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Robust Stabilization of an Autonomous Underwater Vehicle in Depth Channel by PID Interval Type-2 Fuzzy Controller

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Abstract: To stabilize the autonomous underwater vehicle (AUV) in the depth plane, an adaptive two-layer supervisory controller has been designed. The high nonlinearity, time-varying, and uncertain dynamics of this robot make its control a complex problem. With the aim of depth stabilization, the linear model of the vehicle in the XZ plane is decomposed into two inner and outer models to be controlled by a dual PID controller. In the second control layer two interval type-2 fuzzy controllers adjust PID coefficients adaptively to stabilize the depth position and pitch velocity of the vehicle. As the simulation results, this combined adaptive control method guarantees the robustness performance of the controlled system against the big model parameter perturbations and measurement disturbances. However, PID and PID type-1 fuzzy controllers in some senarios cannot stabilize the position of the robot in depth.

Keywords: Autonomous underwater vehicle, Robust control, PID controller, Interval type-2 fuzzy controller, supervisory control.

1. Introduction

Autonomous underwater vehicle, as one of the fundamental equipment in the marine industry, can accomplish exploring, mapping, and identification operations in deep waters independently of the human operator [1, 2]. At the same time, this system has nonlinear, time-varying dynamics and is always affected by the uncertain underwater environment [3, 4]. The uncertainty in the hydrodynamic forces has turned the precise determination of model parameters, tracking control, and stabilization of this system into a challenging concern. Subsequently, the resolution of such a challenge has received much attention from researchers in the field in recent years.

To realize the stability control of autonomous underwater vehicles, the control system must be robust against the uncertainty and parameter fluctuations of the robot model. It should also be self-adaptive against input disturbances, including environmental disturbance and measurement noise, as well as dynamic changes in the robot. Over the past few years, various control methods have been proposed by researchers in the field of classical control, such as linear controllers [5-7], sliding mode control [8], and predictive control [9, 10]. Intensive analysis of these methods exposed that the majority of linear control methods do not consider the high nonlinearity and time-varying nature of the robot. Although the sliding mode control is suitable for the nonlinear nature of robot dynamics, the existence of chattering in the system response and computational and executive complexity have made researchers fuse this technique with other intelligent methods to augment performance. The predictive control method supports smooth and small changes in certain parameters of the model. In the area of intelligent control methods, the use of neural networks [11-13] and fuzzy control [14-16] in robot control has been welcomed by researchers. The neural network method has several limitations such as long training time and slow convergence. The practical application of this method in heavy maneuvers faces undeniable difficulties. Despite the trouble-free implementation of the fuzzy control method and its extraordinary capabilities in addressing the uncertainty and nonlinear nature of the system, the constant coefficients and factors of this method lead to stability errors in resolving uncertainties and the high nonlinear and time-varying nature of the system. The necessity of adapting to uncertainties (uncertainty of model parameters and input disturbance) has led researchers to the type-2 fuzzy control method [15-18]. In the type-2 fuzzy control method, the uncertainty is described through vagueness. Consequently, this method has an exceptional competence to handle the uncertainties of the autonomous underwater vehicle system. Authors in [19] used the type-2 fuzzy method for online control of the robot during operation in an environment with a certain structure. Comparing the results with the type-1 fuzzy control method proved the appropriate performance of the control system by applying fewer rules. In the meantime, the PID controller has various advantages, such as robustness, proper performance in disturbance removal, and simple implementation and maintenance processes. Unlike time-independent linear systems, the proper performance of this controller is not guaranteed on non-linear systems. What's more, a major part of its design is finalized by trial and error [20]. In addition, the offline adjustment of the coefficients of this controller under model uncertainty can degrade the efficiency of the controller. Online adjustment of the coefficients of this controller is also associated with its difficulties. At the same time, combining this controller with intelligent control methods such as fuzzy control can lead to favorable results.

