Adaptive Fuzzy PID Controller for A Compact Autonomous Underwater Vehicle

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Abstract*—This paper presents an adaptive Fuzzy Proportional-Integral-Derivative (PID) controller for navigation of an compact autonomous underwater vehicle. The Autonomous Underwater Vehicle (AUV) is an under-actuated system with three thrusters and a neutrally buoyant, modular ,and close-frame body. Kinematic and dynamic models of the system are presented with parameters estimated from detailed CAD model and Computational Fluid Dynamic (CFD) analysis. 3D way-point navigation with Line-Of-Sight (LOS) strategy is used in the guidance system for trajectory generation. The proposed model of the AUV is a 4 Degree of Freedom (DOF) coupled non-linear system. A partitioning PID control law is developed to maintain the AUV on the desired trajectory. PID controllers are popular for its simplicity and ease of implementation, but for a dynamic system like AUV, the controller gains have to be tuned for different trajectories. To make the AUV follow various trajectories without specifically tuning the gains for each trajectory, a fuzzy controller is introduced. The Fuzzy controller helps to select proper gains for the PID controller for different paths as required. Both the PID and Fuzzy-PID controllers are developed and simulated in MATLAB SIMULINK for 3D trajectories. It is observed that while the PID controller fails to follow the trajectory with gains not tuned for the path, the Fuzzy-PID controller successfully follows the desired trajectory with the same gain parameters.

***Index Terms*—Autonomous Underwater Vehicle (AUV), Line-Of-Sight (LOS), Fuzzy-PID, PID.**

I. INTRODUCTION

AUVs are robotics systems capable of autonomous underwater navigation without human interaction and carry out predefined tasks. These systems have gained popularity over the years because of their potential applications ranging from military, industrial to research and environment protection sectors [1]. The AUV [2] used here is a low-cost, compact system with a neutral buoyant, modular, and closed frame body made of glass fiber composite and operating with three thrusters (Fig. 1). AUV depends on its navigation algorithm and control architecture for its autonomous operation. Accurate mathematical model of the system can help to a great extent the algorithms. Detailed mathematical model of underwater vehicles are presented by Fossen [3], [4], Sahoo [5]. The AUV follows a predefined trajectory to carry out the task at hand. Way-point navigation is a trajectory generation method which simply connects the desired points the AUV has to move through by straight lines and arcs to avoid sharp turn. AUV guidance system uses different techniques to follow these trajectories among which Line-of-Sight (LOS) [4], [6] is a simple and popular one. A robust controller is an essential component for the AUV to operate autonomously and complete the predefined objective without human intervention. Controller adjust the thruster output to maintain the AUV on predefined trajectory. PID [7] controllers are most popular for their simplicity and ease of implementation, but it has to be tuned for different working conditions and cannot handle environmental disturbances and variations. Thus, adaptive controllers such as Fuzzy-PID [8] is preferred for dynamic underwater environments. This paper discusses the development of an adaptive Fuzzy-PID controller for an AUV. The content of the paper is presented in four sections. Following the introduction is the section 2 presenting the mathematical model of the AUV. The section 3 discusses the controller and the result and discussion is presented on section 4.

