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Miniature Detection Buoy Based on Fuzzy Adaptive PID Algorithm

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Abstract. The ocean buoy is an important technical means to obtain ocean environmental parameters as a newly developed detection technology. Traditional ocean buoys use hydraulic devices to change the volume of the oil bladder to achieve fixed-depth control, with slow response speed and long detection cycle. Therefore, it can only be applied to deep-sea environment and lacks the ability of rapid and fine detection in shallow waters (<200m). Considering the above problems, the paper designs a miniature detection buoy, which adopts an innovative inner and outer sleeves design. The miniature detection buoy uses a geared motor to drive the internal screw rotation to quickly stretch and shrink the volume of the shell to achieve the functions of floating, diving and fixed-depth. Moreover, the control performance research is carried out by establishing the dynamics model of the miniature detection buoy. According to the model, the fuzzy adaptive PID control algorithm is used to accurately control the speed and steering of the geared motor. The simulation results show that the buoy system with the fuzzy adaptive PID control algorithm has better fixed-depth accuracy and response speed than the classic PID control algorithm.

Keywords: miniature detection buoy, fixed-depth control, fuzzy adaptive PID

1 Introduction

China's vast territory, the ocean area of more than 4.7 million square kilometers, and the Bohai Sea, the East China Sea and the South China Sea coastal areas are shallow, containing a large number of ocean resources. To sustainably develop, utilize and protect these marine resources, it is especially important to conduct ocean environment exploration in shallow waters.

Balke et al. developed a miniature detection buoy for hydrographic environment detection in shallow waters based on the characteristics of miniaturization and convenience, which can be rapidly deployed to form a large area detection network. However, the fixed way of anchoring makes it possible to acquire data only in a fixed area and cannot collect ocean data at different depths [1]. In order to meet the demand of collecting ocean parameters at different depths, miniature ocean buoys that can float up and down as well as fixed-depth, represented by Argo buoys, have been deployed in many places around the world [2]. However, Argo buoys use hydraulic pumps to inject and pump liquid into and out of the oil bladder to adjust the buoyancy, which leads to a complex mechanical structure and large size, resulting in insufficient detection capability in shallow water.

Most of the research related to the control of fixed-depth for underwater detection equipment has been developed by the control technology of underwater robots such as AUV (Autonomous Underwater Vehicles), UUV (Unmanned Underwater Vehicles) and underwater gliders.

The control algorithms for underwater robots are relatively mature, and adaptive control, sliding mode control, fuzzy control, neural network, reinforcement learning and other strategies have been adopted to realize the fixed-depth hovering and attitude control of underwater robots [3-5]. Qiao et al. proposed a dynamic sliding film tracking controller, which was applied to UUV to adjust its motion trajectory and eliminate the influence of environmental disturbances [6]. Lakhekar et al. investigated a fuzzy logic controller for AUV fixed-depth control, which does not need to establish a dynamics model. At the same time, the controller compensates for uncertainty through an observer and adaptive fuzzy control, which effectively enhances the robustness of the control [7].Wu et al. propose a model-free reinforcement learning algorithm applied to AUV depth control to solve the problem that the control object cannot be mathematically modeled [8]. He et al. proposed a neural network parameter self-tuning model for automatic tuning of gain parameters based on the study of nonlinear models of small underwater robots [9]. Mohanad et al. proposed a nonlinear fuzzy controller for controlling the trajectory and velocity of multi-input and multi-output AUV. And the fuzzy controller has a faster response and higher immunity to dis-

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turbances, as well as the ability to maintain adequate holding stability in a nonlinear system environment [13]. In addition, the PID control algorithm is often combined with other control methods due to its simple structure, high stability, and robustness in practical applications [10-12]. The combination of neural network and PID algorithm is used to train the parameter model by the neural network, which can realize automatic adjustment of PID parameters [14]. However, the above control algorithm is mainly used to adjust the attitude of the underwater robot by adjusting the direction and force of the thrusters, which does not apply to the underwater detection equipment without thrusters.

In response to the above problems, the miniature detection buoy adopts a new concept design to achieve three detection modes of surfacing, diving and fixed-depth by stretching and contracting the inner and outer shells. Moreover, the miniature detection buoy adopts a miniaturized and lightweight design, which can be quickly deployed over a large area to form a dense shallow waters detection network and collect data at different depths. To improve the effect of fixed-depth control of miniature detection buoy, the fuzzy adaptive PID control algorithm is introduced to adjust the gain parameters online and in real-time. It can effectively improve the fixed-depth control accuracy and response speed.

