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Trajectory Tracking Control of UUV Based on Backstepping Sliding Mode With Fuzzy Switching Gain in Diving Plane

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ABSTRACT Considering the actual situation of time-varying interference in the underwater environment, a trajectory tracking control method for an underactuated Unmanned Underwater Vehicle (UUV) underwater exploration based on backstepping sliding mode with fuzzy switching gain is designed in this paper. Firstly, the motion equations of UUV in diving plane are given. Secondly, the virtual control variable is designed to replace the pitch angle to avoid the singular value phenomenon. Combining with the backstepping technique, the fuzzy switching sliding mode controller is proposed. Thirdly, in order to decrease the chattering phenomenon of sliding mode control, the fuzzy rule of sliding mode gain is designed. Fourthly, based on Lyapunov theory and comparison principle, the global asymptotic stability of UUV closed-loop tracking error system is proved. Finally, the simulation results demonstrate the effectiveness and robustness of the proposed controller.

INDEX TERMS Unmanned underwater vehicle (UUV), trajectory tracking control, sliding mode method, backstepping method, fuzzy switching, diving plane.

I. INTRODUCTION

UUVs are small and flexible ocean exploration tools with a wide range of applications in submarine target detection, oil pipeline inspection and seabed topography [1]–[4]. It is particularly important to study the motion control of UUV, which is the basis for UUV's missions. However, due to the complexity of the underwater environment and the underactuation of UUV model, the problems of trajectory tracking control of UUVs become difficult. The disturbance of ocean waves or currents can failure stability and the coupling and nonlinearity of UUVs also add the difficulty for designing controllers [5], [6]. Therefore, higher requirements are put forward for the design of the tracking controller of UUVs, and most of the researches have contributed to these issues.

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To solve the UUV motion control problems, various control techniques have been proposed for trajectory tracking control of UUV by many researchers. The most well-known control methods, Proportional-Differential (PD) and Proportional-Integration-Differential (PID), have been applied to control UUVs due to the simplicity of design. The PD controller that guarantees position error convergence and local stability can be used for the set-point control or regulation of UUVs [7]. The PID controller is proposed by Smallwood and Whitcomb to provide the accurate station keeping of UUVs [8]. However, when UUVs are in more complex environment or the dynamic model of UUVs is coupled and nonlinear, the PID controller cannot ensure the exact trajectory tracking. For better control performance of UUVs, many robust controllers have been designed for trajectory tracking by researchers, for instance, Adaptive control [9]–[14], Backstepping control [15]–[21], Neural-Network based control (NNC) [21], [22], Predictive control [23], Sliding Modes Control (SMC) [5]–[7], [24]–[27], and High Order Sliding Modes Control (HOSMC) [28]–[34], Fuzzy Logic Controllers (FLC) [35]–[41]. Each control method has advantages and disadvantages.

Backstepping control is a one of the most common control methods for trajectory tracking of underactuated UUV. This technique is a kind of nonlinear feedback control method based on Lypaonov theory. Lapierre [15] proposes a path following controller of UUV by using backstepping techniques and Lypaonov theory. All error trajectories of path following converge to zero. However, the unknown sea currents disturbance is not discussed, which is considered in this paper. Li [16], [17] presents an adaptive controllers combining with traditional backstepping method for diving control of an UUV. But the heave dynamics and the pitch kinematics of UUVs is simplified. So we have considered the nonlinear model and add the heave item. In order to resolve the sharp speed jumps problem, a backstepping path-following controller based on a kind of bio-inspired neurodynamics model of UUV is proposed in [18]. Combining with the one-step ahead backstepping method and Lyapunov's direct method a controller that guarantees an under-actuated omnidirectional intelligent navigator (ODIN) track the expected three- dimensional trajectory is presented in [19]. Then Do [20] designs a global trajectory-tracking controller of under-actuated ODINs in two-dimensional space, which considers the deterministic and stochastic disturbances. But the input of controller has obvious chattering throughout the simulation period, which has been improved in this paper. For improving the robustness of the controller, a developed method in combination of the sliding mode algorithm and backstepping scheme is proposed in [21]. The uncertainty of modeling uncertainty and external disturbance is estimated by using the radial basis function neural network.