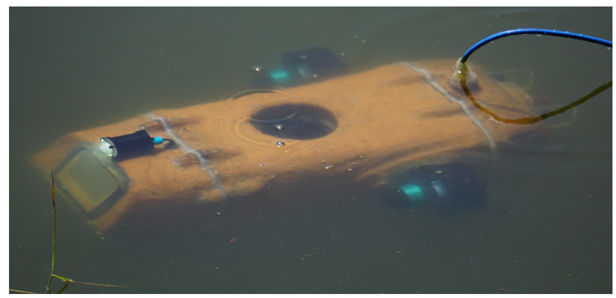


Fig. 1: AUV

II. AUV MODEL

The AUV used for the study is a compact low-cost AUV developed for underwater exploration. It is a closed frame, neutrally bouyant system with a three-part modular structure. The AUV houses three fix-position bidirectional thruster for its motion. From these three thrusters, one placed around the C.G of the body is used for vertical motion and other two placed at the side are used for planar motion. As the system is neutrally bouyant a signle thruster is sufficient for vertical motion and its placement around the C.G avoids pitching of the AUV. Thus during development of the mathematical model pitch and roll is neglected and a 4 DOF mathematical model is proposed for the AUV, which has motion in the surge, heave, and yaw directions. The AUV is a single link manipulator. The kinematic model of the system correlates the local frame placed on the origin of the system to the global NED (north east down) frame placed on the surface of the water. In this work, Position and orientation in local frame: $\eta = [x, y, z, \psi]^T$ linear and angular velocity in global frame: $\nu = [u, v, w, r]^T$ The AUV kinematic model correlating the local and global frame can be expressed using Euler transformation as follows.

$$\begin{aligned} \dot{x} &= ucos(\psi) - vsin(\psi), \quad \dot{z} = w \\ \dot{y} &= usin(\psi) + vcos(\psi), \quad \dot{\psi} = r \end{aligned} \tag{1}$$

And the AUV dynamic model can be presented as:

$$M_{RB}\dot{\nu} + C_{RB}(\nu)\nu + D_l(\nu)\nu + D_n(\nu)\nu = f \tag{2}$$

$$\begin{bmatrix} m & 0 & 0 & -my_g \\ 0 & m & 0 & mx_g \\ 0 & 0 & m & 0 \\ -my_g & mx_g & 0 & I_z \end{bmatrix} \begin{Bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \\ \dot{r} \end{Bmatrix} + \left\{ \begin{bmatrix} 0 \\ 0 \\ 0 \\ m(x_g r + v) \end{bmatrix} \right.$$
$$\begin{bmatrix} 0 & 0 & -m(x_g r + v) \\ 0 & 0 & -m(y_g r - u) \\ 0 & 0 & 0 \\ m(y_g r - u) & 0 & 0 \end{bmatrix} + \begin{bmatrix} X_u & 0 & 0 & 0 \\ 0 & Y_v & 0 & 0 \\ 0 & 0 & Z_w & 0 \\ 0 & 0 & 0 & N_r \end{bmatrix} +$$
$$\left. \begin{bmatrix} X_{u|u|}|u| & 0 & 0 & 0 \\ 0 & Y_{v|v|}|v| & 0 & 0 \\ 0 & 0 & Z_{w|w|}|w| & 0 \\ 0 & 0 & 0 & N_{r|r|}|r| \end{bmatrix} \right\} \begin{Bmatrix} u \\ v \\ w \\ r \end{Bmatrix} = \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \end{bmatrix} \tag{3}$$

Here, M_{RB} is the inertia matrix, $C_{RB}(\nu)$ is the coriolis, and centripetal matrix, $D(\nu)$ is the damping matrix containing hydrodynamic lift and drag terms, f is the thruster output expressed in global frame which can be correlated with the individual thruster output using geometric transformation depending on thruster positions. System parameters are estimated from the detailed CAD model and CFD analysis, presented in Table. I [7], [9].

TABLE I: SYSTEM PARAMETERS ESTIMATED FROM CAD MODEL.

Parameter	Value
m	14.7 Kg
W	144.06 N
B	144.06 N
I_{xx}	0.11 kg.m^2
I_{yy}	0.29 kg.m^2
I_{zz}	0.36 kg.m^2
l_1	0.163 m

Parameter	Value
x_g	-0.0167 m
y_g	0 m
z_g	-0.0097 m
x_b	-0.0167 m
y_b	0 m
z_b	0 m
l_5	0.0009 m

System parameters include AUV weight w, buoyant force B, C.G position (x_g, y_g, z_g), C.B position (x_b, y_b, z_b), mass moment of inertia, position of the thrusters, drag coefficient etc. Some of these such as weight, buoyancy and thruster positions are measured others which are difficult to measure directly such as moment of inertia, position of C.B and C.G are estimated from CAD model. Hydrodynamic drag parameters such as $X_{u|u|}$, X_u etc. are estimated from CFD analysis using ANSYS Fluent. The detailed estimation of all the system parameters can be found in [7], [9].

