS	PB
NB	NVB	NB	NM	NS	Z
NS	NB	NM	NS	Z	PS
Z	NM	NS	Z	PS	PM
PS	NS	Z	PS	PM	PB
PB	Z	PS	PM	PB	PVB

The fuzzy rule base is designed using the logic that, if the error or change in error is high, the required control action should be high, so that the system output reaches the desired output as fast as possible. For example when the error and change in error is high on the negative side, denoted by NB(Negative Big), the control output generated is NVB(Negative Very Big). Similar rule is followed for high error or its rate of change on the positive side. Similarly when the error or change error is small the required control output is small or medium. Taking the case where both error and change are small and in the positive range(PS) a positive medium output is generated. The output could have also been positive small(PS), but for this particular system under study better results were obtained when the output was taken to be positive medium. When the error is going in one direction whereas rate of change of error is going in the opposite direction, no control action is required as the error is ultimately driven to zero. For example if the error is in the positive small range(PS), that is increasing but the change in error is in the negative small range, decreasing, the error is driven to zero and no control action is actually required. When the error and change in error are both zero, the control action generated is also zero. If the rules are properly arranged one of the diagonal will contain all zero(Z) elements thus providing a kind of symmetry, which may be useful while implementing the logic on some embedded platform.

Fuzzy Inference

The fuzzy inference is based on min max principle, that is for a given rule with two fuzzy variables along with the membership value of the crisp variable for each fuzzy variable, the membership value of the output variable will be the minimum of the membership value of the two input variable. Mathematically it can be represented by

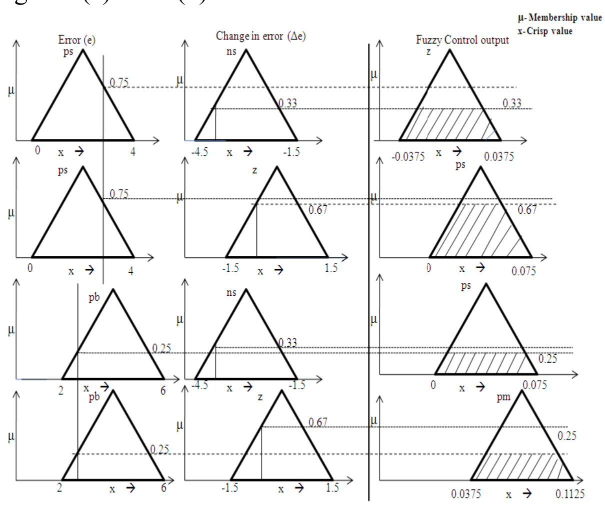
$$\mu_R(x,y) = \min\,(\mu_A(x,y), \mu_B(x,y)) \qquad (10)$$

where$\mu_R(x,y)$ is the membership of the output fuzzy variable. The composite fuzzy output is then found out by taking the maximum of the resulting areas.

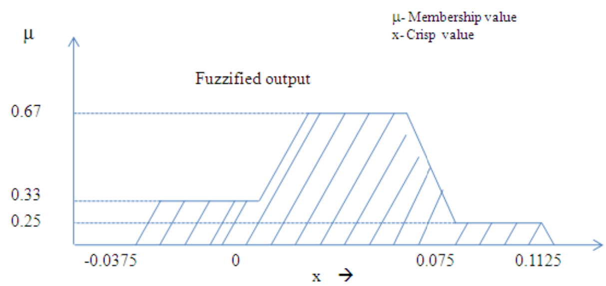
Consider the case where the crisp value of the error is 2.5 and that of change in error is -0.5. The error value can be classified into fuzzy variables positive small(PS) and positive big(PB), as seen from figure 4(a)with membership values of 0.75 and 0.25 respectively. Similarly the change in error crisp value can be classified into fuzzy variables negative small(NS) and zero(Z), with membership values 0.33 and 0.67 respectively. Four fuzzy rules can be formed for these four fuzzy variables from the rule base depicted above.

