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Research Article

Research on the Control Performance of Depth-Fixed Motion of Underwater Vehicle Based on Fuzzy-PID

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The control performance of the fixed-depth motion is related to the performance of the underwater vehicle. Due to the complex and changing environment underwater and various potential risks, the variety of underwater operations, and the variability of the structural parameters and environmental parameters of the underwater vehicle, the control performance is compromised when performing constant depth motion. It is of much significance to study the control method of the fixed-depth motion to improve the performance of the underwater vehicle. The transfer function of underwater vehicle's depth-setting motion was established, and the fuzzy-PID controller was established for simulating the control of depth-setting movements of underwater vehicles. The interaction law between PID initial parameters and controller performance was studied, and the interaction law between the change of underwater vehicle mass and the hydrodynamic coefficient and controller performance was also studied. The results show that the fuzzy-PID controller can realize the control of the underwater vehicle's depth-setting motion, and the control effect was independent of the initial PID parameters, thus avoiding the dependence of the formulation of PID parameters on manual control experience. When the mass and hydrodynamic coefficient of the underwater vehicle change, the fuzzy-PID controller can still maintain good control performance and has strong adaptive ability.

1. Introduction

PID control is a common motion control method for underwater vehicle. The control effect of the PID controller depends on PID parameters. The formulation of PID parameters is highly dependent on manual control experience, so researchers usually use the trial and error method to obtain PID parameters, and the acquisition process is relatively repeated. After determining its parameters, the system cannot respond to the changes of parameters [1]. Once the environment and structure parameters change, the control model parameters change accordingly, and the PID control performance will be affected to a certain extent [2]. Therefore, it is necessary to find the PID control parameters again. Due to the difference of the underwater vehicle operation, the mass of the underwater vehicle changes frequently during the operation. At the same time, in the process of underwater vehicle movement, the change of the motion state will result in the change of the hydrodynamic coefficient. To ensure the motion control capability of the underwater vehicle, the PID parameters need to be adjusted in real time. With the development of industry, the demand for underwater environment detection and underwater resources development is increasing day by day, and the demand for underwater vehicle control technology is also increasing. The combination of PID control and fuzzy control methods can improve the adaptive performance of an underwater vehicle to the hydrodynamic coefficient and its own mass change and reduce the dependence of PID control parameters on manual control experience. Fuzzy reasoning is a kind of control thought which simulates the process of thinking and judging fuzzy things. The advantage of the control method lies in the low dependence on the mathematical model of the system, and the fuzzy rules are formulated according to the characteristics of the control object, so as to constantly adjust the parameters of the control system to achieve the ideal control purpose. Fuzzy control has a high adaptive capacity; combining fuzzy control with other control methods to engineer the controller, the control effect of the control system will be significantly improved; especially in the nonlinear and time-varying system, control achieved better results [3]. Because of the superior performance of fuzzy control, the fuzzy control method has been widely used in industrial production and intelligent manufacturing industry.

In order to adapt to the changes of the structure parameters of the underwater vehicle and the uncertain factors of fluid environment, the fuzzy-PID controller was designed. The PID parameters are adjusted in real time by fuzzy rules, and the control parameters can adapt to the changes of the system in real time, which could improve the control precision and stability of the fixed-depth motion system [4].

The fuzzy-PID control system realizes the real-time tuning of PID control parameters by fuzzy logic reasoning and obtains PID control parameters more suitable for system characteristics, which makes the control system achieve ideal control performance [5]. Zhang et al. aimed at the problem of motion unsynchronization caused by external disturbance in the two-axis synchronous servo system of the tracked vehicle, fuzzy-PID control in the variable theory domain was adopted to improve the synchronization control accuracy. Compared with traditional PID, this method allows for real-time adjustment of parameters as external conditions change and improve the adaptability of the system [6]. Divijesh et al. developed a PID control system for the active vibration isolation device based on the flexible amplification piezoelectric actuator. The forward Bouc–Wen hysteresis model was used to model and estimate the voltage used for FAPs hysteresis compensation. The active vibration isolation experiment of the control system was realized and the percentage of the vibration isolation error was estimated [7]. Lin and Wang builded a heading control model of a certain type of a underwater vehicle and designed a fuzzy controller for the model that can improve the control performance of the integral link. The proposed controller can improve the complex coupling between the degrees of freedom, the instability of the water environment, and the heading control of the nonlinear motion of the underwater vehicle, and underwater vehicle simulation demonstrates that the controller has good robustness and high control accuracy [8]. Yan et al. analyzed the fuzzy adaptive control principle developed by using the identification structure, and combined with the identification model, a set of the adaptive fuzzy-PID algorithm was obtained through calculation. Simulation performance indicates that the proposed algorithm was more stable, adaptable and robust than the PID algorithm [9]. The fuzzy PD-PI controller designed by Yanhui and Zhang has a good promotion effect on various indicators in the process of underwater vehicle turning [10]. Yoerger and Slotine proposed a depth control method combining fuzzy-PID with dynamic compensation. Fuzzy rules were used to adjust PID control parameters online. The designed controller had a good simulation effect and overshoot was less than 10% [11].