The remainder of the paper is structured as follows: section 2 introduces the miniature detection buoy system design; section 3 describes the miniature detection buoy autonomous control method; section 4 compares and analyzes the fuzzy adaptive PID with the classic PID; and section 5 describes the conclusions.

2 Miniature Detection Buoy System Design

2.1 Overall System Description

The design goal of the Miniature detection buoy is to create a convenient, low-cost, and rapidly deployable data acquisition system. Moreover, the miniature detection buoy can precisely control the dive depth to measure the profile data at different depths, providing theoretical and data support for hydrographic environment exploration in shallow waters. The structure of the miniature detection buoy is shown in Fig. 1.

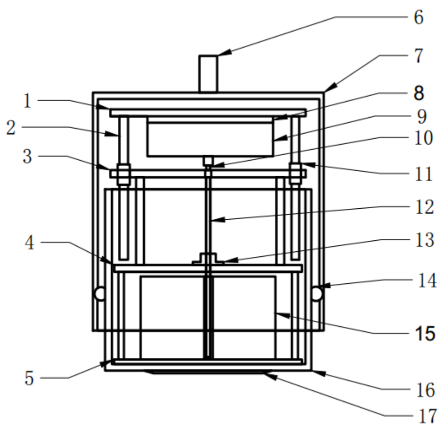


Fig. 1. The structure of the miniature detection buoy

The miniature detection buoy is mainly composed of control circuit board (8), shells, volume adjustment device, power source, communication equipment and various sensors.

The housing consists of inner (16) and outer (7) sleeves nested by sealing rubber ring (14) to form an airtight space. The volume adjustment device is composed of support rods (2), support plates (1)/(3)/(4)/(5), a geared motor, slide sleeves, a flange nut, a screw and a coupling. The geared motor (9) is connected to the screw (12) through a coupling (10). And the screw is connected to the flange nut (13). The geared motor rotates the screw, causing the support rods to slide through the slide sleeves (11) to change the volume of the buoy. The miniature detection buoy uses a battery pack (15) as the power source and is equipped with sensors (17) to detect temperature, water pressure and other data. In addition, it is also equipped with communication equipment (6) to enable remote control.

The miniature detection buoy is a self-ballasting, cylindrical, small-sized underwater drifter with internal mechanical components, actuators, and electronics. The active buoyancy control of the miniature detection buoy implements vertical motion. According to the pre-compiled program, the actuator is precisely controlled by the fuzzy adaptive PID algorithm which can collect seawater temperature information at different depths. When the miniature detection buoy surfaces, the antenna is elevated far enough out of the water to enable GPS satellite positioning as well as LoRa wireless communication. As a result, latitude, longitude, temperature, and depth information can be transmitted to the data processing center. Meanwhile, the miniature detection buoy to maintain the small size and convenience, no thruster system was incorporated. Each miniature detection buoy has a power management system based on the high polymer lithium battery with up to 10,000mah battery power, ensuring continuous operation for 24 hours. At the same time, it is equipped with enough memory to store all sensor data and information about the internal state of the buoy.

2.2 Innovative Sleeve Design

The housing of the miniature detection buoy consists of two concentric POM plastic cylinders, forming inner and outer sleeves. Meanwhile, the inner and outer sleeves can slide over each other to change the volume of the internal piston, thus adjusting the buoy volume and further changing the buoyancy of the buoy. The cylindrical sleeve design increases the relative surface area and concentrates the center of gravity in the lower part of the buoy so that the buoy can improve its drifting ability and stability. The miniature detection buoy designed with inner and outer sleeves has the characteristics of simple structure and small size. And, small incremental internal piston volume change can realize the rapid stretching and shrink of the shells. As a result, the miniature detection buoy can be miniaturized to meet the needs of rapid deployment over a large area.

