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Research Article

Research on Trajectory Planning and Control of Operational Underwater Robots

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For the complex system modeling of operating underwater robots, various modules are built in Simulink to simulate the interaction of various forces and torques inside the underwater vehicle. According to the characteristics of the ROV itself, the ROV dynamics model is reasonably designed. In view of the problems of the position tracking delay, underwater environment interference, and unstable operation of the ROV, the fuzzy fractional PID control algorithm is adopted in the controller in this paper, and the control effect of the fuzzy PID and PID algorithm is compared and analyzed.

1. Introduction

The ocean is a huge treasure house of human resources. The mineral resources are very rich. Among them, the content of important metals is more than ten times that of land mining areas. The content of natural gas is more than twice the total amount of waste coal, oil, and natural gas on land [1]. These resources are of great significance to the economic and social development of human beings, and they are called the substitute for the sustainable development strategy of human beings in the 21st century [2]. Facing the unknown ocean, man invented an underwater robot to explore and understand the underwater environment. An underwater robot is divided into an autonomous underwater vehicle (AUV) and a remotely operated underwater vehicle (ROV). Among them, the main role of a remotely operated underwater vehicle is ocean resource exploration, ocean pipeline detection, underwater mineral or biological sample sampling, unknown underwater area target observation, etc. [3]. With the continuous extension of the application field of underwater robots, people's demands for the stability and autonomy of underwater robots also increase. The types of underwater robots are not clearly divided. In order to make the underwater robot work stably and autonomously, underwater motion control technology becomes more and more important. The motion control system of the underwater robot combines a series of functions such as the design of the control algorithm, the actuator, the data processing, and the autonomous cruise [4]. At present, there are many difficulties in exploring the technical field of autonomous cruising, such as the inability to accurately track the preset path, slow speed, and low efficiency. For this series of problems, suitable motion control algorithms are needed to solve them and provide innovative ideas for subsequent autonomy and intelligence.

First of all, it is necessary to design a favorable underwater robot model. Under the action of the control system, the underwater robot can obtain information about its own motion state and external environment through sensors, and select the appropriate control algorithm and torque according to the obtained information. Thereby, functions such as stable motion can be realized. Liu et al. [5] indicate that the underwater vehicle has the characteristics of six-degree-of-freedom coupling and nonlinear control models, and its pros and cons are directly related to the navigation safety of the underwater robot, and it is an important index to evaluate the performance of the underwater robot. However, the interference of the underwater vehicle in the process of underwater navigation is complex, and the heading and depth control are coupled with each other, so the cost of physical verification of the motion algorithm is huge. Researchers often offer to build models to greatly reduce research costs. Therefore, the modeling of underwater robots is very important. Chang et al. [6] and others used the MATLAB simulation tool to convert the six-degree-of-freedom hydrodynamic equation of the underwater vehicle into a matrix equation, which is better applied to motion control and simulation. Zhu et al. [7] proposed a simulation system, which considers all normal, general, and practical models of nonlinear hydrodynamics and uses the FLUENT software to perform numerical simulation and identification of the parameters of the underwater robot, which proves to have good accuracy. This paper uses the current relatively common underwater robot model, which is formed by the researchers' reasonable simulation and frame construction and then adjusts the parameters according to the characteristics of the designed operational underwater robot.

When the underwater robot performs operations, the quality of its motion control system will be the premise for exploring the operation-type underwater robot. Therefore, in the research process of the underwater robot, the most important thing is the research on the motion control technology of the underwater robot, which is of great significance for the stable driving of the underwater robot and the improvement of its autonomy. Yuan [8] began to explore the field of stable driving of underwater robots very early. The team successfully used the PID algorithm to realize the depth and heading control of the underwater robot. The application of the algorithm guided the research direction of the researchers. According to the introduction by Tian et al. [9], the current comprehensive control of underwater robots mostly relies on various improved PID algorithms, and the complex underwater robot control can be simplified based on the PID algorithm. Due to the complex marine environment, the dynamic model of the ROV has dynamic nonlinearity and time-varying behavior, and many researchers combine the PID control algorithm with other control algorithms. Cao et al. [10] introduced a fuzzy incomplete lead PID (FIDA-PID) control system to achieve heading, depth, and altitude hold. The algorithm effectively solved the problem that the altitude remained unstable at that time, but the response time was not fast enough. Zhao et al. [11] used the genetic algorithm to tune the fractional-order parameters in the heading control of the underwater robot. Although this paper did not conduct in-depth research on the design of the underwater robot, it was also inspired by the team's ideas. The idea also lays a theoretical foundation for a subsequent research study. After that, Dong et al. [12] and Qi et al. [13] used the fuzzy control algorithm to adjust the PID parameters in-depth and obtained better control results, but they were only limited to the control of the z-axis. Chandra Shekar et al. [14] implemented fractional order sliding mode control (FOSMC), which significantly reduces the fast response time. Therefore, this paper proposes a fractional-order fuzzy control algorithm based on the research and experimental results of several previous researchers, weighing the pros and cons of various algorithms.

Although the control goal can be achieved, most of the designed motion ignores the dynamics of the system itself. Based on the characteristics of the underwater robot itself, this paper proposes to design a kind of fuzzy fractional order controller. By adding a fractional order calculus operator into the PID calculus function and using a fuzzy algorithm to train the error twice, the simulation and experimental results show that the proposed method not only makes the system have strong speed tracking and robustness but also improves the dynamic and static performance of the system. In the future, after the continuous exploration of scientific researchers, the control technology of underwater vehicles will become more and more mature. In the future, after the continuous exploration of scientific researchers, the control technology of underwater vehicles will become more and more mature. In scientific research and industrial applications, underwater vehicles will play a vital role in ocean research and ocean development. It can complete many tasks, such as the measurement of marine physical parameters (temperature, salinity, etc.), the detection and modeling of the three-dimensional marine environment, the discovery of marine targets (such as wreckage of crashed planes), underwater positioning, information transmission, and load delivery.

