Fuzzy Adaptive Control for Trajectory Tracking of Autonomous Underwater Vehicle

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Abstract: In this paper, the problem of the position and attitude tracking of an autonomous underwater vehicle (AUV) in the horizontal plane, under the presence of ocean current disturbances is discussed. The effect of the gradual variation of the parameters is taken into account. The effectiveness of the adaptive controller is compared with a feedback linearization method and fuzzy gain control approach. The proposed strategy has been tested through simulations. Also, the performance of the proposed method is compared with other strategies given in some other studies. The boundedness and asymptotic convergence properties of the control algorithm and its semi-global stability are analytically proven using Lyapunov stability theory and Barbalat's lemma.

Index Terms: Autonomous underwater vehicles, adaptive control, nonlinear control, fuzzy approximation.

I. Introduction

Autonomous underwater vehicle (AUV) is a field of increasing interest due to its many interesting applications. Underwater vehicles are extensively employed in the offshore industry, subaquatic scientific investigations and rescue operations, finding sunken ships, searching for lost artifacts. As they are untethered, they may operate under ice, opening up vast, largely unexplored Arctic areas that are inaccessible to any other kind of research vessel, and operate at depths too deep for tethered vehicles. They are also of military interest (e.g. see [1]). Many control methods for underwater vehicles have been discussed in the literature in the past 15 years to handle uncertainties related to the dynamics, hydrodynamics and external disturbances. see for instance Fossen & Fjellstad, 1995; Hsu et al., 2000, Antonelli et al., 2004; Wang & Lee, 2003; Do et al., 2004. Especially, for developing advanced control strategies for Autonomous Vehicles. Recent developments in this area are well summarized in [2,3] in which different motion control algorithms have been developed under various hypotheses. Adopting a linearized model, some linear control techniques such as PID controller [4] and LQR algorithm [5] have been developed with acceptable performance in only special kinds of maneuvering. Taking square integrable bounded disturbances into account, linear H_∞controller has been also presented [6], in the absence of parameter variations. Some more recent investigations concern with model uncertainties and present non-linear based methods such as sliding mode control in which the upper bounds of uncertainties and disturbances are known in advance [7,8]. In the horizontal trajectory tracking control algorithm, a sliding mode control algorithm based on the line of sight method has been proposed [9,10], which achieves trajectory tracking through reducing the error of yaw angle continually. But this method cannot guarantee to converge the tracking error to a minimum, which is a low-precision sliding mode control algorithm. Intelligent control algorithms based on neural networks and fuzzy logic have been also applied to those classes of underwater vehicles, for which the experimental data is available [11]. However, the new AUVs are highly coupling non-linear and time-varying system. Taking into account the uncertainty of environmental interference, it is difficult to establish an accurate motion model.

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Therefore, the control method used for new AUV should get rid of the dependence on the precise mathematical model. The nonlinear trajectory tracking control of the AUVs in complex sea conditions has been a key issue in AUV design which is also concerned by AUV designers. So, it has important theoretical and practical significance to study this issue. It is difficult to obtain high performance by using the conventional control strategies. The control system should be able to learn and adapt to the changes in the dynamics of the vehicle and its environment. In [12] a discrete adaptive control strategy for coordinated control of AUVs is presented. In [13] a variety of control methodologies, including sliding mode control, adaptive control and output feedback control of AUVs are given. Some studies applying fuzzy control to under water robots can be found in [14], [15] and [16]. This paper, addresses the problem of position and attitude tracking of an AUV in the horizontal plane, using two rudders in front and rare side of the vehicle. An adaptive control law is presented to effectively compensate the hydrody-namic effects; Then the effectiveness of the adaptive controller is compared with a feedback linearization approach, in the presence of external disturbances [17]. Moreover, in some references to achieve the better stability performance of the system, the complicated mathematical operations are used. On the other hand, more stability of the system can be guaranteed by means of combining fuzzy logic controller with the control strategies [18]. The main contribution of this paper is online approximation of adaptive gain with fuzzy system, In addition, the adaptive control method has been compared with fixed gain and fuzzy gain approach and eventually simulation results have presented. The remainder of this paper is organized as follows. Introductory materials and a review of the current research trends in literature are treated in section I. Section II addresses a brief discussion on the dynamic modeling of AUV followed by controller design details and its stability analysis. Uncertain parameters are introduced in this section, as well. The feedback linearization control law is presented in section III-A. In section III-B, the adaptation law and control law are derived and parameter uncertainties are taken into account in the control law. Section III-C introduces the fuzzy system and online estimation of the adaptive gain. Numerical values used for the simulation, are given in section IV-A. Section IV-B presents the simulation studies when the feedback linearization law is implemented. The simulation results of the impleme-ntion of the adaptive controller is presented in section IV-C and the results are compared with that of the feedback linearization. Section IV-D presents the simulation for fuzzy gain approximation in which the results described and compared with fixed gain in adaptive control law.