Another robust control method used widely in UUVs is sliding mode control, which has the strengths in robustness against model uncertainties and environmental disturbances. In order to decrease or eliminate the chattering phenomenon in first order SMC, Fossen [7] uses sigmoid functions to smooths the control inputs, however the stability of tracking the expected trajectory is reduced. In [24], a re-configuring sliding mode controller for UUV is proposed considering environmental disturbances. The gain of the sliding-mode controller update according to the disturbance distribution information for increasing the robustness. But the control model is not underactuated. So the controller cannot be applied to complex underactuated UUVs, which is considered in this paper. An adaptive sliding mode controller based on the principle of sliding mode is designed in [25]. The local recurrent neural network is introduced to estimate the unknown uncertainties, and by using switch gain adjust method to reduce chattering issue. Kim [5] proposes an integral sliding mode controller for precise manoeuvring of UUV, which is effective in resolve the problem of uncertainties in the hydrodynamic and hydrostatic parameters and the unpredictable disturbance caused by ocean waves, tides and currents. In the case of input nonlinearities and unknown disturbances, Cui [6] presents a sliding-mode-based adaptive controller is developed for the attitude control of UUVs. However, the controller only design for control the attitude and the values of input have more chattering compared with this paper which is not allowed in the actuators.

High Order Sliding Mode Control has better performance in reducing the chattering effect than the first order SMC. Joe [28] presents a second-order sliding-mode controller, and closed-loop system of UUV is exponentially stable in the presence of modeling errors and environmental disturbances. In [29], based on the equivalent output injection adaptive sliding mode observer a novel multivariable output feedback adaptive nonsingular terminal sliding mode controller is designed. The trajectory tracking error of UUV can converge to a small field in finite time and the undesired chattering decreases effectively. Sarfraz [30] uses an adaptive integral sliding mode control to stabilize a new underwater system of UUV which has uncertainties in matched form. Path following control of UUV is also one of underwater surveillance missions. An adaptive second order sliding mode path following control for a portable UUV is proposed in [31], which provides faster convergence and eliminates the chattering effect of control output. However, it increases the amount of calculation compared to this article. Qiao [32] focuses on the control of trajectory tracking for fully actuated autonomous underwater vehicles. In order to stabilize UUVs in the presence of dynamic uncertainties and time-varying external disturbances, an adaptive second-order fast nonsingular terminal sliding mode control scheme is given. And Qiao proposed double-loop integral terminal sliding mode control scheme and adaptive non-singular integral terminal sliding mode control scheme for UUVs in [33], [34]. The results show that the two proposed control schemes improve the convergence rate and enhance robustness in position tracking. But the complex underactuated problem of UUVs is not discussed.

Compared with control method and the references above, the main contributions of this paper can be emphasized as follows: (1) We give the motion equations in the diving plane, that consider the heave item and external disturbances. (2) Based on the control objective, we design a backstepping controller combining with sliding mode method for trajectory tracking of the under-actuated UUV, and introduce the virtual control variables and fuzzy switching gain to improve the effect of the controller.

In this paper, a trajectory tracking controller based on backstepping sliding mode with fuzzy switching gain is designed. The kinematics and kinetics of UUV in diving plane are given. In order to simplify the design of the backstepping method and avoid the singular value, the virtual control variable is designed. As the chattering phenomenon of sliding mode control is obvious, the fuzzy rule of sliding mode gain is proposed to eliminate the chattering effect. The global asymptotic stability of UUV closed-loop tracking error system is demonstrated by using Lyapunov theory and comparison principle. Simulation shows that by using the