e	µ(e)	Δe	µ(Δe)	output	µ(output)
PS	0.75	NS	0.33	Z	0.33
PS	0.75	Z	0.67	PS	0.67
PB	0.25	NS	0.33	PS	0.33
PB	0.25	Z	0.67	PM	0.25

The membership values of the output variable is found out by using equation (10), that is by taking the minimum membership value of the two input fuzzy variables. The composite fuzzified output is then found out by taking the maximum of the covered area.
For the case under study, between crisp values -0.0375 and 0 , fuzzy variable zero with membership value 0.33 is taken. Between crisp values 0 and 0.075 we have two cases where the output fuzzy variable is positive small(PS), but with membership values of 0.67 and 0.33. So according to the min-max inference principle, the area under the curve with membership value 0.67 is considered in the final output. Lastly between crisp value 0.075 and 0.1125, fuzzy variable with membership 0.25 is considered.
The fuzzy inference mechanism and the composite fuzzy output is shown diagrammatically in figure 5(a) and 5(b).



(a)

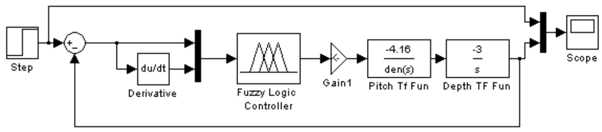


(b)

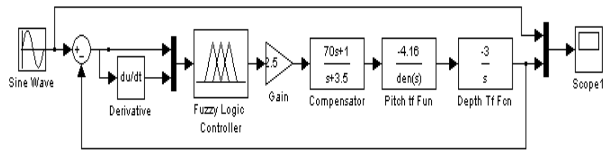
Figure 5(a) fuzzy inference mechanism (b) composite fuzzy output.
(graphs show crisp value x along horizontal axis, membership µ along vertical axis).

Defuzzification

Many kinds of defuzzification techniques are available, like centroidal method, center of sums and mean of maxima method. The centroidal and center of sums method are most commonly used ones.
In this paper defuzzification is done by the centriodal method, that is the crisp output is given by the centroid of the composite fuzzy output.
The depth loop is a third order system. As a result the system response is quiet slow. So even with a fuzzy logic controller a small phase difference was observed between the desired and obtained output. For effective trajectory tracking it is very important that the system response be fast.In order to reduce the response time we have introduced a phase lead compensator along with the fuzzy logic controller.This effectively reduces the system response time and we get satisfactory results for depth trajectory tracking as shown in figure 9(c).



(a)



(b)