In this research, a nonlinear and time-varying model of autonomous underwater vehicles around the operational point is converted into a linear model by considering a few approximations. Then, a two-layer controller is designed for the robust control of the underwater vehicle in three channels of depth, pitch angle, and velocity of the robot in the longitudinal plane. This controller presents a mixture of the traditional classic PID control method and interval type-2 fuzzy control method in the form of a supervisory intelligent control method in two different layers. To stabilize the control system, the proportional-integral-derivative coefficients of the two PID controllers in the first layer for each of the sub-systems of the inner and outer loops of the longitudinal linear model of the robot are configured offline based on the Ziegler-Nichols method. With the aim of automatic and online adjustment of the initial coefficients of each PID controller under the uncertainty of model parameters caused by hydrodynamic coefficients, linearization approximations, and input disturbances, the interval type-2 fuzzy controller is designed in the second layer in a supervisory manner. If the PID controller performs poorly in providing stability, this controller automatically adjusts the controller coefficients. The robust stabilization performance of the proposed adaptive supervisory controller is compared with the PID controller and type-1 fuzzy PID supervisory controller through scenario design and simulation.

The rest of this article is organized as follows. The dynamics of the robot and the corresponding system model are explained in the second section. The third section focuses on the introduction of the controller and its structure. The results of simulation and robustness analysis are presented in the fourth section. Finally, the conclusion of the study is presented in the fifth section.

2. System dynamics and model [20]

The relocation of the autonomous underwater vehicle in a three-dimensional space in two coordinate systems, i.e. the independent ground coordinate system (x, y, z) and the body coordinate system (X, Y, Z) is described with six degrees of freedom including the linear velocities of surge, sway, heave, and the angular velocities of roll, pitch, and yaw represented by [r, q, p, w, v, u], respectively. The six degrees of freedom in ground coordinates are defined by the position and angles [x, y, z, φ, θ, ψ]. The dynamics of underwater vehicle is modeled by applying the Newton-Euler method based on Newton's second law and hydrodynamic and hydrostatic forces and torques. Such dynamics are described by differential Equations (1) as follows.

$$M\dot{v} + C(v)v + D(v) + G = \tau \qquad (1)$$

where $M_{6\times6}$ as positive definite and symmetric matrix represents the mass and inertia matrix, C(υ) is the Coriolis matrix and the centripetal force effects created by the added mass, D(υ) represents the hydrodynamic damping matrix, G is a 1×6 vector representing buoyancy and gravity forces, τ is the vector of control forces and external torques on the robot, and υ is the velocity vector. The matrix M is reflected in Equation (2).

$$M = \begin{bmatrix} m & 0 & 0 & 0 & mz_g & -my_g \\ 0 & m & 0 & -mz_g & 0 & mx_g \\ 0 & 0 & m & my_g & -mx_g & 0 \\ 0 & -mz_g & my_g & I_x & -I_{xy} & -I_{xz} \\ mz_g & 0 & -mx_g & -I_{xy} & I_y & -I_{yz} \\ -my_g & mx_g & 0 & -I_{xz} & -I_{yz} & I_z \end{bmatrix} \tag{2}$$

The linear form of the hydrodynamic damping matrix and vector G are defined in Equations (3) and (4), respectively.

$$D(v) = \begin{bmatrix} X_u & X_v & X_w & X_p & X_q & X_r \\ Y_u & Y_v & Y_w & Y_p & Y_q & Y_r \\ Z_u & Z_v & Z_w & Z_p & Z_q & Z_r \\ K_u & K_v & K_w & K_p & K_q & K_r \\ M_u & M_v & M_w & M_p & M_q & M_r \\ N_u & N_v & N_w & N_p & N_q & N_r \end{bmatrix} \tag{3}$$

where K is the rolling moment, M is pitching moment, and N represents the yawing moment.

$$G = \begin{bmatrix} (B-W)\sin\theta \\ -(B-W)\sin\phi\cos\theta \\ -(B-W)\cos\phi\cos\theta \\ B\cos\theta(z_B\sin\phi - y_B\cos\phi) \\ B(x_B\cos\phi\cos\theta + z_B\sin\theta) \\ -B(x_B\sin\phi\cos\theta + y_B\sin\theta) \end{bmatrix} \tag{4}$$

where B and W represent the buoyancy and weight of the robot immersed in water, respectively. Subsequently, the matrix C(v) models the centripetal force and Corellius based on Equation (5).