2. Overall Design of Modeling of Underwater Robot

2.1. ROV Mathematical Model. We establish the geodetic coordinate system $E - \xi\eta\zeta$ and the carrier coordinate system $o - xyz$, as shown in Figure 1.

The parameters recommended in the International Towing Tank Conference (ITTC) and the Shipbuilding and Marine Engineering Association (SNAME) terminology bulletin [15]. The meaning of the parameter is shown in Table 1.

In the moving coordinate system, the 6-DOF dynamic model of the underwater vehicle is [16]

$$M\dot{v} + C(v)v + D(v)v + g(\eta) = \tau, \quad (1)$$

$$\dot{\eta} = J(\eta)v, \quad (2)$$

where M is the inertia matrix of the ROV; $v = \begin{bmatrix} u & v & w & p & q & r \end{bmatrix}^T$ are the linear and angular velocities of the system in motion; $C(v)$ is the coriolis and centripetal force matrix of the ROV; $D(v)$ is the fluid resistance matrix of the ROV;$g(\eta)$ is a restorative force matrix composed of gravity and buoyancy; τ is the thrust provided by the ROV thruster; $\eta = \begin{bmatrix} x & y & z & \varphi & \theta & \psi \end{bmatrix}^T$ represents the position and attitude of the system in the inertial coordinate system; $x = \begin{bmatrix} x & y & z & \varphi & \theta & \psi \end{bmatrix}^T$ is the position and attitude vector in the fixed coordinate system. According to equations (1) and (2), a nonlinear uncertain system in the form of a state space equation can be obtained.

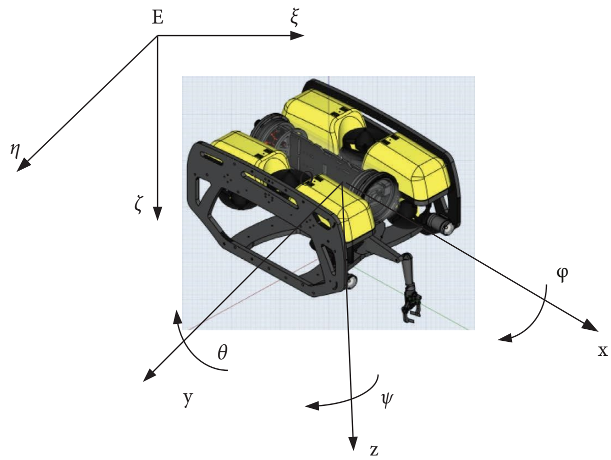


FIGURE 1: ROV motion coordinate system.

$$\begin{aligned} \dot{x}_2(t) &= f(\dot{x},t) + \Delta f(\dot{x},t) + Bu + d(t), \\ y &= x_1(t), \end{aligned} \tag{3}$$

where $u = M^{-1}\tau$ is input for system control, $x_1(t)$ 和 $x_2(t)$ is the system state vector, y is the output vector, B is the control coefficient, $f(\dot{x},t) = M^{-1}(C(v)v + D(v)v + g(\eta))$ is the nonlinear term of the system, $\Delta f(\dot{x},t)$ is the uncertain term of the nonlinear system, and $d(t)$ is the random interference outside the system. Suppose it satisfies $\|d(t)\| \le D$, where D is the upper bound value of interference.

$$\begin{aligned}
M &= \begin{bmatrix} m - X_{\dot{u}} & 0 & 0 & 0 & 0 & 0 \\ 0 & m - Y_{\dot{v}} & 0 & 0 & 0 & 0 \\ 0 & 0 & m - Z_{\dot{w}} & 0 & 0 & 0 \\ 0 & 0 & 0 & I_{xx} - K_{\dot{p}} & -I_{xy} & -I_{xz} \\ 0 & 0 & 0 & -I_{yx} & I_{yy} - M_{\dot{q}} & -I_{yz} \\ 0 & 0 & 0 & -I_{zx} & -I_{zy} & I_{zz} - N_{\dot{r}} \end{bmatrix}, \\
C(v) &= \begin{bmatrix} 0_{3\times3} & C_{12} \\ -C_{12}^T & C_{22} \end{bmatrix}, \\
C_{12} &= \begin{bmatrix} m(y_G q + z_G r) & -m(x_G q - w) - Z_{\dot{w}} w & m(x_G r + v) + Y_{\dot{v}} v \\ -m(y_G q + w) + Z_{\dot{w}} w & m(z_G r + x_G p) & -m(y_G r - u) - X_{\dot{u}} u \\ -m(z_G p - v) - Y_{\dot{v}} v & -m(z_G q + u) + X_{\dot{u}} u & m(x_G p + y_G q) \end{bmatrix}, \\
C_{22} &= \begin{bmatrix} 0 & -I_{yz} q - I_{xz} p + I_{zz} r - N_{\dot{r}} r & I_{yz} r + I_{xy} p - I_{yy} q + M_{\dot{q}} q \\ I_{yz} q + I_{xz} p - I_{zz} r + N_{\dot{r}} r & 0 & -I_{xz} r - I_{xy} q + I_{xx} p - K_{\dot{p}} p \\ -I_{yz} r - I_{xz} p + I_{yy} q - M_{\dot{q}} q & I_{xz} r + I_{xy} q - I_{xx} p + K_{\dot{p}} p & 0 \end{bmatrix}, \\
D &= -\mathrm{di\,ag}\left\{ \begin{matrix} X_u + X_{u|u|}|u|, Y_v + Y_{v|v|}|v|, \\ Z_w + Z_{w|w|}|w|, K_p + K_{p|p|}|p|, \\ M_q + M_{q|q|}|q|, N_r + N_{r|r|}|r| \end{matrix} \right\},
\end{aligned} \tag{4}$$

where $m = 34$ kg, gravitational acceleration $g = 9.81$ kg•m^2, I is the moment of inertia of ROV. $X_{\dot{u}}$, $Y_{\dot{v}}$, $Z_{\dot{w}}$, $K_{\dot{p}}$, $M_{\dot{q}}$, and $N_{\dot{r}}$ represent the corresponding additional mass and additional inertia. The parameters of the operation-type underwater robot system refer to the open-source underwater robot (blue-ROV) launched by Hangzhou Aohai Ocean Engineering Technology Co., Ltd. The system parameters of ROV are shown in Table 2.