GUIDANCE SYSTEM

This study presents a adaptive trajectory tracking control. The trajectory is predefined for the AUV and this is defined by connecting the desired way-points by straight lines. The guidance system helps the AUV to follow this trajectory using different techniques and Line Of Sight(LOS) is most common of them because of its simplicity. In this technique the AUV tries to follow the line of sight vector between the previous and next way-point closely. The yaw direction will be along the line joining the current position and the next way-point and can be calculated using Eqn.(4).

$$\psi_{desired} = \tan^{-1}\left(\frac{y_m - y(t)}{x_m - x(t)}\right) \tag{4}$$

Here (x_m, y_m) are the x y position of the N way-points and m = 1, 2 . . . N , and $(x(t), y(t))$ are the x y coordinates of the AUV position at time t.

Vertical motion of the AUV is independent from the planar motion. The system is neutrally bouyant thus the vertical component of the motion can be achieved quickly but to maintain the AUV close to the LOS vector the desired vertical depth should be proportional to the current depth. To obtain this desired depth first the angle between the line from previous point (x_0, y_0, z_0) to next (x_d, y_d, z_d) and the horizontal plane is calculated as:

$$\varphi_0 = \tan^{-1}\frac{z_d - z_0}{\sqrt{(x_d - x_0)^2 + (y_d - y_0)^2}} \tag{5}$$

For the AUV to keep moving towards, the target along this angle the desired depth can be calculated as:

$$z_p(t) = z_d - \tan\varphi_0 \times \sqrt{(x_d - x(t))^2 + (y_d - y(t))^2} \tag{6}$$

The guidance system provide the next desired target location and the controller help the AUV achieve that target by adjusting the thruster output. When the AUV is within certain acceptable radius of the way-point, it is considered that the target is reached and next way-point is selected. This radius of acceptance is generally selected as twice the size of the AUV at maximum and depends on the application. The radius of acceptance is tracked using:

$$r(t)^2 = [x_d - x(t)]^2 + [y_d - y(t)]^2 + [z_d - z(t)]^2 \leq r(t)^2 \tag{7}$$

III. CONTROLLER

The AUV model is a 4 DOF non-linear coupled system. Thus, a partitioning control law is used, which divides the system into a model-based portion and a servo portion. System parameters $(M_{RB}, C_{RB}, D_n and D_l)$ comes in the model-based portion and is independent of the control part. The system model is expressed as:

$$M_{RB}\ddot{X} + C_{RB}\dot{X} + D_l\dot{X} + D_n|\dot{X}|\dot{X} = f \tag{8}$$

The System to be of unit mass, the model-based portion is expressed as follows.

$$f = (M_{RB})f' + (C_{RB}\dot{X} + D_l\dot{X} + D_n|\dot{X}|\dot{X}) \tag{9}$$

And the system equation becomes

$$\ddot{X} = f' \tag{10}$$

The desired trajectory is a function of time, $X_d(t)$, which should be double differentiable thus desired position and velocity cab be obtained. The error between the desired and current position can be defined as $e = X_d - X$. Designed PID control law to compute f' :

$$f' = \ddot{X}_d + K_d\dot{e} + K_p e + k_i\int edt \tag{11}$$

Here K_d, K_p and K_i are the derivative, proportional and integral control gain respectively. Combining this control law with eq. 10,

$$\ddot{X} = \ddot{X}_d + K_d\dot{e} + K_p e + k_i\int edt \tag{12}$$

$$\ddot{e} + K_d\dot{e} + K_p e + k_i\int edt = 0 \tag{13}$$

In presence of a constant steady-state error, the modified control law can be presented as follows.

$$\ddot{e} + K_d\dot{e} + K_p e + k_i\int edt = f_{dist} \tag{14}$$

Here f_{dist} is the constant disturbance.