$$C = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ -m(y_g p_y + z_g p_z) & m(y_g p_x + w) & a_1 \\ m(x_g p_y - w) & -m(z_g p_z + x_g p_x) & a_2 \\ m(x_g p_z - v) & m(x_g p_y - u) & a_3 \\ m(y_g p_y + z_g p_z) & -m(x_g p_y - w) & a_4 \\ -m(y_g p_x + w) & m(z_g p_z + x_g p_x) & a_5 \\ -m(z_g p_x - v) & -m(z_g p_y + u) & a_6 \\ 0 & -I_{yz} p_y - I_{xz} p_x + I_z p_z & a_7 \\ I_{yz} p_y + I_{xz} p_x - I_z p_z & 0 & a_8 \\ -I_{yz} p_z - I_y p_x - I_y p_y & I_{xz} p_y + I_{xy} p_y - I_x p_x & 0 \end{bmatrix} \tag{5}$$

where $a_1 = m(z_g p_x - v)$, $a_2 = m(z_g p_y + u)$, $a_3 = -m(x_g p_x + y_g p_y)$, $a_4 = -m(x_g p_z + v)$, $a_5 = -m(y_g p_z - u)$, $a_6 = m(x_g p_z - u)$, $a_7 = I_{xy} p_z + I_{xy} p_x - I_y p_y$, and $a_8 = -I_{xz} p_z - I_{xy} p_y + I_x p_x$. Also, $\left[p_x, p_y, p_z\right]$ indicates angular velocities.

1.2. Longitudinal model of autonomous underwater vehicle

Due to the complexity of robot dynamics as well as the focus on depth control and pitch angle, the system model is considered in the vertical plane (longitudinal subsystem). Based on the assumptions made in [21], the dynamic equations of the robot in the depth plane are simplified and described based on the surge velocity (u), heave velocity (w), pitch angular velocity (q), ground coordinate system parameters, position (x), depth (z), and pitch angle (θ). The depth dynamics of the underwater vehicle can be expressed in the form of a longitudinal model such thatthe pitch angle is its control. . Then the longitudinal model is linearized around the operational point and expressed in the matrix form of Equation (6). The operational point of the robot is formed as follows [5].

$$\begin{bmatrix} u=1.54,\ v=0,\ w=0,\ p=0,\ q=0, \\ r=0,\ x\ y\ z\ =0,\ \theta=0,\ \varphi=0 \end{bmatrix} \quad (6)$$

$$\begin{bmatrix} \dot{q} \\ \dot{z} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \frac{M_q}{I_{yy}-M_{\dot{q}}} & 0 & \frac{M_\theta}{I_{yy}-M_{\dot{q}}} \\ 0 & 0 & -U \\ 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} q \\ z \\ \theta \end{bmatrix} + \begin{bmatrix} \frac{M_{\delta_s}}{I_{yy}-M_{\dot{q}}} \\ 0 \\ 0 \end{bmatrix} [\delta_s]$$

where δs represents the deflection angle of the fin in the control plane of the rear rudder angle of the vehicle [21].

3. Control method

The movement of the autonomous underwater vehicle in the depth plane is realized by controlling the deflection of the rudder fins. This study discusses three control methods, namely PID, adaptive PID type-1, and adaptive PID type-2 control methods to adjust the fin angle and control the depth and pitch angle.

3.1 Depth and position control using PID controller

Four factors including heave w(t), pitch velocity q(t), pitch velocity θ(t), and depth z(t) are variables affecting the depth and position control of the robot, which are adjusted by controlling the angle of the fins and herringbone sides. Setting the position and pitch velocity are ignored. Instead, two state variables θ and z are considered. The control structure of the linear system using Equation (6) can be composed of two nested inner and outer control loops, respectively pich controller and depth controller. In this method, the pitch angle reference input is set by the outer control loop. Also, the inner pitch control loop controls the fin angle. An overview of this control system is represented in Figure (1).