Table 1: The parameter definition.

Motion parameters				Force parameter	
Name	Parameter	Name	Parameter	Name	Parameter
Longitudinal displacement	x	Longitudinal movement speed	U	Longitudinal force	X
Lateral displacement	y	Lateral movement speed	v	Lateral force	Y
Vertical displacement	Z	Vertical movement speed	w	Vertical force	Z
Roll angle	Φ	Roll angular velocity	p	Roll moment	K
Pitch angle	Θ	Pitch angle velocity	Q	Pitch moment	M
Yaw angle	Ψ	Yaw angle velocity	R	Yaw moment	N
Longitudinal displacement	X	Longitudinal movement speed	U	Longitudinal force	X

Table 2: Primary damping coefficient.

Name	Parameter (kg•m^2)	Name	Parameter (N•m$^{-2}s^2$)
$X_{\dot{u}}$	54.778	X_u	130
$Y_{\dot{v}}$	60	Y_v	140
$Z_{\dot{w}}$	97.319	Z_w	150
$K_{\dot{p}}$	2.110	$X_{u\|u\|}$	155.1615
$M_{\dot{q}}$	4.468	$Y_{v\|v\|}$	165
$N_{\dot{r}}$	2.848	$Z_{w\|w\|}$	175
$X_{\dot{u}}$	54.778	K_p	65.0
I_{xx}	1.44	M_q	65.0
I_{yy}	1.11	N_r	65.0
I_{zz}	1.79	$K_{p\|p\|}$	95
I_{xy}	−0.0001	$M_{q\|q\|}$	95
I_{xz}	0.066	$N_{r\|r\|}$	95

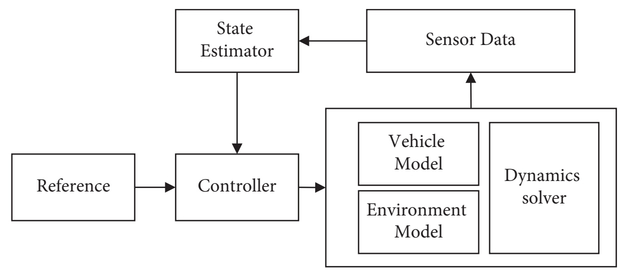


Figure 2: System modeling framework.

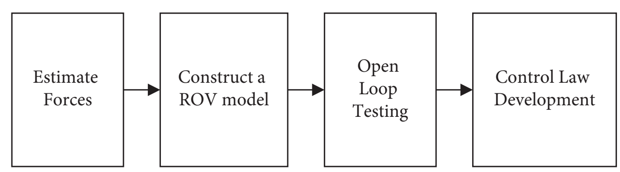


Figure 3: System modeling flow chart.

2.2. The System Structure. As shown in Figure 2, the model used in this paper is for the actual modeling of dynamics and control. The idea behind the modeling of the underwater vehicle is as follows: first, there is a reference value, which can also be called a state variable, so that the control object follows a certain task movement, and the state variable is input to the controller. Then, the controller provides input to the propeller of the underwater vehicle system, which includes the propeller model, the environment model, and the mathematical model of the robot. Finally, the sensor captures the output information of the ROV system and inputs the signal to the controller through the state estimator.

As shown in Figure 3, in order to make the system model more mature, the following steps were followed before modeling: (1) estimating all types of forces; the force and direction of the force acting on the robot body by the propeller, the amount of resistance in the water calculated according to the drag coefficient, the buffer force of the robot body on the body by the grasping of the manipulator, etc. (2) To create the ROV model; dynamic solvers are placed to actually deal with all of the aforementioned types of forces, calculating the forces generated as the model moves. (3) For open-loop testing; the reference value is placed in a certain direction to see whether it is consistent with the motion state of the robot body. If so, the open-loop pressure test is successful. (4) Making the controller; appropriate control laws are used to make the robot complete more complex tasks.

As shown in Figure 4, the overall framework of the system is composed of the propulsion force and torque subsystem, the environmental force fidelity subsystem, the 6-DOF Euler Angle system, the sensor information fusion subsystem, and the controller. The input of the propulsion force and torque subsystem is the output value of the controller. The control command is converted into a PWM wave signal and provided to the motor in the subsystem. The motor model is built according to the data provided by the T100–200 propellers, and the PWM wave is converted into the actual thrust output by using the motor model. Environment will hold true system mainly gravity, buoyancy, and drag force into environment parameters, it is important to fidelity system design is very clever, buoyancy, and resistance can choose is not a fixed value, they can be based on the actual state of robot ontology change size, such as robot body tilt, the buoyancy coefficient, and drag coefficient will change; The function of the sensor information fusion subsystem is to return the output signal of the traditional sensor to the controller. It contains an internal filter composed of six low-pass filters. Its function is to reduce the high-frequency noise and get the actual position signal needed. The controller uses the fractional-order fuzzy control algorithm to control the three-way position signal, which makes the system have strong position tracking and robustness, and improves the dynamic and static performance of the system.