II. Vehicle Dynamics Model

AUV dynamics are highly nonlinear, coupled, and time varying, including hydrodynamic parameter uncertainties. Several modeling and system identification techniques have been proposed by researchers ([19] and [20]). Restricting our attention to the horizontal plane, the mathematical model consists of the nonlinear sway (translational motion with respect to the vehicle longitudinal axis) and yaw (rotational motion with respect to the vertical axis) equations of motion. In a local (moving) coordinate frame fixed at the vehicle's geometrical center, Newton's equations of motion are

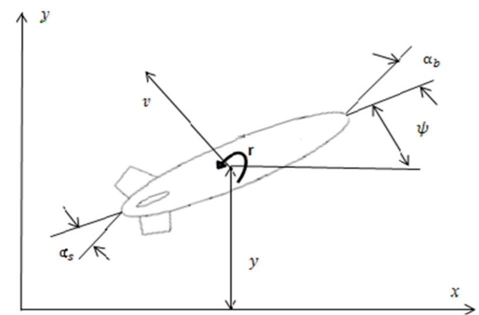

Fig. (1): AUV coordinate

$$m(\dot{v} + ur + x_G\dot{r} - y_G r^2) = Y \quad (1)$$
$$I_z\dot{r} + mx_G(\dot{v} + ur) - my_G vr = N \quad (2)$$

where *v* and *r* are relative sway and yaw velocities of the moving vehicle with respect to water. Y and N represent the total excitation sway force and yaw moment, respectively. x_G and y_G are the coordinates of the vehicle center of gravity in the body fixed local frame. m and I_z are the vehicle mass and mass moment of inertial. Following standard ship maneuvering assumptions, these forces can be expressed as the sum of quadratic drag terms and first order memoryless polynomials in v and r, which represent added mass and damping due to water. In this way the nonlinear equations of motion in the horizontal plane become

$$\dot{v}[m - Y_{\dot{v}}] + \dot{r}[mx_G - Y_{\dot{r}}] = Y_{\delta_s}\alpha_s u^2 + Y_{\delta_b}\alpha_b u^2 - d_1(v,r) + Y_v uv + (Y_r - m)ur \quad (3)$$

$$\dot{v}[mx_G - N_{\dot{v}}] + \dot{r}[I_Z - N_{\dot{r}}] = N_{\alpha_s}\alpha_s u^2 + N_{\alpha_b}\alpha_b u^2 - d_2(v,r) + N_v uv + (N_r - mx_G)ur \quad (4)$$

where d_1 (v, r) and d_2 (v, r) are defined as

$$d_1(v,r) \triangleq \frac{\partial}{2}\int_{tail}^{nose} CD_y h(\zeta)\frac{(v+\zeta r)^3}{|v+\zeta r|}d\zeta \quad (5)$$

$$d_2(v,r) \triangleq \frac{\partial}{2}\int_{tail}^{nose} CD_y h(\zeta)\frac{(v+\zeta r)^3}{|v+\zeta r|}d\zeta \quad (6)$$