As the PID controller has to be tuned for individual path, use of Fuzzy controller to adapt to different path and scenario brings robustness to the controller. A PID controller with some variation in control gain can be formulated as:

$$\begin{aligned} f'(t) &= [K_p(t)e(t)] + \int_0^t [K_i(\tau)e(\tau)]d(\tau) + \frac{d[K_d(t)e(t)]}{dt} \\ &= [k_p^0 + \Delta k_p(t)]e(t) + \int_0^t [k_i^0 + \Delta k_i(\tau)]e(\tau)d(\tau) \\ &+ \frac{d[k_d^0 + \Delta k_d(t)]e(t)}{dt} \end{aligned} \tag{15}$$

Where, $K_p(t) = k_p^0 + \Delta k_p(t)$; $K_i(t) = k_i^0 + \Delta k_i(t)$; $K_d(t) = k_d^0 + \Delta k_d(t)$ are the control gains with some allowable variation;

k_p^0, k_i^0, k_d^0: time independent, constants obtained from PID controller;

$\Delta k_p(t)$, $\Delta k_i(t)$, $\Delta k_d(t)$: time dependent, variable, adapted during simulation.

Here a Fuzzy Logic Controller (FLC) is proposed for generating $\Delta k_p(t)$, $\Delta k_i(t)$, $\Delta k_d(t)$. The FLC is the fuzzy linguistic variables NL, NM, NS, ZR, PS, PM, PL which represent Negative Large, Negative Medium, Negative Small, Zero, Positive Small, Positive Medium, and Positive Large, respectively. The FLC has two inputs. One is the system error e(t) and the error rate. To produce the three signals, the FLC needs three outputs. Consequently, the FLC has two inputs and three outputs that are shown in Fig. 2.

When the error is large, k_p should be large to have fast response. Large instantaneous error can be avoided by taking a smaller kd. Small k_i value will help to avoid overshoot.

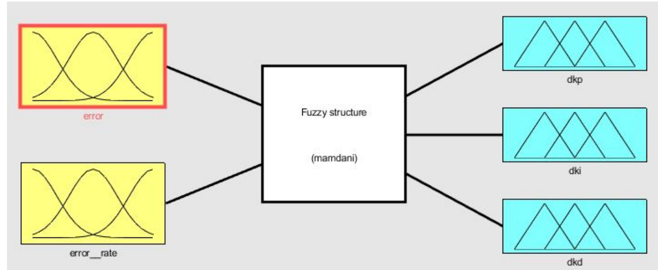


Fig. 2: Fuzzy logic controller

When the error is medium, in order to ensure fast system response and have small overshoot, k_p should be reduced, while larger kd increase the impact of system response, k_i should be appropriate. When error is small, to ensure that the system has the ideal static performance, k_p and k_i should be large. Considering these facts fuzzy rules for k_p, k_d and k_i are designed which are presented in the Tables. II, III and IV [8].

TABLE II: FLC rules for $\Delta k_p(t)$

$\dot{e}$ \ e	NL	NM	NS	Z	PS	PM	PL
NL	PL	PL	PM	PM	PS	PS	Z
NM	PL	PL	PM	PM	PS	Z	Z
NS	PM	PM	PM	PS	Z	NS	NM
Z	PM	PS	PS	Z	NS	NM	NM
PS	PS	PS	Z	NS	NS	NM	NM
PM	Z	Z	NS	NM	NM	NM	NL
PL	Z	NS	NS	NM	NM	NL	NL

TABLE III: FLC rules for $\Delta k_i(t)$

$\dot{e}$ \ e	NL	NM	NS	Z	PS	PM
NL	NL	NL	NL	NM	NM	Z
NM	NL	NL	NM	NM	NS	Z
NS	NM	NM	NS	NS	Z	PS
Z	NM	NS	NS	Z	PS	PS
PS	NS	NS	Z	PS	PS	PM
PM	Z	Z	PS	PM	PM	PL
PL	Z	Z	PS	PM	PB	PB