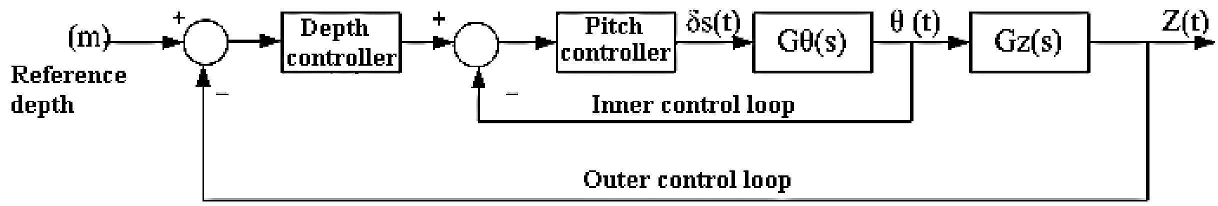


Figure (1): Block diagram of the depth control system

The transfer function of inner system is expressed in the form of Equation (7).

$$G_\theta(s) = \frac{\theta(S)}{\delta_s(s)} = \frac{\frac{M_{\delta_s}}{I_{yy}-M_{\dot{q}}}}{s^2 - \frac{M_q}{I_{yy}-M_{\dot{q}}}s - \frac{M_\theta}{I_{yy}-M_{\dot{q}}}} \quad (7)$$

Also, the transfer function of outer system is developed in the form of Equation (8).

$$G_z(s) = \frac{Z(s)}{\theta(s)} = -\frac{U}{S} \quad (8)$$

The inner systemhas a right side zero and is not a minimum-phase. To stabilize the inner system and achive a good performance PID controller is designed using the traditional Ziegler-Nichols method. Note, the time constant of inner control loop should be lower than the outer control loop. Simultaneusely, the coefficients of the PID controller in the outer loop is set.

dePID controller is designed ofline, so in online operationg condition, the performance of this controller may be disturbed due to the change in model parameters, system uncertainty, and measurement disturbances. To guarantee the stability, online adjustement of the controller coefficients according to the new conditions is necessary in the design stage.

3.2 Interval type-2 fuzzy controller

In this study, the interval type-2 Takagi-Sugeno fuzzy controller is embedded in the second layer of the proposed controller. In such a fuzzy system, the first part of of each rule, represent a uncertain variable based on fuzzy sets. However, the consequent part is crisp. The structure of a type-2 fuzzy system consists of at least four main parts, including fuzzification, if-then rule base, fuzzy type-reducer, and de-fuzzification. This structure is represented in Figure (2).

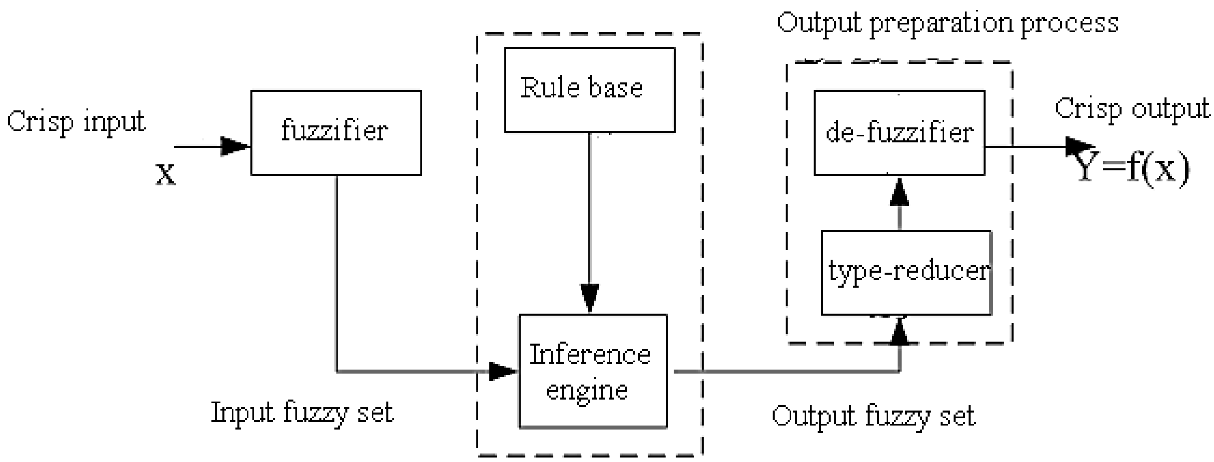


Figure (2): The structure of a type-2 fuzzy system

The fuzzification step determines the highest and lowest membership functions of the input linguistic variables of the system. In this study, normal interval type-2 triangular membership functions are used, which are similar to fuzzy type-1 membership functions, with the difference that the degree of membership of each linguistic variable is not unique. The degree of membership can take values limited to an upper bound and a lower bound. In this way, the effect of uncertainty is considered in the description of fuzzy sets. This leads to better handling of model uncertainties. Figure 3 shows the fuzzy type-1 and fuzzy type-2 triangular membership functions.