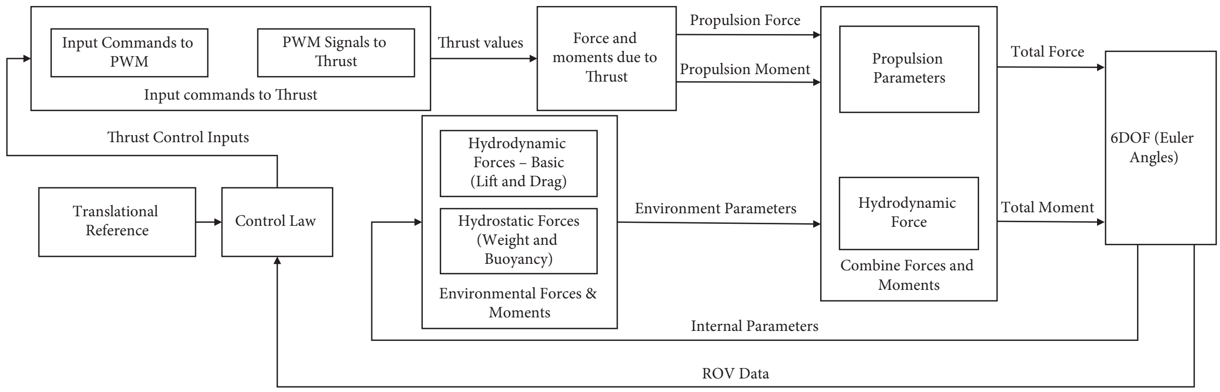


Figure 4: Overall block diagram of the system.

3. Fractional Order Fuzzy Controller

3.1. Track Differentiator TD. In a control system, the error is the difference between a set value and the system output. A sudden rise in the set value can easily cause an overshoot. In order to solve the contradiction between system rapidity and overshoot, the transition process is arranged for the initial target value.

$$\begin{cases} x_1(k+1) = x_1(k) + h \cdot x_2(k) \\ x_2(k+1) = x_2(k) + h \cdot u \\ u = fhan\left(x_1(k) - x_d(k), x_2(k), r, h_0\right) \end{cases}. \tag{5}$$

In Formula (5), h is the integral step, h_0 is a new variable independent of h, which has a certain filtering effect on noise, k is the k-th sampling time and the transition process of reference displacement, $x_2(k)$ is the differential of the transition process, and $fhan(x_1(k) - x_d(k), x_2(k), r, h0)$ is a nonlinear function, whose expression is shown in the following formula:

$$\begin{cases} d = r \cdot h_0 \\ d_0 = h_0 \cdot d \\ y_0 = x_1(k) - x_d(k) + h_0 \cdot x_2(k) \\ a_0 = \sqrt{d_2 + 8r \cdot |y_0|} \\ a = \begin{cases} x_2(k) + \dfrac{a_0 - d}{2} \cdot sign(y_0), & |y_0 > d_0|, \\ x_2(k) + \dfrac{y_0}{h_0},, & |y_0 \le d_0|. \end{cases} \end{cases} \tag{6}$$

There are three parameters of TD that need to be adjusted, which are r, h, and $h0$. Combined with the underwater robot system, define the values of the three parameters of the track differentiator: $h = 0.01$, $h_0 = 1$, and $r = 10$. Among them, r determines the tracking speed of the TD tracking signal. The larger the r, the faster the system tracking speed, but the filtering effect will also become worse. In order to suppress system overshoot, generally $r < 1$. The filter factor $h0$ is usually 3 h–10 h. The larger the integration step h, the stronger the filtering effect, but it will have a certain impact on the tracking performance of the signal. In the parameter adjustment process, r can be used for coarse adjustment of TD tracking performance, and parameter h can be used for fine adjustment. Choosing appropriate parameters can ensure that the system obtains smoother tracking performance and a better filtering effect.

3.2. Fractional Calculus Controller. Strictly speaking, fractional calculus should be called noninteger calculus, and integer calculus is a special case of it, so using fractional calculus modeling will be more in line with the characteristics of real-world systems. We define ${}_aD_t^\alpha$ as the operator of fractional calculus, as shown in formula (7), where a and t are its upper and lower limits, and α is the order of calculus, which is the integral variable.

$${}_aD_t^\alpha = \begin{cases} \dfrac{d^\alpha}{\mathrm{d}t^\alpha}, & \mathrm{Re}(\alpha) > 0, \\ 1, & \mathrm{Re}(\alpha) = 0, \\ \displaystyle\int_a^t (\mathrm{d}\tau)^{-\alpha} & \mathrm{Re}(\alpha) < 0. \end{cases} \tag{7}$$

There are currently three mainstream fractional calculus definitions in the field of control, namely, the Riemann–Liouville (RL) definition, Grünwald–Letnikow (GL) definition, and Caputo definition [17]. The three definition forms are as shown in the following equations (8)–(10), where $\Gamma(\cdot)$ is the gamma function:

$${}_aD_t^\alpha f(t) = \frac{1}{\Gamma(m-\alpha)} \left(\frac{d}{\mathrm{d}t}\right)^m \int_a^t \frac{f(\tau)}{(t-\tau)^{1-(m-\alpha)}} \mathrm{d}\tau, \tag{8}$$

$${}_aD_t^\alpha f(t) = \lim_{h \longrightarrow 0} \frac{1}{\Gamma(\alpha) h^\alpha} \sum_{k=0}^{(t-a)/h} \frac{\Gamma(k+\alpha)}{\Gamma(k+1)} f(t-kh), \tag{9}$$

$$ {}_aD_t^{\alpha} f(t) \frac{1}{\Gamma(m-\alpha)} \int_a^t \frac{f^{(m)}(\tau)}{(t-\tau)^{\alpha-m+1}} \mathrm{d}\tau. \quad (10) $$