TABLE IV: FLC rules for $\Delta k_d(t)$

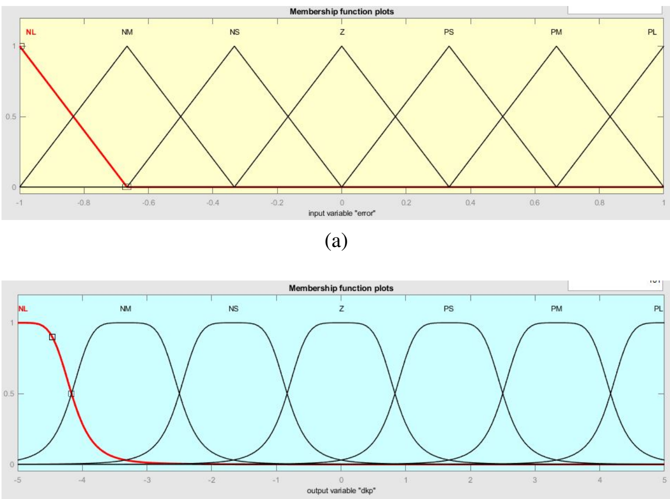
$\dot{e}$ \ e	NL	NM	NS	Z	PS	PM
NL	PS	PS	Z	Z	Z	PL
NM	NS	NS	NS	NS	Z	NS
NS	NL	NL	NM	NS	Z	PS
Z	Z	Z	Z	Z	Z	Z
PS	NL	NM	NS	NS	Z	PS
PM	NM	NS	NS	NS	Z	PS
PL	PS	Z	Z	Z	Z	PL

The membership functions for the inputs and the outputs are trimf and gbellmf, respectively. Here gbellmf and trimf represent generalized bell curve membership function and triangular curve member function respectively in fuzzy logic as shown in the Fig. 3. FLC input and output range of the

TABLE V: FLC input output parameter range

	$\dot{e}$	e	$\Delta k_p(t)$	$\Delta k_i(t)$	$\Delta k_d(t)$	k_p^0	k_i^0	k_d^0
X	[-1 1]	[-0.5 0.5]	[-5 5]	-	[-9 9]	10	-	17.7
Y	[-0.7 0.7]	[-1 1]	[-0.3 0.3]	[-0.06 0.06]	[-1.5 1.5]	0.7074	-0.1	1.68
Z	[-0.2 0.2]	[-0.4 0.4]	[-9 9]	-	[-15 15]	18	-	30.527
ψ	[-4 4]	[-1300 1300]	[-100 100]	-	[-50 50]	200	-	90

membership functions and the parameter values are presented in the Table. V.



(a)

(b)

Fig. 3: Fuzzy Logic Membership Functions (a) trimf and (b) gbellmf

IV. RESULTS AND DISCUSSIONS

First the developed PID controller is simulated [9]. Simulation for a curved multi way-point path is carried out and the position tracking result is presented in Fig. 4. Way-points are 10 equidistant points in x and z axes from 0 to 6 and 0 to 3 respectively and y-coordinates are in form of a sine function of x-coordinates. The tuned control gains of the PID controller for this 3D path is presented in the Table. VI.