2. Modeling of Fixed Depth Motion

Underwater vehicles need to complete translation, rotation, yaw, and other actions when performing underwater operations. In order to facilitate the analysis of mechanical characteristics of underwater vehicles, it is necessary to establish a fixed coordinate system based on earth and a motion coordinate system based on underwater vehicles [12].

In Figure 1, $E-\xi\eta\zeta$ is a fixed coordinate system, which generally takes a point on the earth or water as the origin of coordinates. $O-\mathrm{xyz}$ is the motion coordinate system, the origin O is usually set as the initial position of the center of gravity of the underwater vehicle, so make the Oxy axis directed to the direction of bow movement of the underwater vehicle, make the Oy axis to the point in the right wing of the underwater vehicle, and make the Oz axis to the point in to the earth perpendicular to the line between the head and tail.

The force expression of the underwater vehicle in the motion coordinate system $O\text{-}xyz$ is the space motion equation of the underwater vehicle.

$$
\begin{aligned}
X &= m\left[\dot{u} - vr + wq - x_G\left(q^2 + r^2\right) + y_G\left(pq - \dot{r}\right) + z_G\left(\mathrm{pr} + \dot{q}\right)\right],\\
Y &= m\left[\dot{v} - wp + ur - y_G\left(r^2 + p^2\right) + z_G\left(qr - \dot{p}\right) + x_G\left(pq + \dot{r}\right)\right].
\end{aligned}
\tag{1}
$$

$$
Z = m\left[\dot{w} - uq + vp - z_G\left(p^2 + q^2\right) + x_G\left(rp - \dot{q}\right) + y_G\left(qr + \dot{p}\right)\right].
\tag{2}
$$

In the above equations, X, Y, and Z are the forces of the underwater vehicle on x-axis, y-axis, and z-axis, respectively. m is the mass of the underwater vehicle; u, v, and w are the velocity of the underwater vehicle along the Ox, Oy, and Oz axes; p, q, and r are the angular velocity of the underwater vehicle along the Ox, Oy, and Oz axes, and x_G, y_G, *and* z_G are the center of the gravity position of the underwater vehicle.

The force of the underwater vehicle in the vertical direction is obtained as follows:

$$
Z = Z_E + Z_I + Z_N + T_P,
\tag{3}
$$

where Z_E is the static force received by the underwater vehicle during movement, namely, the vector sum of gravity and buoyancy; Z_I is the inertial hydrodynamic force; Z_N is the viscous hydrodynamic force; and T_P is the thruster's thrust.

In conjunction with equations (2) and (3), the equation of fixed-depth motion can be simplified from the

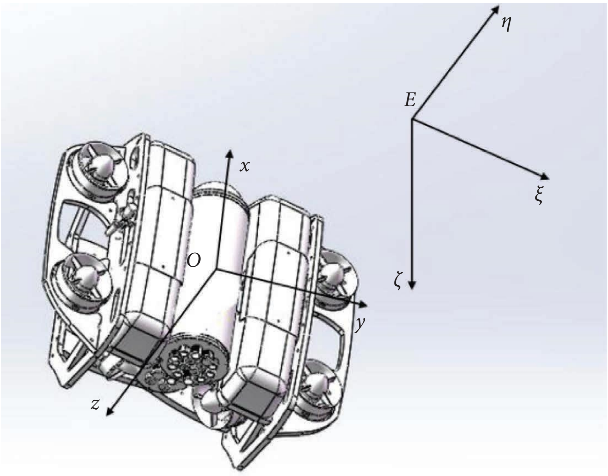

Figure 1: Relative coordinate system of a underwater vehicle.

relationship between space force and hydrodynamic force as follows:

$$(m - Z_{\dot{w}})\dot{w} = T_{zi} + Z_{\dot{w}}\dot{w} + Z_w w + Z_{|w|}|w| + Z_w|w|Z_{ww}w^2, \tag{4}$$

where m is the mass of underwater vehicle, $Z_{\dot{w}}$ andZ_w are transverse and vertical hydrodynamic coefficients, respectively, and T_{zi} is thruster thrust.