Note that the hydrodynamic forces and moments are written in accordance with the SNAME notation [21]. In the horizontal plane, the kinematic equations of motion of the vehicle yaw rate and the inertial position rates, can be written as

$$\dot{\psi} = r \quad (7)$$
$$\dot{x} = u cos\psi - v sin\psi \quad (8)$$
$$\dot{y} = u sin\psi + v cos\psi \quad (9)$$

solving (3) and (4) for $\dot{v}$ and $\dot{r}$, results in

$$\dot{v} = a_{11}uv + a_{12}ur + d_v(v,r) + b_{11}u^2\alpha_s + b_{12}u^2\alpha_b \quad (10)$$

$$\dot{r} = a_{21}uv + a_{22}ur + d_r(v,r) + b_{21}u^2\alpha_s + b_{22}u^2\alpha_b \quad (11)$$

where a_{ij}, b_{ij} and c_i are the related coefficents that appear when solving (3) and (4).

During regular cruising, the drag related terms $d_v(v,r)$ and $d_r(v,r)$ are small, and can be neglected [22]. Note that since, all the parameters a_{ij} and b_{ij} include at least two hydrodynamic coefficients, such as $Y_{\dot{v}}$, $Y_{\dot{r}}$, $N_{\dot{v}}$, $N_{\dot{r}}$; hence they are uncertainties for this system. Later, when adaptive control is introduced, all these parameters will be estimated, to account for the changes in the environment and vehicle properties.

III. Control Law

A. Feedback linearization

A feedback linearization approach is adopted, by taking the time derivative of (7) and (9)

$$\ddot{y} = u\dot{\psi}cos\psi + \dot{v}cos\psi - v\dot{\psi}sin\psi \quad (12)$$
$$\ddot{\psi} = \dot{r} \quad (13)$$

substituting (10) and (11), into the last two equations, results in:

$$\ddot{y} = \dot{\psi}cos\psi + (a_{11}uv + a_{12}u\psi + b_{11}u^2\alpha_s + b_{12}u^2\alpha_b)cos\psi - v\dot{\psi}sin\psi \quad (14)$$

$$\ddot{\psi} = a_{21}uv + a_{22}ur + b_{21}u^2\alpha_s + b_{22}u^2\alpha_b \quad (15)$$

Let us consider a signal $\mathcal{Z}$(t) as follows:

$$\mathcal{Z}(t) = y_m^{(n)} - \beta_{n-1}e^{(n-1)} - \ldots - \beta_0 e \quad (16)$$

with $\beta_1,\ldots,\beta_n$ being positive constants chosen such that $p^n + \beta_{n-1}p^{n-1} + \cdots + \beta_0$ is a stable (Hurwitz) polynomial. Thus we let $\ddot{y} = \mu$, and $\ddot{\psi} = v$ in (14) and (15), and solve the (14) and (15) to obtain α_s and α_b

$$\alpha_s = \{b_{22}(\mu sec\psi + v\dot{\psi}tan\psi - u\dot{\psi} - a_{11}uv - a_{12}ur) - b_{12}(v - a_{21}uv + a_{22}ur)\}/(b_{11}b_{22} - b_{21}b_{12})u^2 \quad (17)$$

$$\alpha_b = -\{b_{21}(\mu sec\psi + v\dot{\psi}tan\psi - u\dot{\psi} - a_{11}uv - a_{12}ur) - b_{11}(v - a_{21}uv + a_{22}ur)\}/(b_{11}b_{22} - b_{21}b_{12})u^2 \quad (18)$$

where μ and v are the equivalent inputs to be designed (equivalent in the sense that determining each, amounts to determining α_s or α_b, and vice versa). Let the tracking error of position and attitude of the vehicle be:

$$\tilde{y} = y - y_d \quad (19)$$
$$\tilde{\psi} = \psi - \psi_d \quad (20)$$

where y_d and ψ_d are the desired model reference. Defining two signals as

$$\mu \triangleq \ddot{y}_d - 2\lambda_1\dot{\tilde{y}} - \lambda_1^2\tilde{y} \quad (21)$$
$$v \triangleq \ddot{\psi}_d - 2\lambda_2\dot{\tilde{\psi}} - \lambda_2^2\tilde{\psi} \quad (22)$$