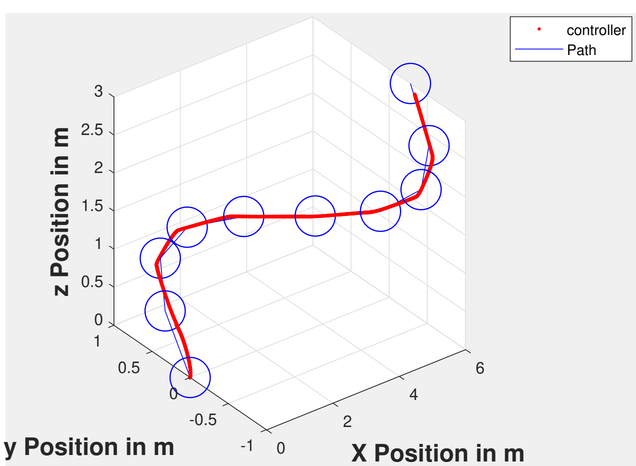


Fig. 4: Position with time

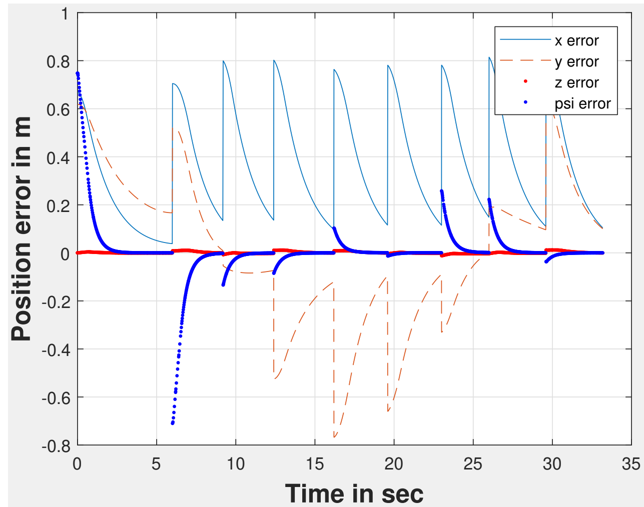


Fig. 5: Position error with time

TABLE VI: Controller gain parameters

position	k_p	k_i	velocity	k_v
x	12	0	u	17.694
y	0.7074	-0.1	v	1.68214
z	20	0	w	30.527
ψ	200	0	r	92.99

Developed Fuzzy-PID controller is simulated in MATLAB SIMULINK for multi waypoint trajectory(Fig. 6). Controller is able to flow different the trajectory successfully. For comparison and validation of the Fuzzy-PID controller a multi Way-point path is simulated with PID and Fuzzy-PID controller changing the control gains. Control gain parameters used on this simulation for both the controllers are presented in the Table. 7. As the the control gains are not the tuned parameters for the PID controller, it failed to follow the path (shown in Fig. 7), Where as the adaptive Fuzzy-PID controller was able to follow the trajectory (shown in Fig. 8). The error tracking results of the Fuzzy-PID controller is presented in the Fig. 9.

TABLE VII: CONTROLLER GAIN PARAMETERS

Posi-tion	Tuned		Untuned		Velo-city	Tuned	Untuned
	k_p	k_i	k_p	k_i		k_d	k_d
x	12	0	10	0	u	17.694	17.694
y	0.7074	-0.1	0.7074	-2	v	1.68214	1.68214
z	20	0	18	0	w	30.527	30.527
ψ	200	0	160	0	r	92.99	50