The general expression of the fractional PID controller is $PI^{\lambda}D^{\mu}$, which has two more adjustable parameters λ and μ than the integer order PID, which are the integral order and the differential order respectively. The expression of the designed fractional order controller is

$$ C(s) = K_p + \frac{K_i}{s^{\lambda}} + K_d s^{\mu}. \quad (11) $$

3.3. Fractional Calculus Controller. As shown in Figure 5, the structure diagram of the fractional fuzzy PID controller consists of four parts: tracking differentiator TD, fractional calculus operator, input scale factor, and fuzzy control module. The idea of controller design comes from PODLUBUY [18] who first proposed the fractional-order PID controller in 1999. Subsequent researchers have applied this method to various fields. Numerous experiments have proved that the control effect of fractional-order PID is higher than that of integer-order PID better. The most important reason for the good control effect is that the parameter adjustment is more flexible so that the controller has two more degrees of freedom. Regarding the parameter adjustment of the controller, there is currently no better algorithm for calculation in the field of underwater robots. In this paper, the empirical method is used to adjust the parameters. The system has high complexity and strong coupling. It cannot be expressed by a transfer function. It is not a single-input single-output system, so it is impossible to solve the fractional calculus operator by solving the zero-pole method. The fuzzy PI controller has the characteristics that the transient response is poor in the high-order system. Adding a fractional operator and scale factor is more convenient for the design of a fuzzy controller, and the structure of two inputs and one output also greatly reduces the difficulty of formulating fuzzy rules.

The fuzzy control is combined with the Fractional-order PID controller, which has better dynamic performance and robustness than the fractional-order PID controller. The input of the fuzzy control part is error E and error change rate ΔE. First, the error E and error change rate ΔE should be fuzzily processed and transformed into fuzzy quantities E and EC. The fuzzy controller detects E and EC in real time and adjusts Kp and Ki.

(1) The input of the studied system is multiplied by the appropriate gain coefficient into the domain of theory, and the variable change process is traced with language variables. The membership degree of the input value is expressed in an appropriate language value. The membership relationship between input and output is shown in Figure 6.

(2) Fuzzy control rule base mainly stores control language description control rules. The output variable is defined as U, and the fuzzy set of each variable is defined as [−1.0, 1.0]. It is divided into three levels, namely negative, zero, and positive. The fuzzy control rules of the system are shown in Table 3, and the schematic diagram of the control law relationship is shown in Figure 7.

(3) Fuzzy reasoning: Fuzzy reasoning is a logical inference based on the combination rule and fuzzy implication relation between fuzzy relation and fuzzy set manage strategy. Fuzzy reasoning is not only the theoretical basis of fuzzy control but also the premise of fuzzy decision. Commonly used fuzzy reasoning in fuzzy control, single-input reasoning to get a single output, multiple-input reasoning to get a single output, and multiple-output reasoning to get multiple outputs [19]. In this paper, the Mamdani reasoning method is adopted, and the Mamdani reasoning method is synthesized by "taking the maximum first and then taking the minimum" operation method.

(4) Fuzzification: get the output fuzzy subset by fuzzy reasoning, and finally get the output control precision after the fuzzification amount. At present, the most commonly used methods of defuzzification are the area center of gravity method, weighted average method, and maximum membership degree method. According to the abscissa and the membership function curve, the area barycenter point of the graph is enclosed by the area barycenter point, which is used as the final output value of the fuzzy control [20]. The calculation formula is as follows:

$$ v_0 = \frac{\int_v v\mu_v(v)\mathrm{d}v}{\int_v \mu_v(v)\mathrm{d}v}. \quad (12) $$

For the discrete domain with m output quantization series

$$ v_0 = \frac{\sum_{k=1}^{m} v_k \mu_v(v_k)}{\sum_{k=1}^{m} \mu_v(v_k)}. \quad (13) $$

4. Simulation Results and Analysis

The response curve of the intelligent control algorithm is compared and analyzed by modeling an underwater robot system. By the simulation test analysis, fuzzy fractional order PID control algorithm in the stability, overshoot, response speed, and high-fidelity system after the addition of stability, overshoot, response speed effect.

A high-fidelity system is added to the system, that is the water flow changes from time to time and the force is no longer set as a fixed force. The size of the buoyancy will change with the change in the center of gravity caused by the slight roll of the underwater robot. A sensor part is also added, and the feedback information is accompanied by Gaussian noise. PID algorithm has the characteristics of a simple structure, strong application, and low dependence on the model. It can satisfy most control objects. An underwater

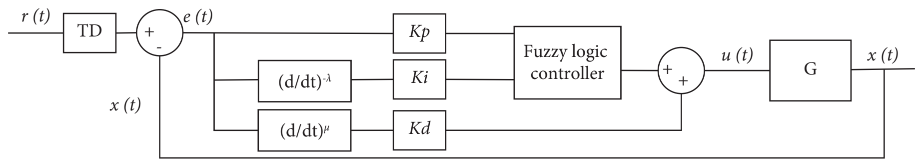


Figure 5: Fractional fuzzy controller structure.