where $\lambda_1 > 0$ and $\lambda_2 > 0$ are design parameters, will lead to

$$\ddot{\tilde{y}} + 2\lambda_1\dot{\tilde{y}} + \lambda_1^2\tilde{y} = 0 \quad (23)$$
$$\ddot{\tilde{\psi}} + 2\lambda_2\dot{\tilde{\psi}} + \lambda_2^2\tilde{\psi} = 0 \quad (24)$$

which are Hurwitz polynomials.

B. Parameter Uncertainties

As stated before, all the parameters $a_{ij}$and b_{ij} comprise hydrodynamic uncertainties which must be estimated. On the other hand, the vehicle's forward velocity u is assumed to be constant or updated by hydrodynamic coefficients, but subjected to changes from environment and ocean currents. Thus all terms including u must also be estimated. To this end, instead of estimating all a_{ij} and b_{ij}, parameter functions, p_i, are defined in a linear parameterization process.

$$\alpha_s = p_1\left(\frac{\mu + vrsin\psi}{cos\psi}\right) + p_2 v + p_3 r - p_4 v \quad (25)$$

$$\alpha_b = -p_5\left(\frac{\mu + vrsin\psi}{cos\psi}\right) + p_6 v + p_7 r + p_8 v \quad (26)$$

where p_i for $i=1,\ldots,8$ are parameter functions, in terms of a_{ij} , $b_{ij}$and u.

$$p_1 = \frac{b_{22}}{(b_{11}b_{22} - b_{21}b_{12})u^2} \qquad p_2 = \frac{b_{12}a_{21}u - b_{22}a_{11}u}{(b_{11}b_{22} - b_{21}b_{12})u^2}$$

$$p_3 = \frac{b_{12}a_{22}u - b_{22}a_{12}u - b_{22}u}{(b_{11}b_{22} - b_{21}b_{12})u^2} \qquad p_4 = \frac{b_{12}}{(b_{11}b_{22} - b_{21}b_{12})u^2}$$

$$p_5 = \frac{b_{21}}{(b_{11}b_{22} - b_{21}b_{12})u^2} \qquad p_6 = \frac{b_{21}a_{11}u - b_{11}a_{21}u}{(b_{11}b_{22} - b_{21}b_{12})u^2}$$

$$p_7 = \frac{b_{21}a_{21}u - b_{11}a_{22}u - b_{21}u}{(b_{11}b_{22} - b_{21}b_{12})u^2} \qquad p_8 = \frac{b_{11}}{(b_{11}b_{22} - b_{21}b_{12})u^2}$$

The vector form of the above equations will be rather more useful in the derivation of the adaption law

$$\begin{Bmatrix}\alpha_s \\ \alpha_b\end{Bmatrix} = WP \quad (28)$$

where P=$[p_1, p_2, p_3, p_4, p_5, p_5, p_6, p_7, p_8]^T$, and W is the regressor matrix. Equations (25) and (26) will represent the dynamic equations of the system, if μ and ν are replaced by $\ddot{y}$ and $\ddot{\psi}$ respectively.

Since, the uncertain parameters existed in P are all unknown, they must be estimated. Thus, the control law is modified as follows:

$$\alpha_s = \hat{p}_1\left(\frac{\mu+vrsin\psi}{cos\psi}\right) + \hat{p}_2 v + \hat{p}_3 r - \hat{p}_4 v \qquad (29)$$

$$\alpha_b = -\hat{p}_5\left(\frac{\mu+vrsin\psi}{cos\psi}\right) + \hat{p}_6 v + \hat{p}_7 r + \hat{p}_8 v \qquad (30)$$

where $\hat{p}_i$ represents parameter estimations. Let the estimation error of parameters be $\tilde{p}_i$=$p_i - \hat{p}_i$. One can find the error dynamics by substituting (29) and (30) into the system dynamic equations. This will result