The depth-fixing motion of the underwater vehicle is vertical, and the motion action other than the vertical direction is not considered, that is, $u = \dot{u} = v = \dot{v} = p = \dot{p} = q = \dot{q} = r = \dot{r} = 0,\ \theta = 0$ The force equation of constant depth motion is as follows:

$$T_P = (m - Z_{\dot{w}})\dot{w} - Z_w w. \tag{5}$$

Ignoring the dimensionless viscous hydrodynamic term, the Laplace transform is applied to the above equation, and the transfer function between the motion depth of the underwater vehicle and the thrust of the propeller is obtained as follows:

$$\begin{aligned} H(s) &= \frac{\zeta(s)}{T_P(s)} \\ &= \frac{1}{(m - Z_{\dot{w}})s^2 - Z_w s}. \end{aligned} \tag{6}$$

The propeller of underwater vehicle is a cylindrical propeller. The number and position of propeller determine the driving performance of the underwater vehicle. The calculation formula of propeller thrust is

$$T = \rho n^2 D^4 K_T, \tag{7}$$

where ρ is the fluid density, n is the propeller speed (r/s), D is the propeller diameter, and K_T is the thrust coefficient.

According to the expression of thrust, the relationship between thrust and rotational speed is nonlinear. The propeller equation is linearized with small deviation, and the propeller linearization equation is obtained as follows:

$$T = Cn - c. \tag{8}$$

Among them, $C = 2K_T\rho D^4 n_0, c = K_T\rho D^4 {n_0}^2$. Then, the propeller transfer function is obtained as follows:

$$T(s) = C. \tag{9}$$

According to equations (6) and (9), the transfer function of fixed-depth motion control can be obtained as follows:

$$\begin{aligned} G(s) &= H(s)T(s) \\ &= \frac{C}{(m - Z_{\dot{w}})s^2 - Z_w s}. \end{aligned} \tag{10}$$

3. Design of Fuzzy-PID Controller

3.1. Fuzzy-PID Control Principle. Fuzzy control is an intelligent control method for a nonlinear system. Fuzzy reasoning generally has the following processes: fuzzifying the input and output of the system, designing the number of fuzzy languages and naming fuzzy languages; formulating fuzzy rules according to the characteristics of the control system; and refining the fuzzy rules[13]. The sampling value of the fuzzy reasoning system is generally a continuous real number, and the calculated value of the control system is a discrete value when the input and output are analyzed to obtain the modified value. Therefore, the quantization factor k_e andk_{ec} and scale factor k_u are usually introduced into the fuzzy control in the working process to achieve the consistent form of the sampled data and the calculated data for data conversion.

The fuzzy-PID control method not only has the characteristics of rapid response of PID control but also embodies the excellent performance of strong robustness in the ability to adjust parameters online [14]. Taking a certain type of an underwater vehicle as the research object, the fuzzy-PID control model of depth-fixing motion for underwater vehicle is established. The steady-state performance of fuzzy-PID is verified by simulation, and the effects of environmental and structural parameters on the control performance are studied.

The architecture of the fuzzy-PID controller consists of fuzzy logic inference and a PID controller [15]. The composition of the fuzzy-PID system is given in Figure 2. The fuzzy controller obtains the system error E and the error change rate EC by sampling as the input of the fuzzy controller. The adjustment value obtained $\Delta k_p, \Delta k_i, \Delta k_d$ by analyzing sampling data k_p, k_i, k_d is output to the PID controller through formulated fuzzy rules to realize real-time tuning of PID control parameters. Thus, this improves the adaptive ability to control system changes [16].

The parameter k_p, k_i, k_d adjustment equation of the fuzzy-PID control system is as follows:

$$\begin{aligned} k_p &= k_{p0} + \Delta k_p, \\ k_i &= k_{i0} + \Delta k_i, \\ k_d &= k_{d0} + \Delta k_d. \end{aligned} \tag{11}$$

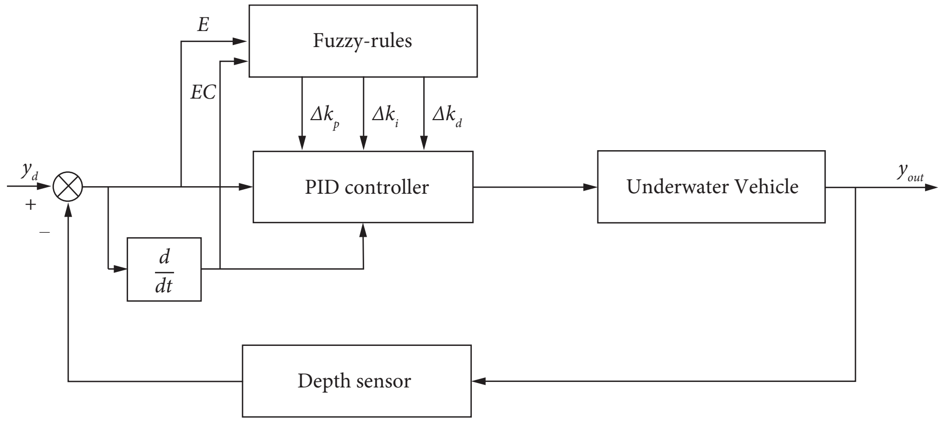

Figure 2: Fuzzy-PID control schematic diagram.