The working principle of miniature detection buoy adopting the inner and outer sleeves to slide over each other to adjust the volume means that in a high hydraulic pressure environment, a large thrust is needed to push the shells to slide. Therefore, a high-torque geared motor is used as the driver to increase the torque through a suitable geared ratio. Meanwhile, the geared motor is equipped with a high precision optical encoder, which can precisely control the number of turns of the screw rotation to meet the fine adjustment of the miniature detection buoy. To cope with the oscillation and overshoot problems occurring in geared motors and the effects of the ocean environment, a fuzzy adaptive PID control algorithm is introduced. The fuzzy adaptive PID control algorithm controls the input voltage of the geared motor to precisely control the speed and steering. At the same time, the output of the geared motor is combined with the dynamics model of the miniature detection buoy to reduce the influence of the ocean environment and improve the accuracy of the fixed-depth control.

3 Miniature Detection Buoy Autonomous Control Method

3.1 Miniature Detection Buoy Dynamics Model

In the actual working process, the miniature detection buoy is often affected by environmental factors such as wind, waves and currents, resulting in a non-linear coupled mode of its underwater motion. The nonlinear coupling mode is usually characterized by time-varying and uncertainty, which makes it difficult to achieve accurate control effects. Therefore, a dynamics model is developed to research the motion control of the miniature detection buoy. The model includes a variety of static factors, such as buoy mass, seawater density, buoy radius and flow drag factor, etc.

The miniature detection buoy adopts a space rectangular coordinate system that conforms to the right-hand system to carry out motion state studies. The sea level is selected as the reference horizontal plane as the X-Y plane of the coordinate system. Meanwhile, any point on the sea level is chosen as the origin O of the coordinate system. Based on this, the Z-axis is perpendicular to the sea level, and the direction pointing to the center of the earth is specified as the positive direction.

According to the above limitations, the force analysis of the miniature detection buoy is carried out. As shown in Fig. 2, the miniature detection buoy is subjected to the action of gravity F_G , buoyancy force F_f and flow resistance F_R during the motion.

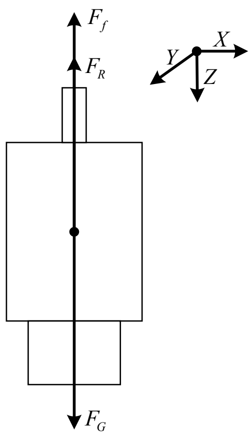


Fig. 2. The force state of the miniature detection buoy

The summation of forces on the miniature detection buoy is as follows:

$$\sum F = F_G - F_f - F_R . \tag{1}$$

The buoyancy force during the motion of the buoy is as follows:

$$F_f = \rho \cdot g \cdot V(t) . \tag{2}$$

Since the buoy operates in shallow water, the seawater density ρ is considered to be constant. $V(t)$ is the volume of the buoy at the time t, which can be expressed as the difference between the initial volume of the buoy V_0 and the change in volume of the internal piston $V_p(t)$. The direction of buoyancy is the negative direction of the Z-axis.

$$F_f = -\rho \cdot g \cdot (V_0 - V_p(t)) . \tag{3}$$

According to the principle of fluid mechanics, the flow resistance during the buoy motion is as follows:

$$F_R = C_D \frac{\rho \upsilon^2}{2} A . \tag{4}$$

A is the cylindrical cross-sectional area of the buoy; υ is the speed of buoy motion; C_D is the flow resistance factor. Let the drag coefficient $r = \frac{\rho A}{2} C_D$, and the direction of flow resistance and buoy movement in the opposite direction. Therefore, the flow resistance during the buoy motion is as follows:

$$F_R = r \cdot \upsilon \cdot |\upsilon| . \tag{5}$$

In summary, the summation of forces on the miniature detection buoy is as follows:

$$\sum F = m \cdot g - \rho \cdot g (V_0 - V_p(t)) + r \cdot \upsilon \cdot |\upsilon| . \tag{6}$$

In the initial state, the gravity of the miniature detection buoy F_G is equal to the buoyancy F_f, and it is suspended at the water surface. Based on this, the initial state dynamics equation of the miniature detection buoy is as follows:

$$\begin{cases} F_G = F_f(0) = \rho \cdot g \cdot V_0 \\ a(0) = 0 \\ \upsilon(0) = 0 \\ h(0) = 0 \end{cases} . \quad (7)$$

$F_f(0)$ is the buoyancy force of the initial state buoy; V_0 is the volume of the initial state buoy; $a(0)$, $\upsilon(0)$, and $h(0)$ are the acceleration, velocity, and depth of the initial state buoy respectively.