$$\begin{Bmatrix} \frac{\ddot{y}-\mu}{cos\psi} \\ \ddot{\psi} \end{Bmatrix} = \hat{H}^{-1} W \tilde{p} \qquad (31)$$

where $\tilde{p}$ is the estimation error vector and $\hat{H}$ is defined by

$$\hat{H} = \begin{bmatrix} \hat{p}_1 & -\hat{p}_4 \\ \hat{p}_5 & -\hat{p}_8 \end{bmatrix} \qquad (32)$$

error dynamics are achieved by substituting (29) and (30) into the dynamic equations of the system (3) and (4). This results

$$\overbrace{\begin{bmatrix} \hat{p}_1 & -\hat{p}_4 \\ \hat{p}_5 & -\hat{p}_8 \end{bmatrix}}^{\hat{H}} \begin{Bmatrix} \frac{\ddot{y}-\mu}{cos\psi} \\ \ddot{\psi} \end{Bmatrix} = \underbrace{\begin{bmatrix} -\frac{\ddot{y}+vrsin\psi}{cos\psi} & -v & r & \ddot{\psi} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{\ddot{y}+vrsin\psi}{cos\psi} & v & r & \ddot{\psi} \end{bmatrix}}_{W} \tilde{p} \qquad (33)$$

one can write Eq. (31) in state space form by defining the state vector X and the output vector Y

$$\dot{X} = AX + B(\hat{H}^{-1} W \tilde{p}) \qquad (34)$$

$$Y = \tilde{N}_f = \dot{\tilde{N}} + \Phi \tilde{N} = CX \qquad (35)$$

where $\Phi = diag[\phi_1, \phi_2]$ is a filtering matrix, and $\tilde{N}_f$ is the vector of filtered errors, and N=$[\tilde{y}, \tilde{\psi}]^T$.

Adaption Law:

Having written the error dynamics in state space form, we employ a Lyapunov-based approach to derive the adaptation law. Consider the following Lyapunov candidate

$$V = X^T \mathbb{p} X + \tilde{P}^T \Gamma^{-1} \tilde{P} \qquad (36)$$

where $\mathbb{p}$ is a positive definite matrix, and Γ_i=$diag[\gamma_1, \gamma_2, \dots, \gamma_r]$ with $\gamma_i > 0$. Taking the time derivative of (36) yields

$$\dot{V} = \dot{X}^T \mathbb{p} X + X^T \mathbb{p} \dot{X} + 2\tilde{P}^T \Gamma^{-1} \dot{\tilde{p}} \qquad (37)$$

Substitution of the state space equations of error dynamics into (37) results

$$\dot{V} = 2\tilde{P}^T\left[\Gamma^{-1}\dot{\tilde{p}} + W^T \hat{H}^{-T} B^T \mathbb{p} X\right] + X^T(A^T \mathbb{p} + \mathbb{p} A)X \qquad (38)$$

This equation can further be simplified, by adopting the following lemma

Lemma 3.1 (Kalman-Yakubovich-Popov): Consider a controllable linear time-invariant system

$$\dot{X} = AX + bu \qquad (39)$$

$$y = CX \qquad (40)$$

The transfer function *h(p)*= $c[pI - A]^{-1} b$ is strictly positive real if, and only if, there exist positive definite matrices $\mathbb{p}$ and $\mathbb{Q}$ such that

$$A^T \mathbb{p} + \mathbb{p} A = -\mathbb{Q} \qquad (41)$$

$$\mathbb{p} b = c^T \qquad (42)$$

According to the above lemma, one can write $(A^T \mathbb{p} + \mathbb{p} A) = -\mathbb{Q}$ in Eq. (38). The adaptation law is found by setting the first term on the right side of (38) equal to zero

$$2\tilde{P}^T\left[\Gamma^{-1}\dot{\tilde{p}} + W^T \hat{H}^{-T} B^T \mathbb{p} X\right] = 0 \qquad (43)$$

Rearranging the above equation and noting that $\dot{\tilde{P}} = -\dot{\hat{P}}$ and using Lemma 2.1, the adaptation law is found as:

$$\dot{\hat{P}} = \Gamma W^T \hat{H}^{-T} Y \qquad (44)$$

and Eq. (38) will become:

$$\dot{V} = -X^T \mathbb{Q} X \qquad (45)$$

One can simply prove the convergence of tracking error to zero, using Barbalat's Lemma which is given here.