3.2. Fuzzy Rules. The number of language variables determines the accuracy of fuzzy reasoning, and the more the number of language variables, the higher the accuracy of fuzzy reasoning [17]. However, setting too many language variables will lead to the consistency of fuzzy rules, complicated operation, increased workload, increased memory consumption, and editing difficulties. In the design of fuzzy-PID controller, five language variables are defined: NB (negative large), NS (negative small), ZE (zero), PS (positive small), and PB (positive big). In the formulation of fuzzy rules, it is necessary to determine the permutation function state of fuzzy rules. Membership functions of the fuzzy regular permutation state have various forms [18]. The design performance of the triangle membership function is only related to the triangle slope, which reduces the complexity of the operation. In the designing of the fuzzy controller, the membership function of the fuzzy input and output chooses the triangle shape, the shape of the trigonometric affiliation function is shown in Figures 3 and 4.

Set the fuzzy set theory domain of bias E and EC as follows:

$$E, \mathrm{EC} = [\,-6 \;\; 6\,]. \tag{12}$$

The fuzzy set theory domain of parameters $\Delta k_p, \Delta k_i, \Delta k_d$ adjustment is

$$\Delta k_p, \Delta k_i, \Delta k_d = [\,2 \;\; 5\,]. \tag{13}$$

The Madani fuzzy inference rule is used as fuzzy inference rule [19], as shown in Tables 1, 2, and 3. By analyzing the sampling signal, the fuzzy controller calculates the PID parameter setting value $\Delta k_p, \Delta k_i, \text{and} \Delta k_d$ as discrete value and defuzzies the discrete data into continuous data through the defuzzification process. The principle of barycenter method is to get the output variables of the fuzzy controller by weighting and averaging the values of language variables in fuzzy control rules and get the integral quantity of PID parameters.

4. Controller Performance Simulation

4.1. Simulation Model. The propeller specifications of the underwater vehicle are shown in Table 4:

The propeller thrust coefficient is related to the pitch ratio [20], the thrust coefficient $K_T = 0.2$, and fluid density $\rho = 1.0 \times 10^3 kg/m^3$; insert propeller blade diameter and rotational speed into the thrust expression formula (9), then $C = 0.8$. In [21], the relevant hydrodynamic coefficients are $Z_{\dot{w}} = -1.42$ and $Z_w = -0.17$, and the transfer function of fixed-depth motion can be obtained according to equation (10).

$$G(s) = \frac{0.8}{16.42s^2 + 0.17s}. \tag{14}$$

4.2. Simulation Study. Figure 5 shows the simulation model of underwater vehicle's deep-setting motion control, the system input is step signal, and the step value is 1. The fuzzy inference inputs PID parameter adjustment value into the PID controller through fuzzy rules, so as to obtain the PID parameters after setting, and control simulation is carried out on the depth fixing motion model.

To achieve the deep-setting motion control of underwater vehicle and avoid the dependence of PID parameters on manual experience, a fuzzy-PID controller was designed. Randomly select multiple sets of PID parameters to confirm the control performance of the controller. Four groups of initial PID parameter values are randomly selected as shown in Table 5, and the PID parameters in the table are simulated to verify whether the control system can achieve the expected control effect.

The above four groups of PID parameters were, respectively, applied to the depth fixing motion controller, and the step response curve is obtained as displayed in Figure 6. It can be observed from the diagram of the simulation that the designed fuzzy-PID controller can achieve the desired control effect for any selected PID parameters, which indicates that the designed fuzzy-PID controller can realize the control of fixed-depth motion of the underwater vehicle, avoiding the requirement of control experience for PID parameter formulation. The behavior of fuzzy-PID controller was independent of any initial PID parameters.