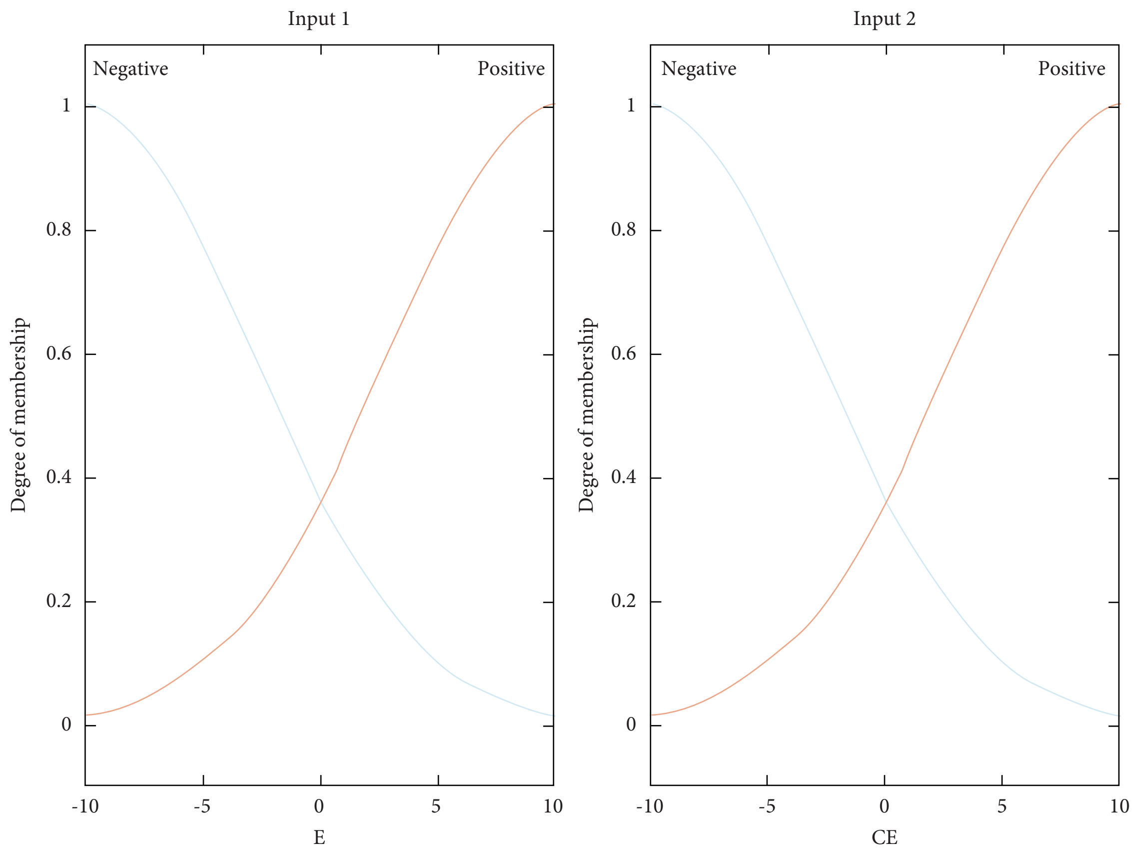


Figure 6: Variable membership curve.

Table 3: Fuzzy inference rules table.

EC	E Negative	E Positive
Negative	Min	Zero
Positive	Zero	Max

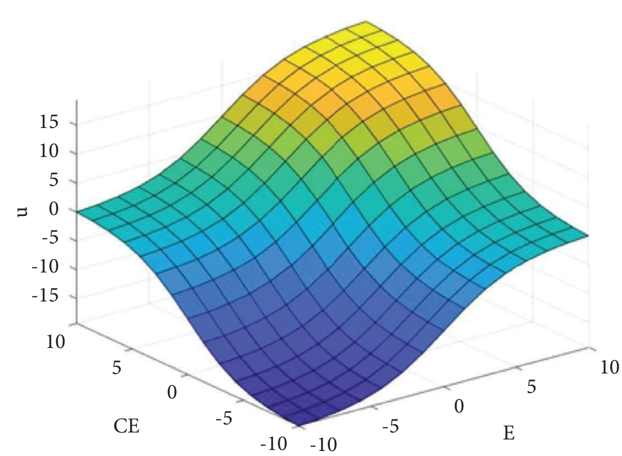


Figure 7: Schematic diagram of the control law relationship.

robot is a complex and high-performance system, and the application of this algorithm is limited.

Formula (14) is the expression of PID, and Table 4 is the specific value of PID controller parameters. As shown in Figure 8, the PID controller does not track the path up in all directions very well. When $t = 0\,\text{s}–150\,\text{s}$, there is an initial speed disturbance when the system starts to run, and the PID controller cannot realize fast convergence and has poor

Table 4: The PID controller parameters.

Parameters	Designed value	Parameters	Designed value
*Kp*_surge	0.035	*Ki*_sway	0.00387
*Kd*_surge	0.591	Filter order	438.6
*Ki*_surge	0.0004685	*Kp*_heave	0.035
Filter order	260.0628	*Kd*_heave	0.931
*Kp*_sway	0.173	*Ki*_heave	0.000463
*Kd*_sway	1.7164	Filter order	205.9

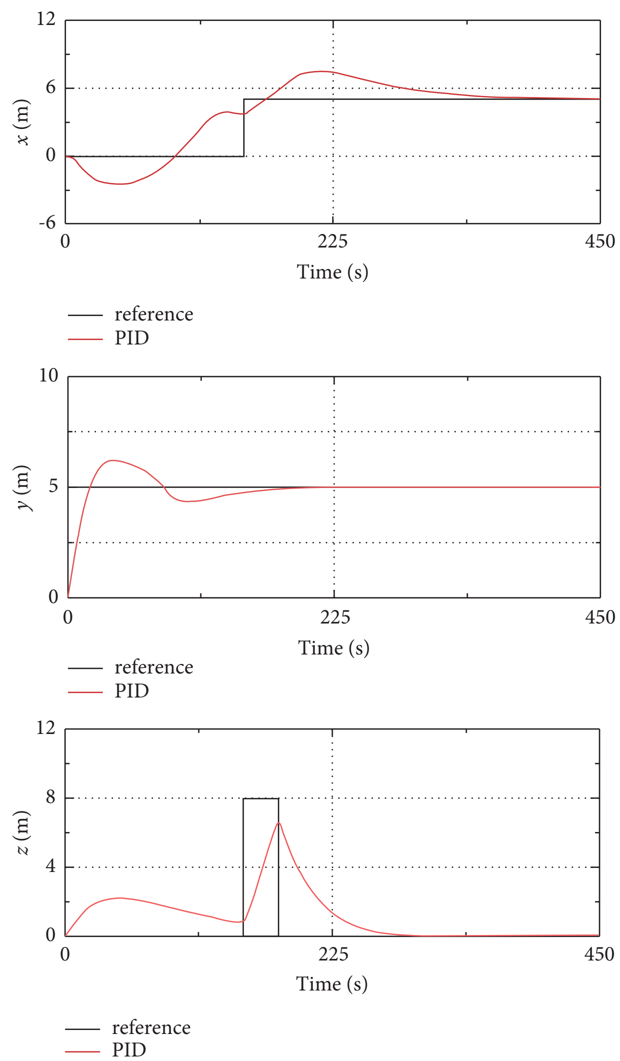


Figure 8: Fractional fuzzy controller structure.

robustness. When $t = 150\,\text{s}$–$300\,\text{s}$, with the change of reference value, the coupling of all directions of the system is strong, and the real-time performance of PID controller tracking is poor, which cannot achieve the effect of accurate tracking. When $t = 300\,\text{s}$–$450\,\text{s}$, the tracking condition of the PID controller was close to the reference value and finally stabilized near the reference value. The experimental results verified that the PID controller could not achieve the control accuracy, but was not strongly dependent on the model, and had strong practicability and adaptability.