During the motion of the miniature detection buoy, due to the short sampling interval, the motion between two sampling moments can be regarded as uniformly accelerated. According to Newton's law and the above conditions, the kinetic equations of the miniature probe buoy can be obtained as follows:

$$\begin{cases} \sum F = F_G + F_f + F_R \\ a = \dfrac{\sum F}{m} \\ \upsilon(t) = \upsilon(t-\Delta t) + a \cdot \Delta t \\ h(t) = \upsilon(t-\Delta t) \cdot \Delta t + \dfrac{1}{2} a \cdot \Delta t^2 \end{cases} . \quad (8)$$

$\upsilon(t)$, $h(t)$ are the motion velocity and motion depth of the miniature detection buoy at the time t; $\upsilon(t-\Delta t)$ is the motion velocity at the time $t-\Delta t$; Δt is the interval sampling time. Combined with equation (6) is as follows:

$$\sum F = m \cdot a = m \cdot g - \rho \cdot g(V_0 - V_p(t)) + r \cdot \upsilon \cdot |\upsilon| . \quad (9)$$

Meanwhile, the change in volume of the internal piston $v_p(t) = \int_0^t \omega_m(t)dt$. $\omega_m(t)$ is the speed of the geared motor at time t. Combined with equation (8) is as follows:

$$\sum F = m \cdot a = m \cdot g - \rho \cdot g \cdot (V_0 - \int_0^t \omega_m(t)dt) + r \cdot \upsilon \cdot |\upsilon| . \quad (10)$$

Therefore, the input equation for the miniature detection buoy is as follows:

$$\begin{cases} V_p(t) = \int_0^t \omega_m(t)dt \\ \upsilon(t) = \int_0^t \dfrac{m \cdot g - \rho \cdot g(V_0 - V_p(t)) + r \cdot \upsilon \cdot |\upsilon|}{m} \\ h(t) = \int_0^t \upsilon(t)dt \end{cases} . \quad (11)$$

The output equation for the miniature detection buoy is as follows:

$$y(t) = h(t) . \quad (12)$$

According to the input and output equations of the miniature detection buoy, its dynamics model is established. As shown in Fig. 3, the Simulink dynamics simulation model of the miniature detection buoy takes the motor speed $\omega_m(t)$ of the buoy at the time t as the input parameter and the depth of motion $h(t)$ of the buoy at the time as the output parameter.

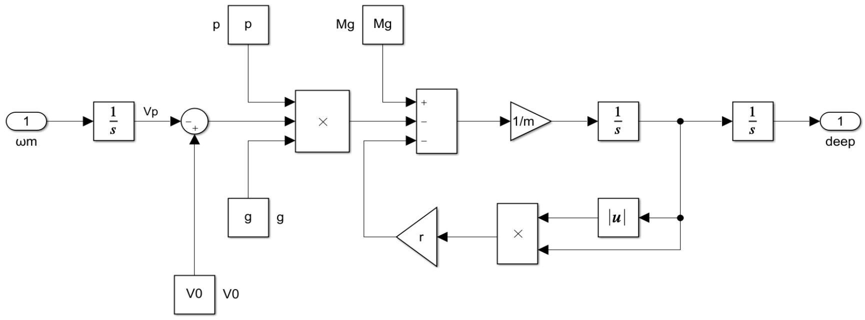


Fig. 3. The simulation of the miniature detection buoy dynamics model

3.2 Dynamics Model of Miniature Detection Buoy Geared Motor

The miniature detection buoy uses a high-torque geared motor as the driver with armature voltage equation is as follow:

$$u_a(t) = L_a \frac{di_a(t)}{dt} + R_a i_a(t) + E_a \,. \tag{13}$$

$$E_a = C_e \omega_m(t) \,. \tag{14}$$

where E_a is the counter-electromotive force, C_e is the counter-electromotive force constant, $\omega_m(t)$ is the motor speed, L_a and R_a are the inductance and resistance of the armature circuit. The electromagnetic torque equation is as follow:

$$T_e(t) = C_m i_a(t) \,. \tag{15}$$

where $T_e(t)$ is the electromagnetic torque and C_m is the motor torque coefficient. The torque balance equation is as follow:

$$J_m \frac{d\omega_m(t)}{dt} + f_m \omega_m(t) = T_e(t) \,. \tag{16}$$

where f_m is the coefficient of viscous friction and J_m is the rotational inertia. According to equations (15) to (16), the differential equation of geared motor with $u_a(t)$ as input and $\omega_m(t)$ as output can be obtained as follows:

$$K_m u_a(t) = \frac{d^2\omega_m(t)}{dt^2} + T_m \frac{d\omega_m(t)}{dt} + K_c \omega_m(t) \,. \tag{17}$$

where $K_c = \dfrac{C_m C_e + R_a f_m}{J_m L_a}$ and $K_m = \dfrac{C_m}{J_m L_a}$ is the motor transfer coefficient, $T_m = \dfrac{L_a f_m + R_a J_m}{J_m L_a}$ is the electromechanical time constant. The Simulink simulation of the geared motor dynamics model is shown in Fig. 4.

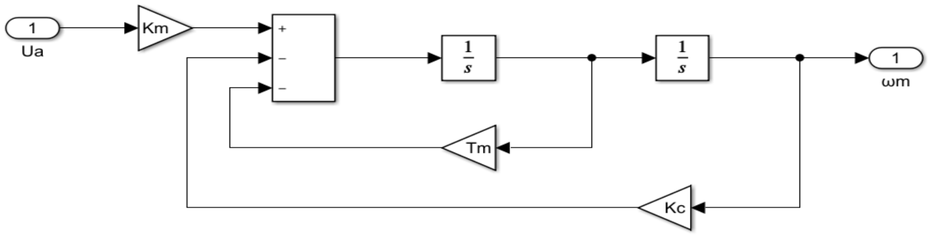


Fig. 4. The simulation of the geared motor dynamics model

3.3 Fuzzy Adaptive PID Control Algorithm

From the above analysis, it can be seen that the dynamics model of the miniature probe buoy motion state is nonlinear, and the classic PID algorithm to deal with the nonlinear model is difficult to achieve the desired control effect. Therefore, to cope with changes in the ocean environment, improve the control effect and response speed of miniature detection buoy, the fuzzy adaptive PID control algorithm is used for real-time parameter adjustment [15].

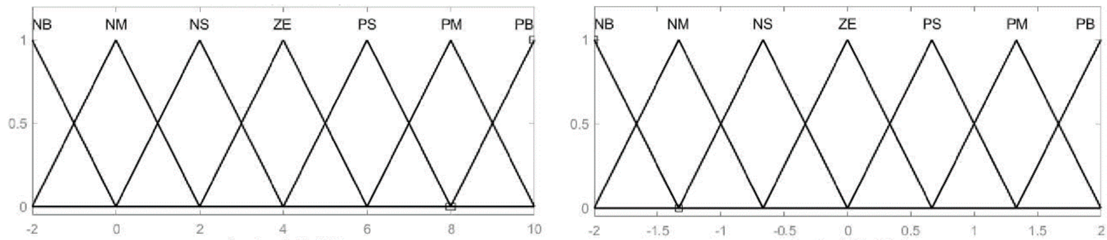
The error value E is the difference between the target depth and the present target. The rate of change of the error E_c is obtained by differentiating the error value E. The fuzzy controller takes E and E_c as input parameters and determines the corresponding affiliation function. According to the fuzzy control rule table, determine the output of the fuzzy controller K_p, K_i and K_d achieve the adaptive PID parameters [16].

According to the actual test requirements, the target dive depth of the miniature detection buoy is 10m and the maximum overshoot is 2m. Therefore, the domain of the error E is determined to be [-2, 10] and the domain of the error rate of change E_c is [-0.3, 0.3]. The error E and error rate of change E_c are fuzzified and classified into seven levels, namely NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium), and PB (Positive Big), and expressed by a triangle membership function. The parameters of the fuzzy controller inputs are shown in Table 1.