The tuning curves of the fuzzy-PID controller for PID parameters are demonstrated in Figures 7 and 8. From the

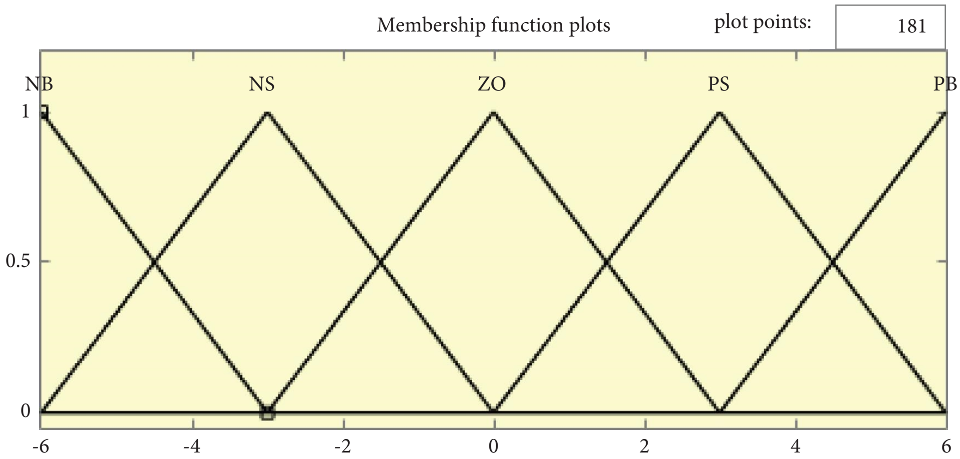

Figure 3: Membership function of E and EC.

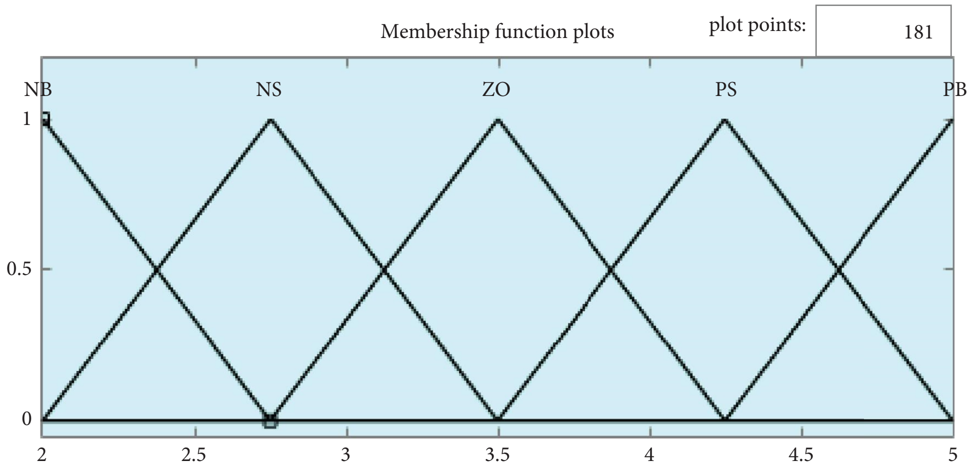

Figure 4: Membership function $\Delta k_p, \Delta k_i$, and Δk_d.

Table 1: Fuzzy rules table Δk_p.

	Δk_p			EC		
		NB	NS	ZO	PS	PB
E	NB	PB	PB	PS	PS	NS
	NS	PB	PS	PS	NS	NB
	ZO	ZO	ZO	ZO	ZO	ZO
	PS	NB	NS	PS	PS	PB
	PB	NS	PS	PB	PB	PB

Table 2: Fuzzy rules table Δk_i.

	Δk_i			EC		
		NB	NS	ZO	PS	PB
E	NB	PB	PB	PS	NS	NB
	NS	PB	PS	PS	NS	NB
	ZO	ZO	ZO	ZO	ZO	ZO
	PS	NB	NS	PS	PS	PB
	PB	NB	NS	PS	PB	PB

Table 3: Fuzzy rules table Δk_d.

	Δk_d	EC				
		NB	NS	ZO	PS	PB
E	NB	PB	PS	NB	NB	NS
	NS	PB	PS	NS	PS	PB
	ZO	PS	ZO	ZO	ZO	NS
	PS	PB	PS	NS	PS	PB
	PB	NS	NB	NB	PB	PB

Table 4: Propeller specifications of the underwater vehicle.