The other parts of the type-2 fuzzy system structure are similar to the type-1 fuzzy system, with one difference being the output of the type-2 fuzzy system includes the fuzzy type-reducing component. This reducer reduces type-2 fuzzy sets in the output to type-1 fuzzy sets so that a crisp output is obtained in the de-fuzzification of the system.

3.3 Two-layer supervisory PID interval type-2 fuzzy controller

Despite the favorable performance in disturbance handling and simplicity of implementation, the nonlinear behavior of the system, the uncertainties of the model parameters, and the input disturbances make the PID controller not guarantee the occurrence of a robust behavior in the closed-loop control system. As a result, it is necessary to reset the proportional-derivative-integral coefficients of the controller. Off course, intelligent and accurate adjustment of these coefficients has its difficulties because the control output is strongly influenced by these coefficients. According to the inherent system characteristics and operating environment of an autonomous underwater vehicle, in this study, a two-layer supervisory controller with the ability to adapt to the longitudinal plane has been designed to control depth and pitch angle.

To achieve stabilization, a dual PID controller is designed in two nested loops of pitch inner and depth outer based on the Ziegler-Nichols method as the first control layer. Then a supervisory interval type-2 fuzzy control system is designed in the upper control layer. If any designed PID controllers cannot satisfy the stability of the system and a gross error is imposed on the depth output and the reference pitch angle, the type-2 fuzzy controller modifies PID coefficeints according tothe error (e(t)) and the error derivative ($\dot{e}(t)$). If the error reaches zero, supervisory control is stop. So in this control structure the first layer guarantees stability. The proposed control is formulated in the form of Equation (10).

$$u(t)=(k_P^0(t)+\Delta k_P)e(t)+(k_I^0(t)+\Delta k_I)\int_0^t e(\tau)d\tau + (k_D^0(t)+\Delta k_D)\frac{de(t)}{dt} \quad (10)$$

where k_P^0, k_I^0 and, k_D^0 are the PID controller gain calculated in the first layer of the proposed control system. The terms Δk_P, Δk_I, Δk_D, and the output of the interval type-2 fuzzy system. Figure (3) represents the diagram of the proposed control system.

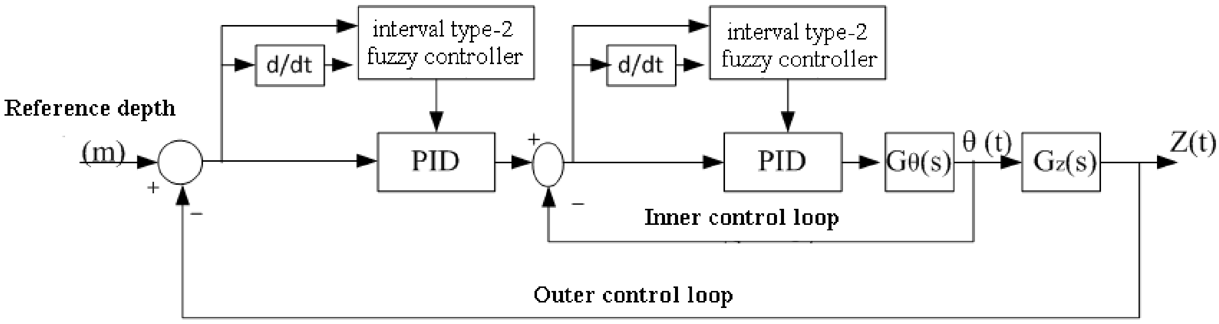


Figure (3): Proposed supervisory control system

In the design of the fuzzifier component of the interval type-2 fuzzy control system, the uncertainty in the error input variables and the error derivative is expressed with 7 fuzzy sets PB, PM, PS, ZO, NS, NM, and NB. In addition, the parameters kP, kI, and kD are defined as outputs of the fuzzy system individually in the form of seven values PB, PM, PS, ZO, NS, NM, and NB. An example of a Takagi-Sugno type-2 fuzzy if-then rules is defined in the form of Equation (10) where Ri denotes the i^{th} rule. Ai is a fuzzy set to introduce the linguistic variable and Ci expresses the crisp output parameter.

$$R_i\text{: If (e is } A_1\text{) and (}\dot{e}(t)\text{ is } A_j\text{) Then } u_i=C_i \quad (10)$$

Table (1) reflects the fuzzy rules of proportional gain adjustment.