Figure 6(a)Fuzzylogic control implementation
(b)Fuzzy logic with compensator

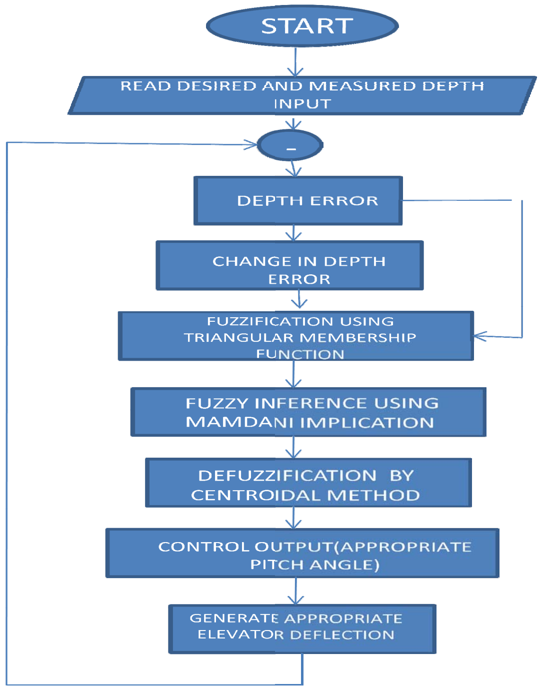


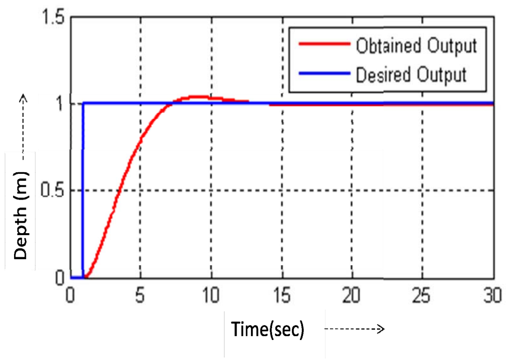
Figure7: Flowchart of Fuzzy Logic Control

5. RESULTS AND CONCLUSION

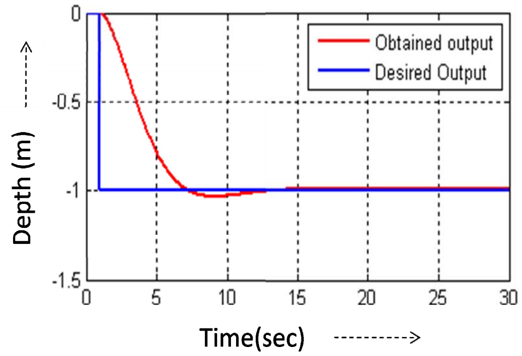
The graphs obtained after simulation are presented below.From the results obtained, it is seen that PID control strategyprovide satisfactory performance in case of regulatory control or set point tracking.But it does not provide good trajectory tracking performance. As seen from figure 8(e) that there is a certain lag between the desired and the obtained output. Fuzzy control on the other hand provides good results for both regulatory control and trajectory tracking control.The system being athird order system was compensated with a lead compensator and it resulted in considerable decrease in responsetime of the system.The advantage of using fuzzy control technique,was that once thecontroller parameters were tuned for a particular input(say step input) the controller was able to produce suitable control action for any type of input signal.The PID controller on the other hand had to be tuned,whenever the input or any system parameter changed.It can be said that we can have a dedicated fuzzy logic controller chip on board itself, that can provide proper control action with changing input conditions. In case of PID controller there has to be arrangements for online tuning of the controller parameters.This is one of the main objective that we want to show in this paper.

The fuzzy logic controller also displays good load rejection capability.Disturbances were introduced at the output but the controller readily stabilized the system, and the system was able to achieve the desired output as shown in figure 9(d).

The fuzzy logic controller implementation in simulink, and the control logic flowchart is shown in Figure 6(a) and Figure 7 respectively. Figure 6(b) shows fuzzy logic controller with phase lead compensator.



(a)



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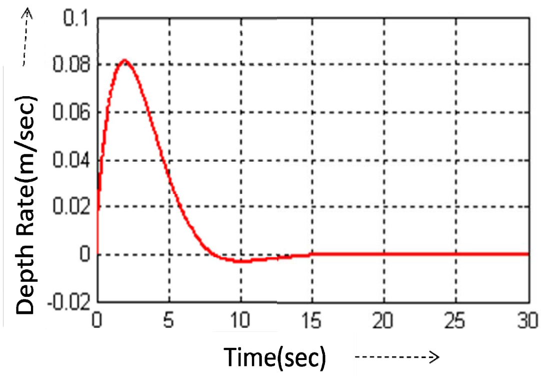