Table 5: The Fuzzy PID controller parameters.

Parameters	Designed value	Parameters	Designed value
*Kp*_surge	0.04	*Ki*_sway	0.004
*Kd*_surge	0.6	*Kp*_heave	0.035
*Ki*_surge	0.0005	*Kd*_heave	1
*Kp*_sway	0.17	*Ki*_heave	0.0005
*Kd*_sway	1.7		

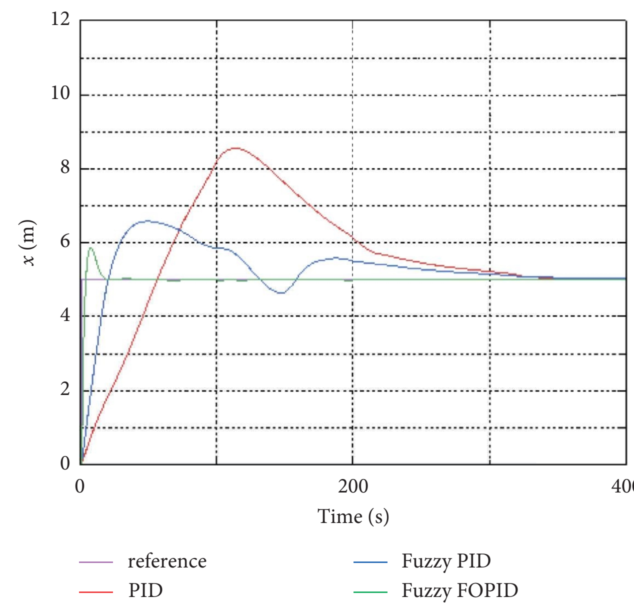


Figure 9: Comparison of X-axis displacement.

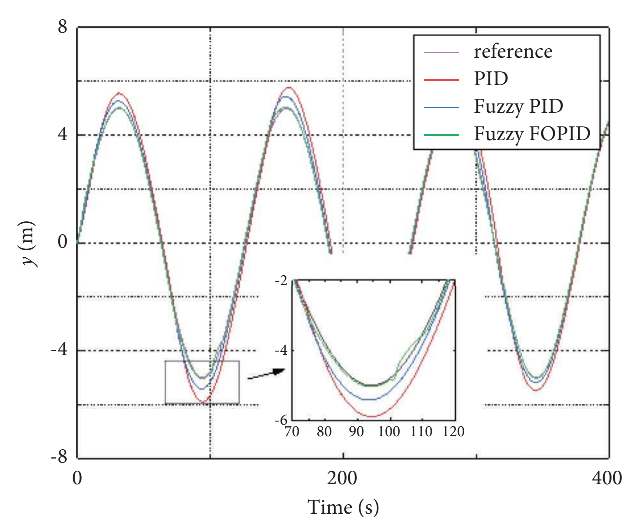


Figure 10: Comparison of Y-axis displacement.

$$C(s) = Kp + Ki\frac{1}{s} + Kd\frac{N}{1 + N1/s}. \tag{14}$$

To explore a more effective algorithm, considering the complexity of the system, and the characteristics of the high performance, this paper proposes a fuzzy algorithm to optimize PID parameters, the method of numerical Table 5 is

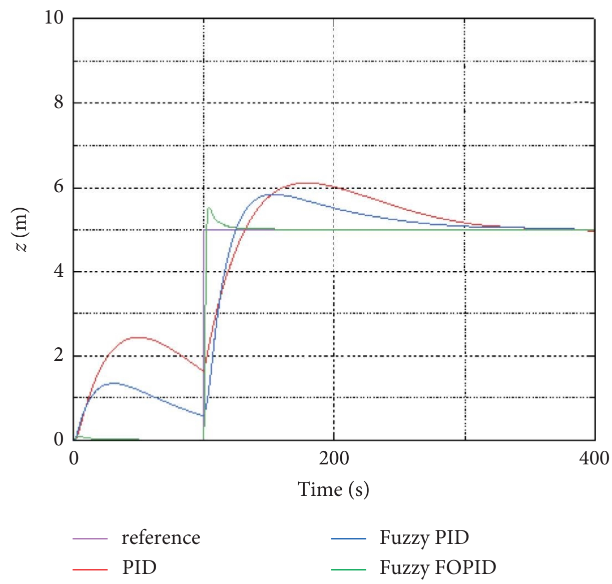


Figure 11: Comparison of Z-axis displacement.

part of the set parameters, as shown in Figures 9 to 11, using the fuzzy algorithm to optimize a certain extent, increased the location tracking rapidity, overshoot is significantly reduced, to some extent become more stable time is short, Specific displacement response indexes are shown in Table 6.

In the process of continuous exploration, advanced algorithms such as genetic algorithms and neural network algorithms are considered, but they cannot face more than 2-order complex systems, and their practicability is not strong. According to the characteristics of the system, the article on the basis of the fuzzy PID algorithm is introduced into the fractional calculus operator, the use of the fractional order calculus model will be more in line with the real-world system features, Table 7 is part of the set parameter values, the control effect as shown in Figures 9–11, displacement response index as shown in Table 6, according to the data shows that the fuzzy fractional order PID algorithm not only fast response, fast convergence, and the overshoot is obviously smaller, achieve very effective improvement effect.