Table (1): Fuzzy rules corresponding to proportional gain adjustment

e / $\dot{e}(t)$	*NB*	*NM*	*NS*	*Z*	*PS*	*PM*	*PB*
NB	*PB*	*PB*	*PM*	*PM*	*PS*	*PS*	*Z*
NM	*PB*	*PB*	*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*	*NB*
PB	*Z*	*NS*	*NS*	*NM*	*NM*	*NB*	*NB*

In the designed fuzzy control system, t-norm multiplication and algebraic mean are used to calculate the intersection and union of fuzzy sets, respectively.

4. Simulation

To evaluate the proposed controller in realizing robust stability of motion in the depth plane under system uncertainty and input disturbance, the system model of the REMUS-100 robot with two inner and outer control loops has been simulated in the MATLAB Simulink platform. The behavior of the PID controller, PID type-1 fuzzy, and PID fuzzy type-2 under the measurement noise and parametric deviation of the outer control loop system will be compared in different scenarios. It is assumed that in all simulations, the movement of the robot starts from zero depth and reaches a depth of one meter. In the first scenario, the stability performance of the robot in the longitudinal plane is investigated under normal operating conditions. The second scenario compares the control results of the three mentioned controllers under the parametric uncertainty of the model and the pole instability of the outer control closed-loop system. The third scenario discusses the effect of input disturbance on the depth stability of the robot with three controllers. It is worth noting that in all the plots, the dotted line, dashed line, and bold line represent the result of the PID controller, fuzzy type-1 PID controller, and fuzzy type-2 PID controller.

4.1 First scenario: Robot depth control in normal conditions

The state space model of autonomous underwater vehicles is formulated based on laboratory data [6] in the form of Equation (11).

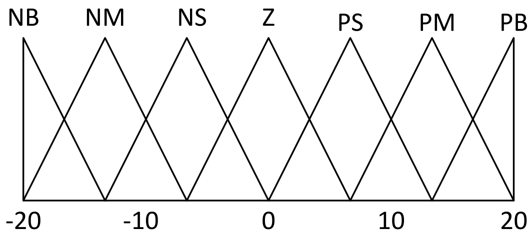
$$\begin{bmatrix} \dot{q} \\ \dot{z} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} -0.82 & 0 & -0.96 \\ 0 & 0 & -1.54 \\ 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} q \\ z \\ \theta \end{bmatrix} + \begin{bmatrix} -4.16 \\ 0 \\ 0 \end{bmatrix} \delta_s \tag{11}$$

The transfer functions of inner and outer control closed-loop subsystems are expressed in Relations (12) and (13), respectively.

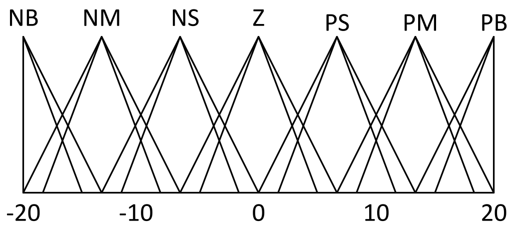
$$G_\theta(s) = \frac{\theta(s)}{\delta_s(s)} = \frac{-4.16}{s^2 + 0.82s + 0.96} \tag{12}$$

$$G_z(s) = \frac{z(s)}{\theta(s)} = \frac{-1.54}{s} \tag{13}$$

The control gains of the PID controller and the values of the membership functions in the design of the fuzzy system are presented in Table (2). For example, Figures (4.a) and (4.b) reflect the error input membership functions in type-1 fuzzy and type-2 fuzzy, respectively.



4.(a)



4.(b)

Figure (4): a) error input membership functions in type 1 fuzzy, b) error input membership functions in type-2 fuzzy

Table (2): Values of input/output membership functions and PID gains

Parameter name	ϴ	Z
E	[-25 25]	[-20 20]
Ec	[-5 5]	[-5 5]
Δk_P	[-3 3]	[-0.885 0.885]
Δk_I	[-0.06 0.06]	-
Δk_D	[-4 4]	-
k_P^0	-6	-0.28
k_I^0	-0.01	-
k_D^0	-1	-

The results obtained in normal conditions show that the efficiency of controllers in creating depth stability is favorable. Figure (4) reflects the changing state of depth over time. In addition, pitch angle control with the aim of depth stability is represented in Figure (5). The type 1 fuzzy PID controller with less drift has brought the pitch angle of the robot to the desired depth, but it has a longer settling time. Depth control in type-2 fuzzy PID system has been done in less settling time due to the flexible definition of coefficients.