Specifications	Numerical value
Rated rotation speed	1200 r/min
Nominal voltage	15 V
Maximum current	25 A
Rated power	350 W
The length	113 mm
The diameter	100 mm
Blade diameter	76 mm
Air weight	344 g
The water weight	156 g

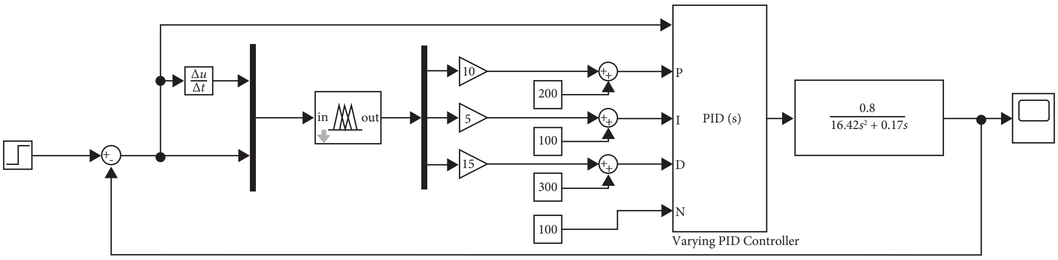

Figure 5: Simulation block diagram of depth control.

Table 5: PID parameter values.

	k_p	k_d	k_i
PID1	100	100	100
PID2	150	150	150
PID3	200	100	300
PID4	300	200	200

figures, it was evident that the PID parameters reach a stable value after being set by the fuzzy-PID controller, indicating that the fuzzy-PID controller has the ability to set PID parameters.

According to the transfer function equation (10), the system performance parameters are mainly related to the inertial hydrodynamic coefficient, the viscous hydrodynamic coefficient, and the quality of the underwater vehicle. The second-order coefficient of the transfer model is the sum of $Z_{\dot{w}}$ and m, so the mass m, and the viscous hydrodynamic coefficient Z_w of the underwater vehicle can be set as variables to study the action rules of structure and environmental parameter changes to fuzzy-PID control performance, respectively.

According to the actual load of underwater vehicle, the maximum load bearing capacity is 50% of its own weight, and the weight of the underwater vehicle was set as a variable with a variation range of 15–22.5 kg. The overshoot and adjusting time under fuzzy-PID control are studied with the change rule of underwater vehicle mass.

The detailed results of the calculations are shown in Tables 6 and 7. From the data in the table, it could be observed that fuzzy-PID control performance changes with the quality change of the underwater vehicle. With the increase of underwater vehicle quality, the fluctuation of performance parameters was small, indicating that the fuzzy-PID controller has a strong adaptive ability to model parameter changes.

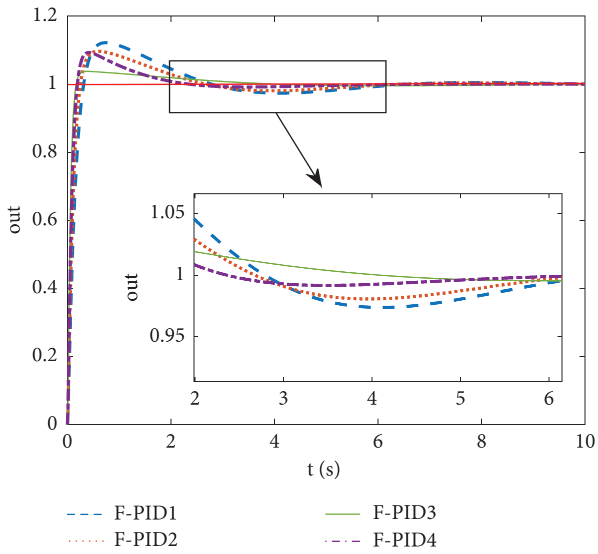

Figure 6: Fuzzy-PID step response curve.