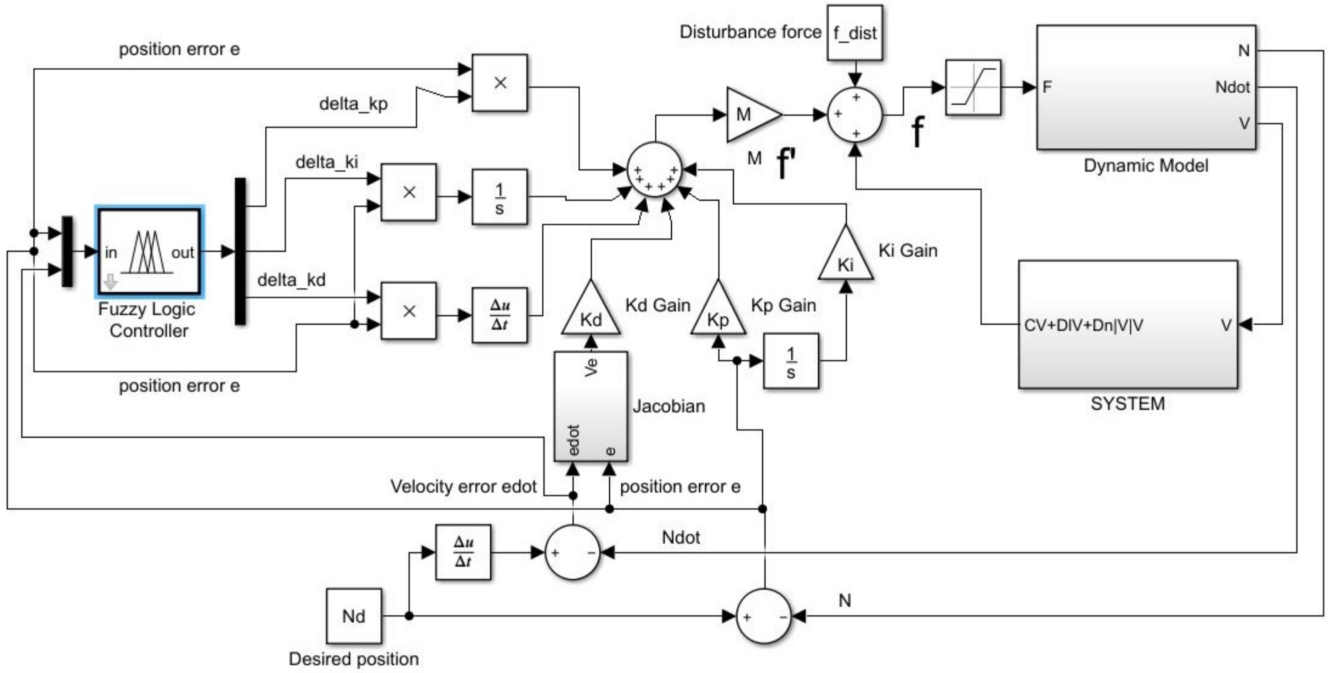


Fig. 6: Fuzzy-PID controller

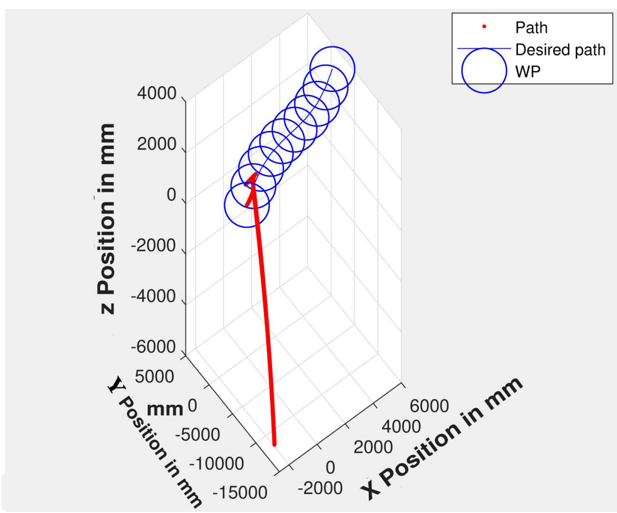


Fig. 7: Position Tracking PID controller

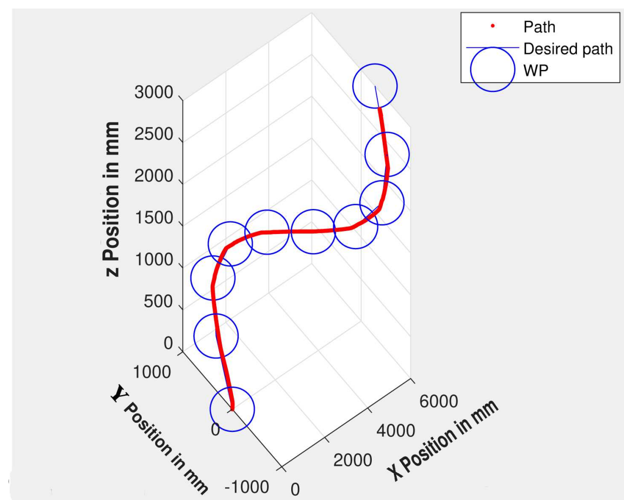


Fig. 8: Position Tracking Fuzzy-PID controller

V. Conclusion

This paper presented the mathematical model of a compact AUV. A 3D guidance system is developed using waypoint technique and LOS strategy. The guidance system provide the next desired target location and the controller help the AUV achieve that target by adjusting the thruster output. Using the system model a closed-loop PID controller is developed using partitioning law for this nonlinear coupled system. The controller is successfully simulated for multi way-point 3D trajectory and results are discussed. A adaptive fuzzy PID controller is also developed using the developed PID controller and Fuzzy logic and simulate with MATLAB SIMULINK. PID controller gains are specific for trajectories but use of fuzzy logic can allow to adapt the controller gains for variation in path. To validate the adaptive nature of the Fuzzy PID controller a simulation is conducted. The PID controller failed to follow the trajectory after introducing little deviation to the gain parameters. Where as the fuzzy controller estimates the variation in control gains and successfully follows the trajectory. The adaptive nature of the Fuzzy-PID controller allows the AUV to handle different trajectories and deviations due to external disturbances.