Given that a function tends towards a finite limit, Barbalat's lemma indicates the additional requirement that can guarantee its derivative actually converges to zero. In other words we have the following lemma.

Lemaa 3.2 (Barbalat's Lemma) If the differentiable function f(t) has a finite limit as t→ ∞, and if f is uniformly continuous, then $\dot{f}$ (t) →0 as t→ ∞

By using Barbalat's lemma [23] for the analysis of dynamic systems, one typically uses the following immediate corollary, which looks very much like an invariant set theorem in Lyapunov analysis

Lemma 3.3 (Lyapunov-Like Lemma): If a scalar function V (x, t) satisfies the following conditions:
V (x, t) is lower bounded and $\dot{V}$ (x, t) is negative semi-definite and $\dot{V}$ (x, t) is uniformly continuous in time then $\dot{V}$ (x, t) →0 as t→ ∞.

C. Fuzzy gain approximation

Fuzzy system consists of four main component; the fuzzifier, the fuzzy rule base, the fuzzy inference and the defuzzifier. The fuzzifier transfers the measured input data into corresponding fuzzy sets which can be un-derstood by the fuzzy inference system. The fuzzy rule base describes the correlation between input and output fuzzy sets in the forms of IF-THEN rules. It is the core of the whole system. The fuzzy inference engine uses techniques in approximate reasoning to determine a mapping from the fuzzy sets in the input space to the fuzzy sets in the output space. The defuzzifier transfers fuzzy sets in the output space into numerical data in the output space. In this section, we assumed that adaptive gain matrix (Γ) is unknown. In order to design a proper control law we employ fuzzy inference system for online estimation of unknown function. The fuzzy inference system used in this study is Mamdani. There are 5 triangular fuzzy sets for input and output taken into account in the fuzzy system. The ranges of these fuzzy sets must be varied in accordance with the variation of output error in the related state. Input error is decomposed to three fuzzy sets expressed as Negative Big (NB), Negative Small (NS), Zero (ZE), Positive Small (PS) and Positive Big (PB). Output is a singleton function expressed as Very Small (VS), Small (S), Medium (M), Large (L) and Very Large (VL). Inference engine in the fuzzy system is completed by a set of IF-THEN rules in the form:

Rule 1: if error is NB then Γ is VS
Rule 2: if error is NS then Γ is S
Rule 3: if error is ZE then Γ is M
Rule 4: if error is PS then Γ is L
Rule 5: if error is PB then Γ is VL

The defuzzification of the output is accomplished by the method of centroid. The fuzzy adaptation law that used and in next section is compared with fixed gain is:

$$\dot{\hat{P}} = \Gamma_{fuzzy} W^T \hat{H}^{-T} Y \qquad (46)$$

IV. Simulation Results

A. Control design parameters

The numerical values and constant parameters used for the simulations, in SI units, are given here. All values have been normalized. Time has also been non dimensionalized.

m = 0.0358	I_z = 0.0022
$Y_{\dot{r}}$ = −0.00178	$Y_{\dot{v}}$ = −0.0343
Y_v = −0.1070	Y_{α_s} = 0.01241
$N_{\dot{r}}$ = −0.00047	$N_{\dot{v}}$ = −0.00178
N_v = −0.00769	N_{α_s} = −0.0047
x_G = 0.0014	Y_r = 0.01187
Y_{α_b} = 0.01241	N_r = −0.0039
N_{α_b} = 0.0035	

B. Feedback Linearization Control

The control objective is to track y_d = 2 sin(2t) when the initial condition for y is zero, and to track ψ_d= sin(2t) when the initial condition for ψ is ψ_0 = 30°. We have chosen λ= 5, since it requires minimum range of rudder deflection. This is important with respect to saturation of rudders which will be discussed shortly. System responses to disturbance are shown in Fig. 2 and Fig. 3.