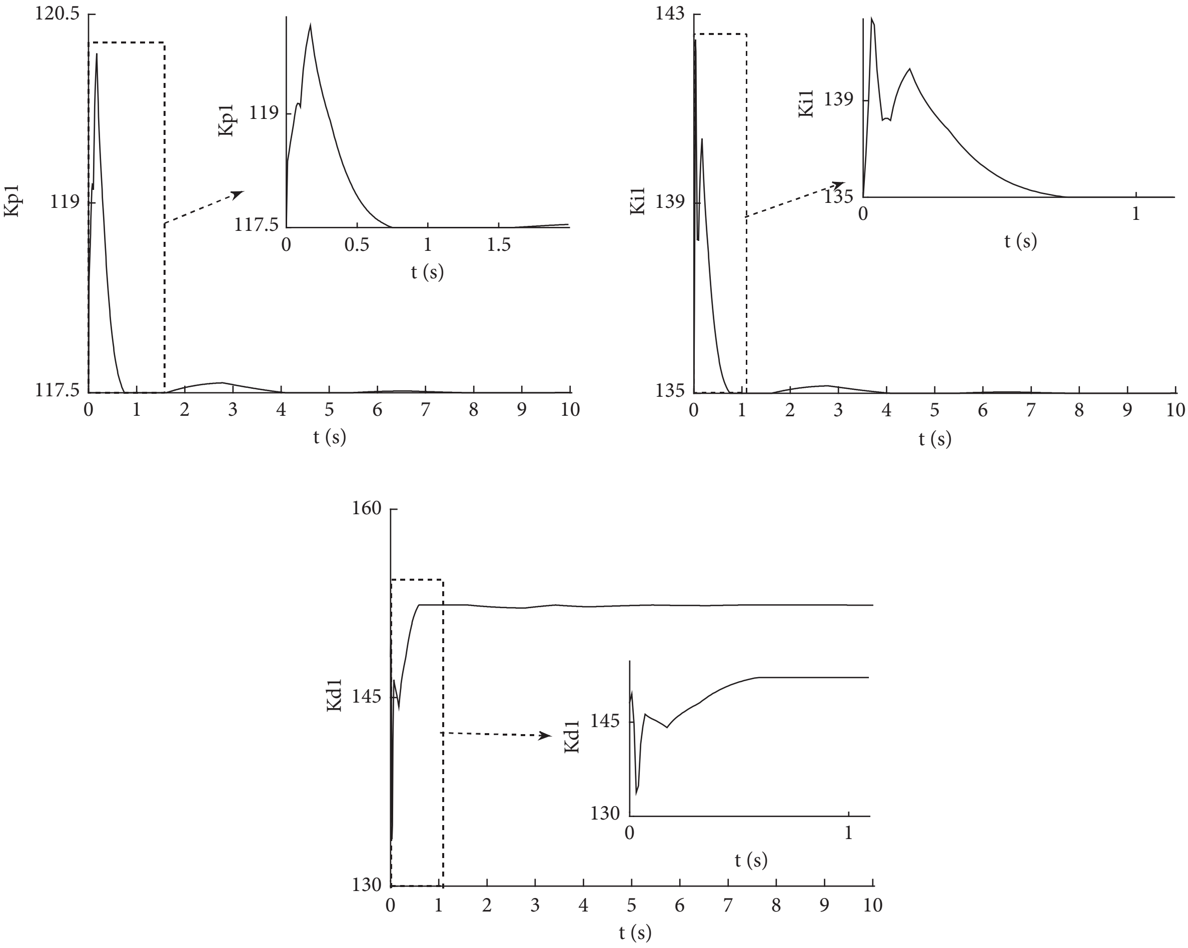

Figure 7: PID1 parameter setting curve.