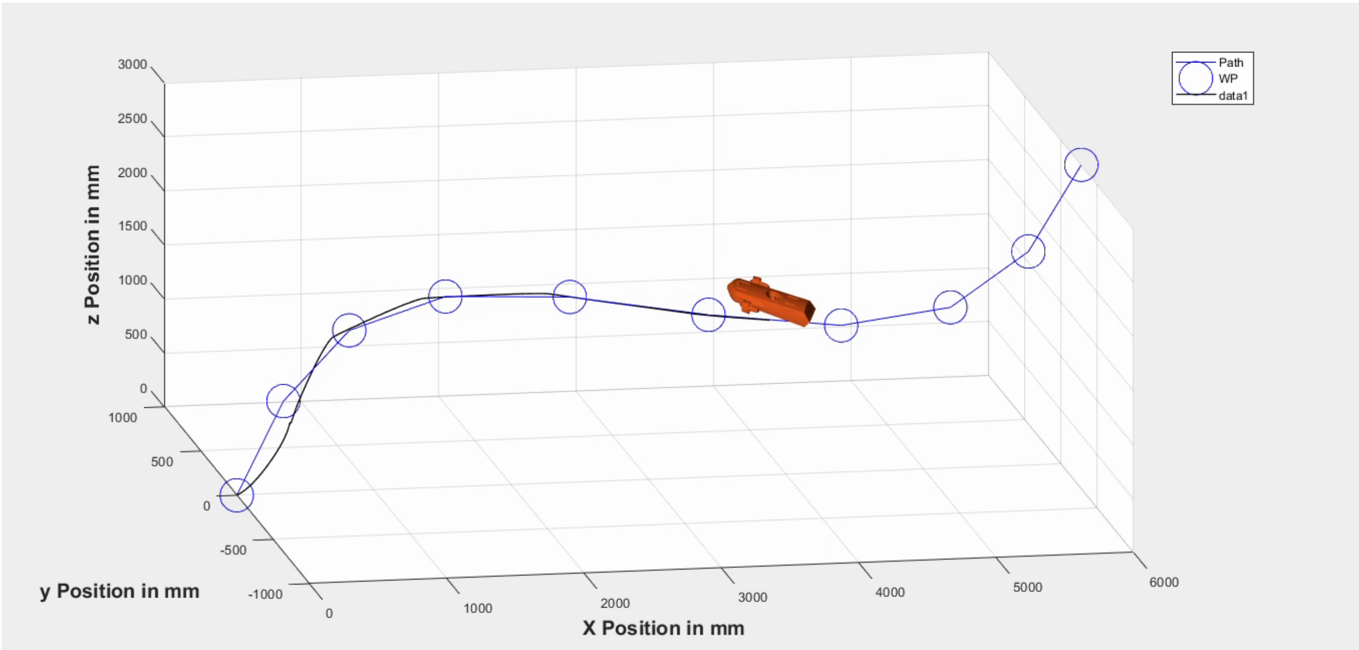


Fig. 10: 3D WAY-POINT TRACKING SIMULATION

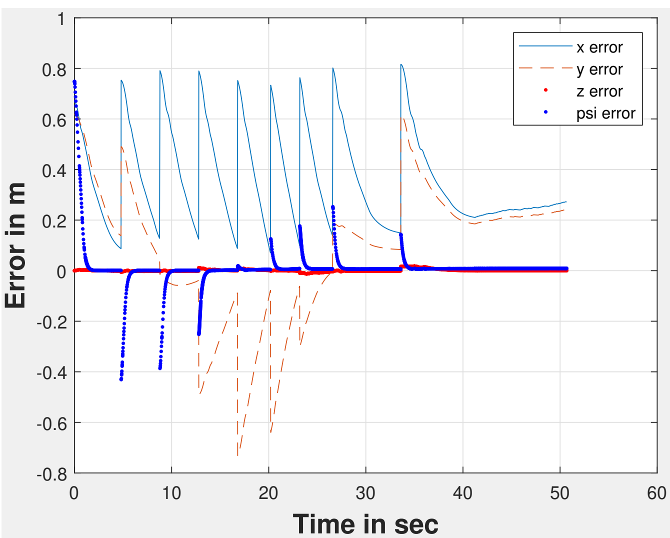


Fig. 9: Error Tracking Fuzzy-PID controller

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