Table 1. The parameters of the fuzzy controller inputs

Fuzzy variable	Fuzzy domain	Fuzzy subset	Membership function range
		NB	[-4.01 -2 0.001]
		NM	[-2 0.001 1.998]
		NS	[0.001 1.998 4]
E	[-2, 10]	ZE	[1.998 4 6.002]
		PS	[4 6.002 7.999]
		PM	[6.002 7.999 10]
		PB	[7.999 10 12.01]
		NB	[-0.3999 -0.3 -0.1999]
		NM	[-0.3 -0.1999 -0.1]
		NS	[-0.1999 -0.1 -0]
E_c	[-0.3, 0.3]	ZE	[-0.1 0 0.1001]
		PS	[0 0.1001 0.2]
		PM	[0.1001 0.2 0.3]
		PB	[0.2 0.3 0.3997]

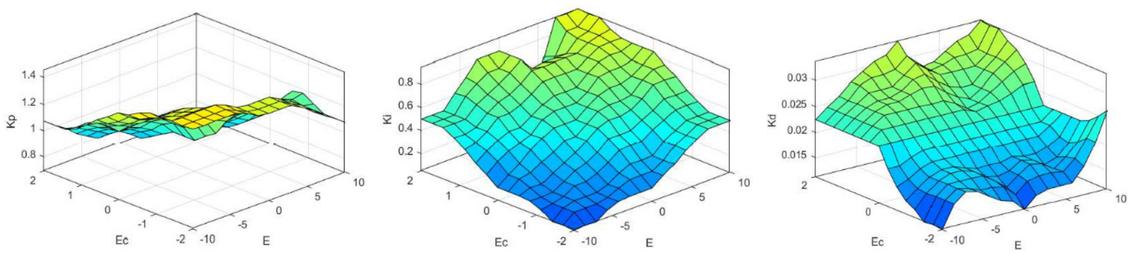
Fig. 5 shows that the error E and error rate of change E_c correspond to the membership function plots of fuzzy variables.



(a)The error E membership function plots (b)The error rate of change E_c membership function plots

Fig. 5. Membership function plots

The output gain parameters of the fuzzy controller were selected in the domain of K_p [0.65, 1.5], K_i [0, 1] and K_d [0.01, 0.035]. The three gain parameters K_p, K_i, and K_d are fuzzified and classified into seven levels, namely NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium), and PB (Positive Big), and expressed by a triangle membership function. The surface observation diagrams of the membership function for the gain parameters are shown in Fig. 6.



(a) K_p surface observation diagram (b) K_i surface observation diagram (c) K_d surface observation diagram

Fig. 6. The surface observation diagrams of the membership function for the gain parameters

The fuzzy controller uses a fuzzy rule table to modify the three parameters online to meet the demand for the control parameters at different c and d during the miniature detection buoy depth setting control. It can achieve the purpose of speeding up the system response, eliminating the system steady-state error and increasing the system stability. The fuzzy control rules for K_p, K_i and K_d are shown in Table 2 to Table 4, respectively. The fuzzy control rules table is shown in Table 2 to Table 4.

Table 2. K_p control rules

E_c	E						
	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NM	NM	NS	ZE	ZE
NM	NB	NM	NM	NS	NS	ZE	ZE
NS	NM	NM	NS	ZE	ZE	PS	PS
ZE	PM	NS	ZE	ZE	PS	PS	PM
PS	NS	ZE	ZE	PS	PS	PM	PM
PM	ZE	ZE	PS	PM	PM	PM	PB
PB	ZE	ZE	PM	PM	NB	PB	PB

Table 3. K_i control rules

E_c	E						
	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NS	NM	NB	NM	NM	ZE
NM	NB	NS	NS	NM	NS	PS	ZE
NS	NM	NS	NS	NS	NS	NS	ZE
ZE	ZE	ZE	ZE	ZE	ZE	ZE	ZE
PS	ZE	PS	PS	PS	NS	PS	PM
PM	ZE	PS	PS	PM	PS	PS	PB
PB	ZE	PS	PM	PB	PS	PM	PB

Table 4. K_d control rules

E_c	E						
	NB	NM	NS	ZE	PS	PM	PB
NB	PB	PB	PB	PM	PM	PS	ZE
NM	PB	PB	PB	PM	PM	PS	ZE
NS	PB	PS	PS	ZE	PS	ZE	PS
ZE	PM	PS	PS	NS	ZE	NS	NS
PS	PS	ZE	ZE	NS	NS	NM	NM
PM	ZE	ZE	NS	NM	NM	NM	NB
PB	ZE	NS	NM	NM	NB	NB	NB

4 Results

4.1 Simulation Results

To verify the autonomous depth setting performance of the miniature detection buoy based on the fuzzy adaptive PID algorithm. The Simulink software is used to construct a fixed-depth control simulation model of the miniature detection buoy. Fig. 7 shows that the simulation models include a geared motor dynamics model, a miniature detection buoy dynamics model, and a fuzzy adaptive control PID controller.