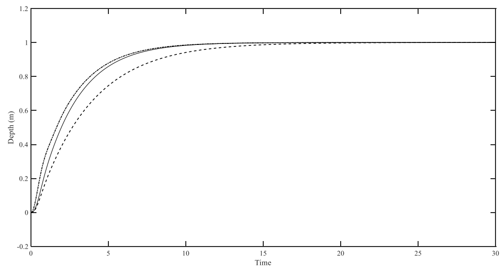


Figure (4): Depth control in normal conditions

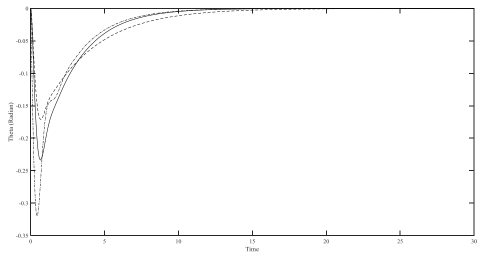


Figure (5): Pitch control in normal conditions

4.2 The second scenario: addressing parametric uncertainty

Applying some assumptions to simplify the model under uncertainty in hydrodynamic coefficients leads to imposing parametric uncertainty in the system model. In this scenario, it is assumed that the parametric uncertainty leads to the instability of the system poles in the transfer function of the outer control loop. The poles of the depth transfer function are moved from the values of -0.41±0.7224 to the values of 2.749 and 0.251 and the transfer function is changed to Equation (14).

$$G_\theta(s) = \frac{\theta(s)}{\delta_s(s)} = \frac{-4.16}{s^2 - 3s + 0.69} \quad (14)$$

How to stabilize the robot at a depth of 1 meter is reflected in Figure0 (6). As shown in the figure, the transient response of the robot under large uncertainty of depth control using PID control is associated with large fluctuations. The reason is the fixed gain of the controller and the inability to adapt this type of controller. The settling time of the supervisory type-1 fuzzy controller of depth control is more than the proposed controller. Taken together, all three controllers can finally achieve depth stability. Figure (7) shows the changes in the pitch angle under parametric collapse. The response of the PID controller regarding drifts and fluctuations is the worst. The response of the proposed controller enters the settling band in a faster time and becomes stable. In this way, the performance of the proposed controller is more suitable for handling relatively large uncertainties.

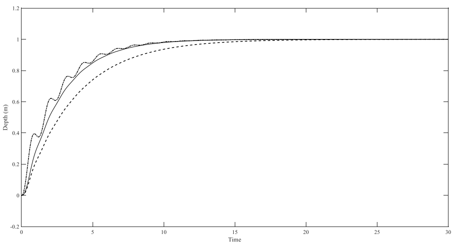


Figure (6): Depth control under parametric uncertainty

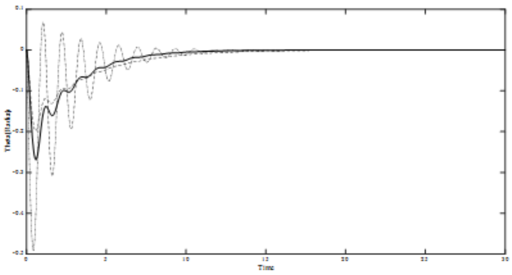


Figure (7): Pitch angle control under parametric uncertainty

When due to the parametric collapse of the model, the poles of the system are placed at 0.3 and 3.2 and the transfer function is converted into Relation (15), the control performance of all three controllers in the field of depth control is expressed in the form of Figure (8).

$$G_\theta(s) = \frac{\theta(s)}{\delta_s(s)} = \frac{-4.16}{s^2 - 3.5s + 0.69} \qquad (15)$$

As shown in Figure (8), the PID controller is not able to stabilize the depth control closed-loop system. The supervisory two-layer type-1 fuzzy controller also placed the depth of the robot in the Lyapunov stable state. However, the proposed controller has placed the robot at a depth of 1 m in Lyapunov's stable state (with a tolerable approximation) under uncertainty.