As shown in Figure 12, in the process of the simulation experiment, Figure 12(a) is an abstract 3D solid figure to represent the body of the underwater robot. It is possible to observe its motion state in real-time and know in time whether the tilting separation occurs. Figure 12(b) is the trajectory state diagram of the starting point of the underwater robot. From the figure, the overall navigation route of the underwater robot can be observed. The simulated underwater environment is more realistic, so the route of navigation is also close to the real navigation path.

As shown in Figure 13, this figure shows the real-time motion state of the operational underwater robot, and the motion data of the underwater robot is collected through multiplatform cosimulation. It is worth mentioning that the platform has been built, but the algorithm has not been completely updated. There is still a lot of room for innovation in the algorithmic design of the platform.

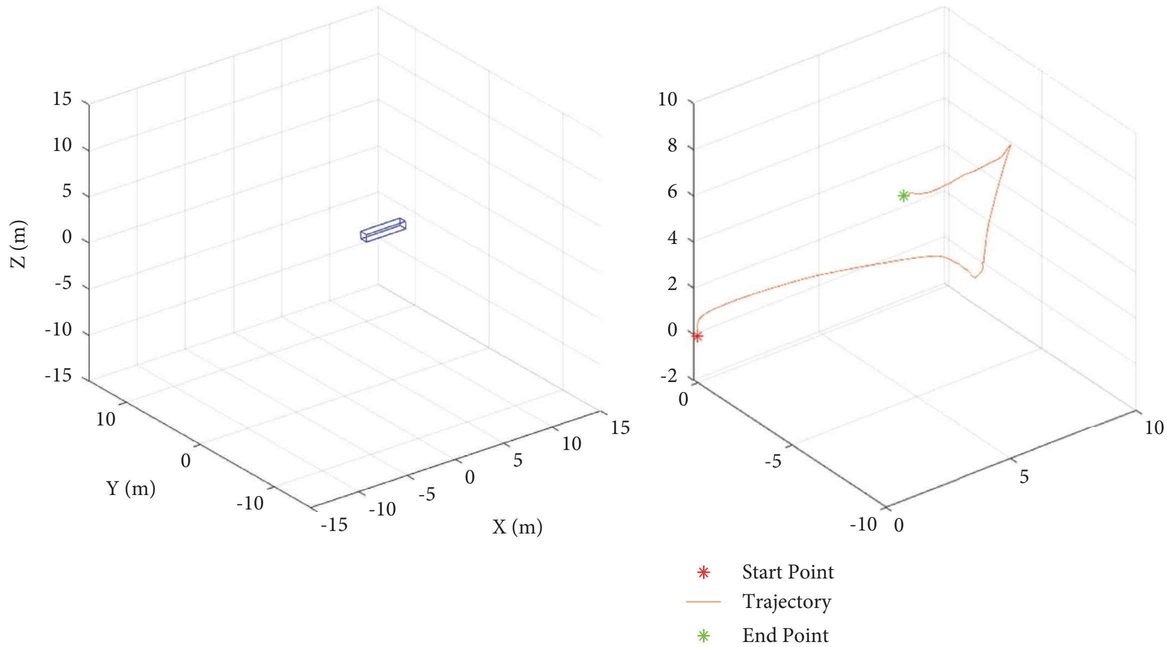
Table 6: The displacement response index of three controllers to position changes in different directions.

Orientation	Controller	Max (m)	Rise time (s)	Setting time (s)
X	PID	8.550	80.855	356.703
	Fuzzy PID	6.582	13.691	340.036
	Fuzzy FOPID	5.874	2.101	84.834
Z	PID	6.118	—	—
	Fuzzy PID	5.843	18.96	—
	Fuzzy FOPID	5.544	1.339	—

Table 7: The fuzzy fractional-order PID controller parameters.

Parameters	Designed value	Parameters	Designed value
Kp_surge	1	Kd_heave	0.1
Kd_surge	8	Ki_heave	1
Ki_surge	0.75	Filter order	5
Filter order	5	λ_surge	0.2
Kp_sway	0.4	μ_surge	0.7
Kd_sway	0.7	λ_sway	0.3
Ki_sway	0.2	μ_sway	0.9
Filter order	5	λ_heave	0.3
Kp_heave	0.4	μ_heave	0.9

The underwater robot system has the characteristics of hysteretisis, time variation, strong coupling, and nonlinearity. The fuzzy control algorithm is a classical control algorithm and an ideal nonlinear controller that is easy to control and master. It has better robustness, adaptability, and fault tolerance. The control algorithm introduced with fractional calculus has the characteristics of strong anti-interference ability, good fault tolerance, and a strong ability to adapt to dynamic condition changes. According to the



(a) (b)

Figure 12: Intuitive diagram of underwater robot simulation experiment: (a) abstract mathematical model and (b) trajectory motion of the underwater robot.

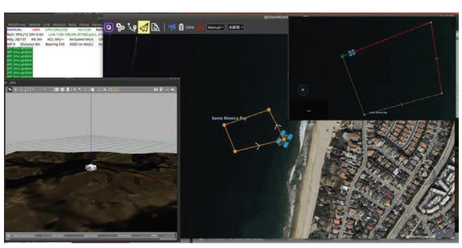


Figure 13: Real-time experimental control status.

experimental simulation data, the fuzzy fractional PID control algorithm combines the characteristics of the fractional PID control algorithm and fuzzy control.

5. Conclusions

In this paper, a fuzzy fractional order PID control strategy is proposed to solve the problems of large steady-state error and low accuracy of position tracking in an integer order PID controller of an underwater robot. Firstly, the Simulink model of the underwater robot system is introduced and designed. Secondly, the controller is designed, and the components of the controller are introduced. Finally, the simulation proves that the fuzzy fractional order PID controller has better speed tracking, robustness, and smaller steady-state error. Experiments also show that introducing fractional calculus can greatly accelerate the convergence rate.

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 they have no conflicts of interest.

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