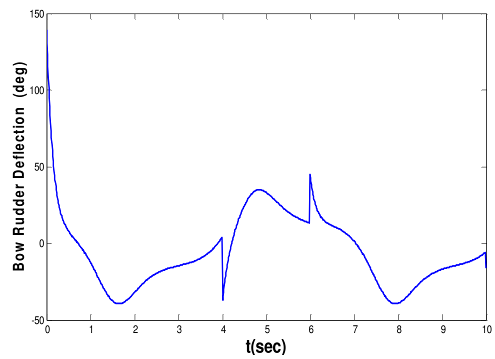

Fig. (2): Bow rudder deflection; feedback linearization approach

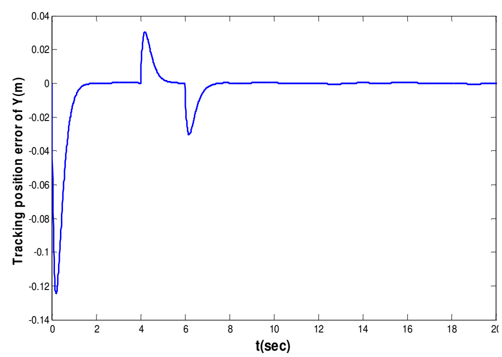

Fig. (3): Tracking error of y; feedback linearization approach

C. Adaptive Control

Numerous simulations were performed and it was concluded that a good compromise between control effort and a good response, can be achieved using the following design parameters

$$\phi_1 = \phi_2 = 100 \qquad (47)$$
$$\gamma_1 = \gamma_2 = \cdots = \gamma_8 = 0.002 \qquad (48)$$
$$\lambda_1 = 10 \qquad (49)$$
$$\lambda_2 = 15 \qquad (50)$$

Tracking error of ψ and y with Adaptive law are shown in Fig. 4 and Fig. 5, a careful observation reveals that its amplitude is decreasing with time. This slow rate of convergence is due to the small value of γ_i, which was inevitably chosen to avoid instability. Adaptive controller compared with feedback linearization approach in Fig. 6., clearly shows more convergence to zero and better trajectory tracking and less undershoot as shown in Fig.7, less stern and bow rudder deflection and better response for this adaptive controller with fixed gain.