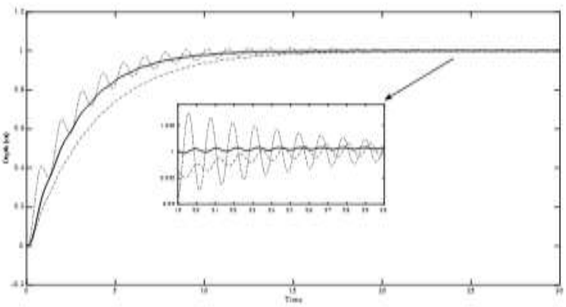


Figure (8): Robot depth control under large uncertainty

As shown in Figure (9), despite the large deviation in the model parameters, the PID controller and the supervisory two-layer type-1 fuzzy controller have been able to stabilize the pitch angle of the robot in the Lyapunov form. Adjustment of the coefficients of each controller has been realized offline. Also, the online conditions of the main operating system of this controller behavior have not been applied. However, the proposed controller can robustly realize pitch stabilization.

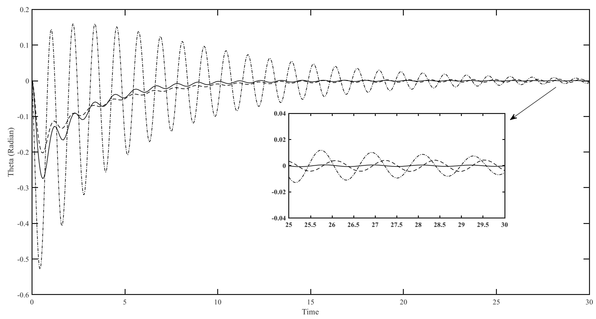


Figure (9): Robot pitch control under large uncertainty

4.3 The third scenario: addressing disturbance

The way to realize the robot's depth stability is represented in Figure (10). As reflected in the figure, using the PID controller and PID type-1 fuzzy controller, the stability of the immersion height of the robot is accompanied by chattering. The final height of the robot fluctuates within a certain range. However, due to the autonomous adaptation capability and dual uncertainty description, the proposed controller has a good performance in-depth control.

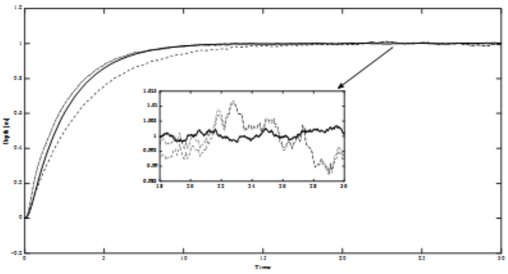


Figure (10): Depth control under disturbance of measurement noise

5. Conclusion

In this study, a supervisory two-layer controller with autonomous adaptation capability is proposed to control the depth and pitch of an autonomous underwater vehicle in the longitudinal plane. First, the closed-loop control system is described in the form of two inner and outer control subsystems. Subsequently, to ensure the stability and disturbance resistance, PID controller based on the Ziegler-Nichols method is designed as the first layer of the proposed controller. In the second layer, an interval fuzzy type-2 supervisory system is used to automatically adjust the control gains in the first layer during control inefficiency. The proposed controller adapt the PID coefficeints based on the values of error and the error changes to achieve a robustness performance. The stabilization performance of the proposed controller was evaluated in the form of three scenarios by simulation in the MATLAB platform. The control results obtained from PID control, PID type-1 fuzzy, and PID type-2 fuzzy were compared. The simulation results showed that the designed PID controller is not adaptable to abnormal operating conditions. The flexibility and self-adaptation of the fuzzy type-1 PID controller depend on the knowledge of the expert. In addition, the range of each of the membership functions and rules in the design of the fuzzy system are fixed. The level of flexibility and self-adaptation in the proposed controller is much higher and its robust performance has been proven. Although other controllers tend to instability in boundary conditions, the proposed controller has robust stability in the face of input disturbance and uncertainty of system parameters. In addition, as soon as the proposed control is applied in the normal operation state of the robot, the pitch angle fluctuation is reduced.

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