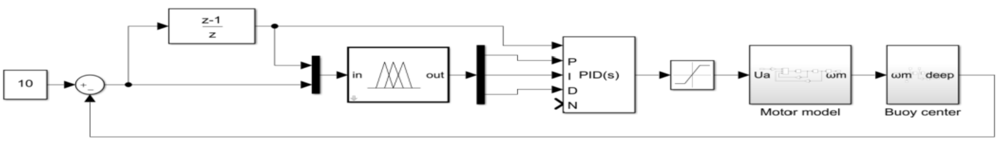


Fig. 7. The fixed-depth control simulation model of fuzzy adaptive PID

The target dive depth is set to 10 meters. The gain parameters K_p, K_i and K_d adjust the PID controller output to obtain the speed and steering of the geared motor. Moreover, it is combined with the miniature detection buoy dynamics model to obtain the dive depth of the buoy. Finally, the miniature detection buoy converges to the target depth.

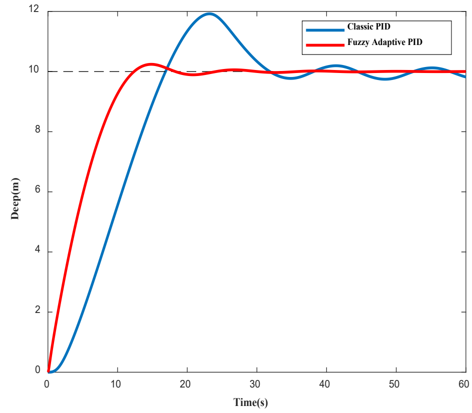


Fig. 8. The simulation results of classic PID and fuzzy adaptive PID

According to the analysis of the simulation results, a set of suitable parameters for the classic PID is determined as = 0.65, K_i = 0.03, and K_d = 0.035. Fig. 8 shows the control effects of classic PID and fuzzy adaptive PID miniature detection buoy applied to the buoy fixed-depth control model respectively. The results show that the fuzzy adaptive PID algorithm has a better control effect than the classic PID algorithm. The system overshoot is reduced from 19.2% to 2.4%, and the response time is reduced from 16.8s to 12.2s.

4.2 Practical Trials Result

Since the complex ocean environment and the working state of the internal mechanical structure of the miniature detection buoy will have an impact on the control effect when it works in practice. Therefore, based on the completion of the fixed-depth control simulation, experimental tests are carried out to verify the performance of the fuzzy adaptive PID algorithm for fixed-depth control.

In sea trials, the miniature detection buoy was programmed to hold 10m depth in 20m of water of the South China Sea and the depth value was stored every 100ms. As shown in Fig. 9, the overshoot of the miniature detection buoy using the fuzzy adaptive control PID algorithm control strategy is 4.1% and the response time is 17.1s.

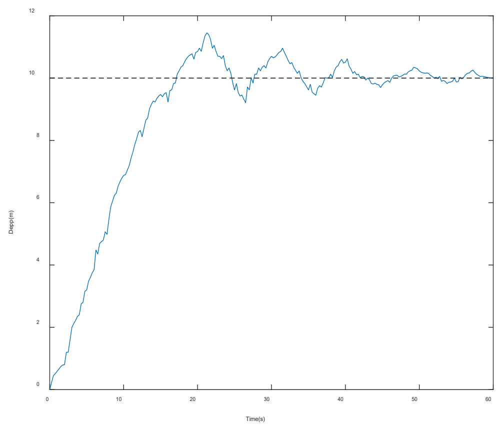


Fig. 9. The practical trials result of fuzzy adaptive PID

5 Conclusion

Based on simulation analysis, compared with the classic PID algorithm, the fuzzy adaptive PID algorithm has small overshoot, small error and fast response time, with satisfactory dynamic performance. The miniature detection buoy with fuzzy adaptive PID algorithm control strategy has high fixed-depth accuracy and fast dynamic response in sea trials. Due to the complex control mechanism and slow response time of traditional ocean buoys, it is difficult to deploy rapidly in shallow waters. The paper research the design and development of a new miniature detection buoy to address the drawbacks of the current traditional miniature buoys. An innovative structure of inner and outer sleeves is used to create a miniature detection buoy of rapid deployment, miniaturization and data collection at a fixed-depth.

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