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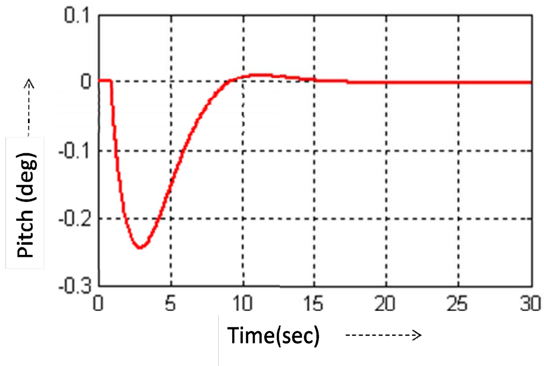
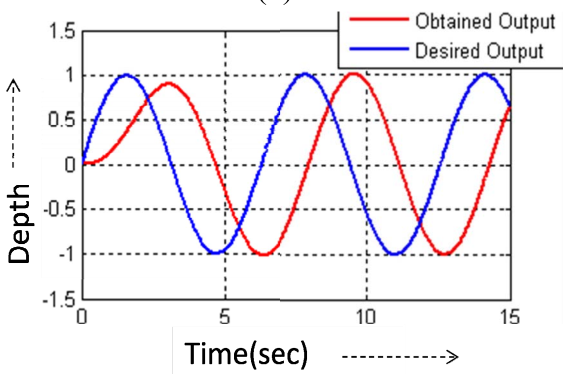
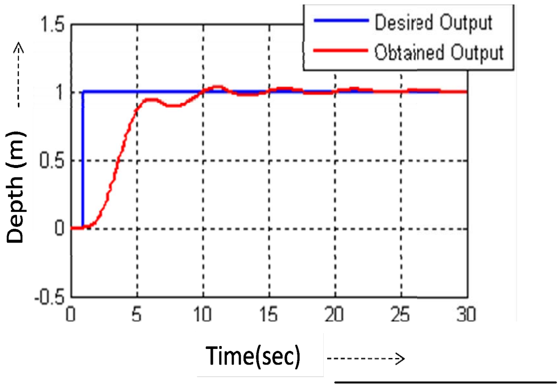


(d)

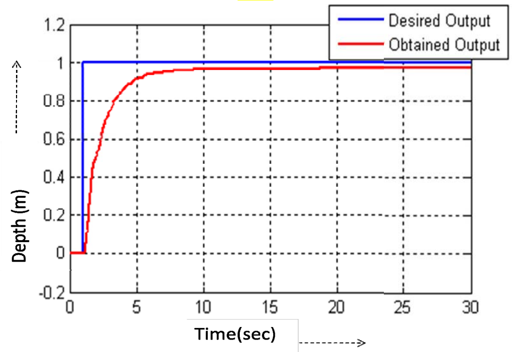


(e)

Figure 8.(a)depth response with positive step (b)depth response with negative step (c)depth rate(d)pitch response with positive step for PID control technique (e)trajectory tracking with PID



(a)



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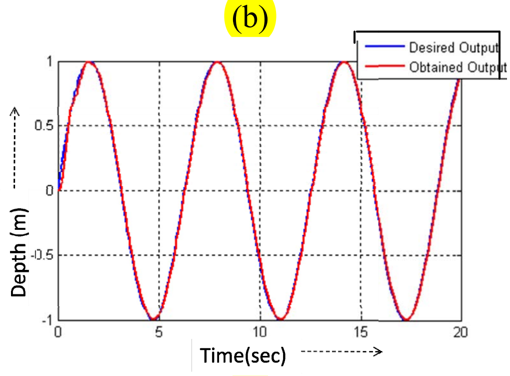

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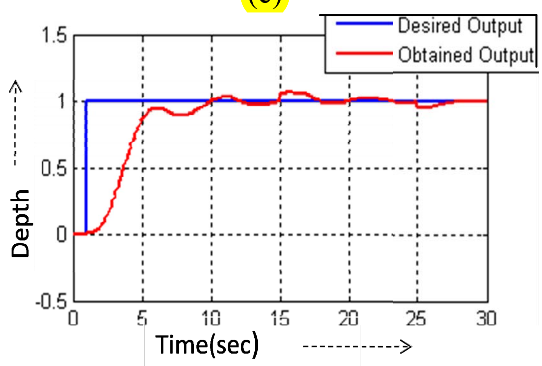

(d)

Figure 9. Results obtained with fuzzy controller (a)Step response without compensator (b) step response with compensator (c) trajectory tracking with sinusoidal input (d) response obtained with disturbance

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