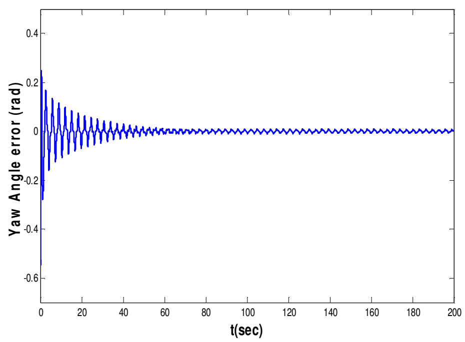

Fig. (4): Tracking error of ψ; Adaptive law

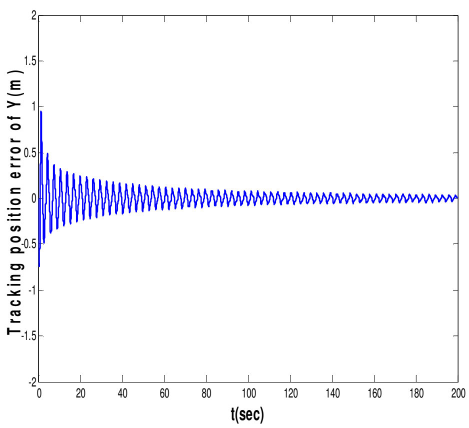

Fig. (5): Tracking error of y; Adaptive law

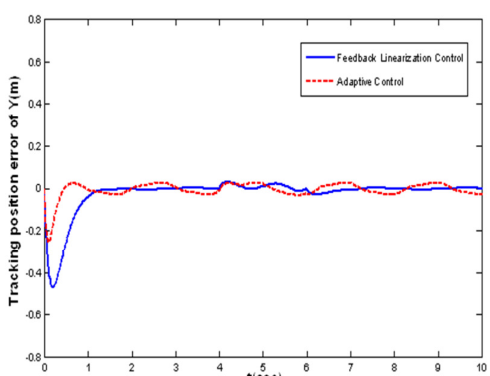

Fig. (6): Tracking position error comparison

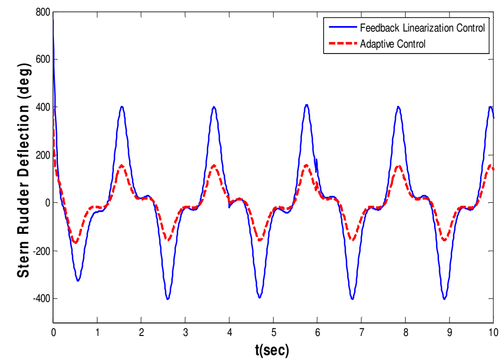

Fig. (7): Stern rudder deflection comparison

D. Adaptive law with fuzzy gain (Γ_{fuzzy})

In this section, some simulation results are provided to demonstrate the effectiveness of the proposed fuzzy gain control technique. Here, the main objective is to control horizontal motion of underwater vehicle by using fuzzy gain for Eq. (46) and compare it with the adaptive control with fixed gain and show the effectiveness of this approach as shown in Fig. 8 and Fig. 9 which results in stern rudder deflection illustrated in Fig. 10.

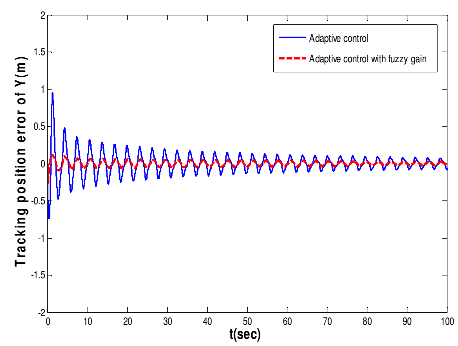

Fig. (8): Tracking position error comparison

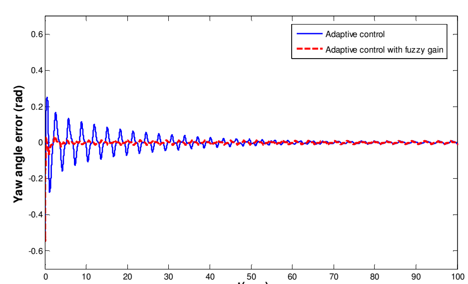

Fig. (9): Yaw angle error comparison

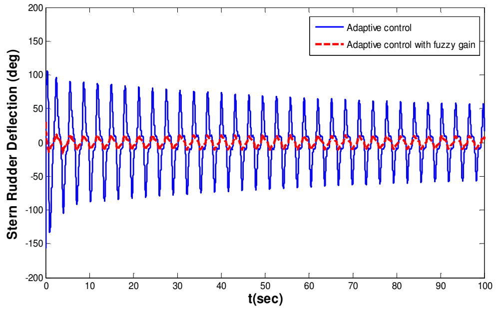

Fig. (10): Stern rudder deflection comparison

V. Conclusion

In this paper, a fuzzy adaptive control system has been addressed for AUVs. The proposed controller was shown to be suitable to compensate the ocean current disturbance and estimate unknown hydrodynamic coefficient with adaptive law. Adaptive controller with fuzzy gain has been effectively utilized to achieve better tracking performance than the case in which the gains are fixed. Simulation results show lower tracking error with shorter convergence time to zero. Moreover, the amplitudes of stern and bow rudder control signals are smaller in fuzzy adaptive controller than those in adaptive. These results show that the proposed controller effectively yields better performance than the case of fixed gains in adaptive rule. However, in this paper, we concentrated on the case of a vehicle workspace free of obstacles. In the future, more work will be done considering collision avoidance to improve the design.

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