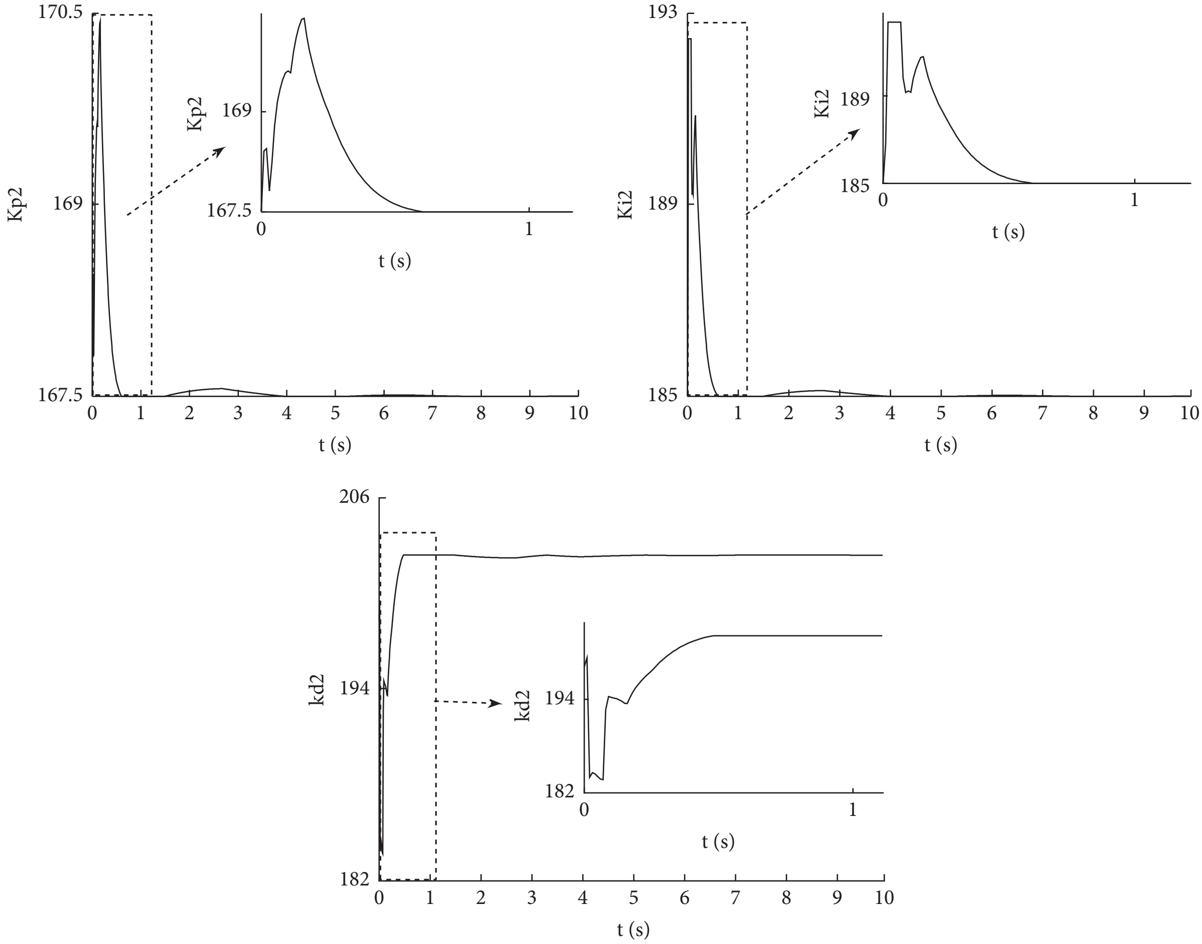

Figure 8: PID2 parameter setting curve.

Table 6: Overshoot changes with the mass of the underwater vehicle.

	m	15	18.75	22.5
$\sigma\%$	F-PID1	12.08	13.52	16.77
	F-PID2	9.50	11.51	12.36
	F-PID3	3.74	4.59	5.43
	F-PID4	9.22	11.14	12.86

Table 7: Regulation time changes with the quality of the underwater vehicle.

	m	15	18.75	22.5
$ts(s)$	F-PID1	1.92	2.04	2.26
	F-PID2	1.59	1.81	1.96
	F-PID3	0	0	0.88
	F-PID4	1.06	1.27	1.42

When the velocity of the underwater vehicle changes, the hydrodynamic coefficient changes. When the vertical velocity w changes, the vertical hydrodynamic coefficient Z_w has a certain relative change rate [22]. $Z_w$will be set to a variable range of change−0.17 ± 10%. The effects of overshoot and regulation on the hydrodynamic coefficient under fuzzy-PID control are studied.

The statistical results are shown in Tables 8 and 9. It can be seen from the data in the table that the overshoot and regulation time of the fuzzy-PID controller are basically unchanged with the increase of the hydrodynamic coefficient, indicating that the performance of the controller does not change with the change of the hydrodynamic coefficient.

Table 8: Variation rule of overshoot with the hydrodynamic coefficient.

	Z_w	0.187	0.170	0.153
$\sigma\%$	F-PID1	12.07	12.08	12.09
	F-PID2	9.49	9.50	9.50
	F-PID3	3.74	3.74	3.75
	F-PID4	9.21	9.22	9.23

Table 9: Regulation time changes with the hydrodynamic coefficient.

	Z_w	0.187	0.170	0.153
$ts(s)$	F-PID1	1.92	1.92	1.92
	F-PID2	1.59	1.59	1.59
	F-PID3	0	0	0
	F-PID4	1.06	1.06	1.06

Through the analysis of the above emulation experiments, the results were as follows:

(1) The fuzzy-PID controller designed has the function of real-time tuning of PID parameters. The actual data simulation shows that the fuzzy-PID controller does not need specific initial PID parameters to meet the control requirements and avoids the dependence of manual experience on the formulation of PID parameters for the underwater vehicle depth determination motion control.

(2) The effects of the mass and hydrodynamic coefficient of the underwater vehicle on the control performance of fixed-depth motion are studied. The results show that the mass of the underwater vehicle has more influence on the control performance than the hydrodynamic coefficient. With the increase of the hydrodynamic coefficient, the control performance of fuzzy-PID controller remains unchanged.

5. Conclusion

Based on fuzzy-PID, the performance simulation model of underwater vehicles was established and the performance simulation research was conducted. The results show that the fuzzy-PID controller has the capacity of PID parameter setting and can optimize PID parameters according to the initial PID parameters, this satisfies the requirements of depth determination motion control of underwater vehicles and avoid the dependence of PID parameter setting on manual experience. The effects of mass and the hydrodynamic coefficient changes on the control performance of underwater vehicles was studied. The experimental findings show that the fuzzy-PID controller has a slight fluctuation with the underwater vehicle mass, and the controller performance was not affected by hydrodynamic coefficient change, indicating that the fuzzy-PID controller has strong adaptive ability to control model parameters.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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