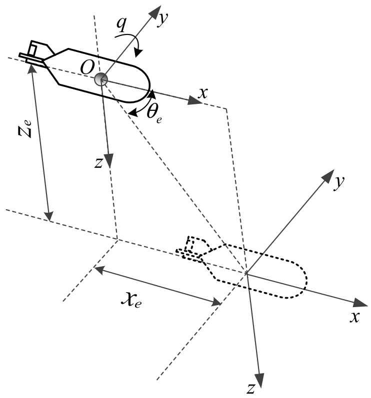

FIGURE 1. UUV's depth dive motion.

controller designed in this paper can accurately control the underactuated UUV tracking desired path, and significantly reduces the chattering of the control input compared with the traditional sliding mode controller.

II. PRELIMINARIES AND PROBLEM FORMULATION

A. MODEL OF UUV

The kinematics of UUV in diving plane can be expressed as [42]–[45]:

$$\begin{cases} m_{33}\dot{w} = m_{11}uq - d_{33}w - \sum\limits_{i\geq 2} d_{w^i}\,|w|^{i-1}w + \tau_{ww}, \\ m_{55}\dot{q} = (m_{33}-m_{11})\,uw - d_{55}q - \sum\limits_{i\geq 2} d_{q^i}\,|q|^{i-1}q + \tau_q + \tau_{qq} \\ \qquad - \rho g\nabla\overline{GM_L}\sin\theta, \end{cases} \tag{1}$$

where, assume the velocity of u is fixed value in this paper, which represents surge. w, q are state vectors of the system, which represent the heave velocity and the pitch angular velocity of the UUV, respectively. $m_{11} = m - X_{\dot{u}}$; $m_{33} = m - Z_{\dot{w}}$; $m_{55} = I_y - M_{\dot{q}}$; $d_{33} = Z_w$; $d_{w^i} = Z_{w^i}$; $d_{55} = M_q$; $d_{q^i} = M_{q^i}$. m is the mass of UUV, $X_{\dot{u}}$, $Z_{\dot{w}}$, $M_{\dot{q}}$ are added mass; I_y is rotational inertia; Z_w, M_q are hydrodynamic damping, Z_{w^i}, M_{q^i} are high order hydrodynamic damping. ρ, g, ∇, $\overline{GM_L}$ represent water density, gravitational acceleration, water volume, and metacentric height. τ_{ww}, τ_{qq} represent external disturbance; τ_q is control input.

Kinetics of UUV in diving plane are expressed as follows:

$$\begin{cases} \dot{z} = -u\sin\theta + w\cos\theta, \\ \dot{\theta} = q, \end{cases} \tag{2}$$

where, z, θ are output vectors of the system, which represent the UUV depth position and pitch angle. The UUV's depth dive motion diagram is shown in Fig. 1:

III. CONTROLLER DESIGN AND STABILITY ANALYSIS

The sliding mode controller is designed based on the backstepping method. In order to reduce the chattering phenomenon existing in the traditional sliding mode controller, a fuzzy switching rule for controlling the gain is designed,

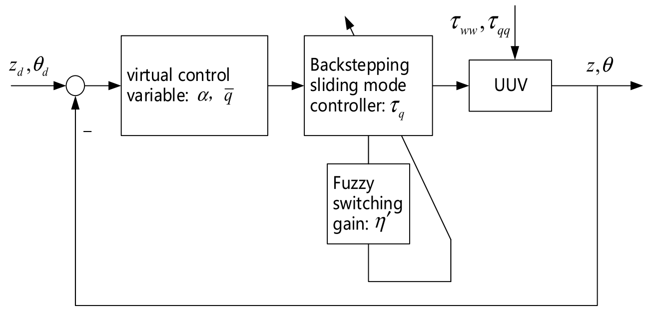

FIGURE 2. UUV's depth dive motion.

which ensures that UUV can accurately track the desired trajectory under the condition of external interference during deep dive, so the control objective is to guarantee the vertical motion error equals zero. Define positon error as follows:

$$z_e = z - z_d, \tag{3}$$

The block diagram of the designed control scheme is shown as follows:

A. BACKSTEEPING SLIDING MODE CONTROLLER DESIGN

Step 1:

$$V_1 = \frac{1}{2}z_e^2, \tag{4}$$

Taking the derivative of both sides of equation (4) substituting equation (2), we obtain equation (5) as follows:

$$\dot{V}_1 = z_e\dot{z}_e = z_e\left(-u_0\sin\theta + w\cos\theta - \dot{z}_d\right), \tag{5}$$

If the error of θ is chosen as to stabilize the error of trajectory tracking, that may cause singular value problems. Therefore, θ_e must be replaced as $\alpha = -u_0\sin\theta_e\cos\theta_d$, where $\theta_e = \theta - \theta_d$.

To guarantee that the value of V_1 is negative, α is used as virtual control variable, its expected value is as follows:

$$\alpha_d = -k_1z_e + u\cos\theta_e\sin\theta_d - w\cos\theta + \dot{z}_d. \tag{6}$$

As α_d is not real control variable, its error term is defined as:

$$\alpha_e = \alpha - \alpha_d, \tag{7}$$

Combining equations (4)-(7), we can obtain:

$$\begin{aligned} \dot{V}_1 &= z_e\left(\alpha - u\cos\theta_e\sin\theta_d + w\cos\theta - \dot{z}_d\right) \\ &= z_e\left(-k_1z_e + \alpha_e\right) \\ &= -k_1z_e^2 + z_e\alpha_e. \end{aligned} \tag{8}$$

Step 2:

Combining equation (4), a new Lyapunov function candidate can be chosen as:

$$V_2 = V_1 + \frac{1}{2}\alpha_e^2, \tag{9}$$

The derivative of α_e is obtained combing with equations (6) and (7) as:

$$\begin{aligned}\dot{\alpha}_e &= \dot{\alpha} - \dot{\alpha}_d \\ &= -u_0 \cos\theta_d \cdot \cos\theta_e \cdot \dot{\theta}_e - \dot{\alpha}_d \\ &= q\left(-u_0 \cos\theta_d \cos\theta_e\right) - \dot{\alpha}_d, \end{aligned} \tag{10}$$

To guarantee that the value of $\dot{V}_2$ is negative, q is used as a virtual variable. Define $\bar{q} = q\cos\theta_e$, its expected value is as follows:

$$\bar{q}_d = \frac{1}{u_0 \cos\theta_d}\left(k_2\alpha_e + z_e - \dot{\alpha}_d\right), \tag{11}$$

Considering that q both $\bar{q}$ are uncontrollable, the error terms are defined as:

$$q_e = q - q_d, \tag{12}$$
$$\bar{q}_e = \bar{q} - \bar{q}_d, \tag{13}$$

According to the above definitions, we can have:

$$\begin{aligned}\bar{q}_e &= \bar{q} - \bar{q}_d \\ &= q\cos\theta_e - \bar{q}_d \\ &= q_e \cos\theta_e + \delta, \end{aligned} \tag{14}$$

where, $\delta = q_d\left(\cos\theta_e - 1\right)$, combing with equation (11) and (14), we can find it is bounded.

Combining equations (10)-(14) and simultaneously deriving both sides of equation (9), we can obtain:

$$\begin{aligned}\dot{V}_2 &= -k_1 z_e^2 + z_e\alpha_e + \alpha_e\dot{\alpha}_e \\ &= -k_1 z_e^2 + \alpha_e\left(z_e + \dot{\alpha}_e\right) \\ &= -k_1 z_e^2 - k_2\alpha_e^2 - \alpha_e u_0 \cos\theta_d \cos\theta_e q_e - \delta', \end{aligned} \tag{15}$$

where, $\delta' = \alpha_e u_0 \cos\theta_d \delta$.

Step 3:

Combining equation (4), a new Lyapunov function candidate can be chosen as:

$$V_3 = V_2 + \frac{1}{2}q_e^2. \tag{16}$$

Taking the derivative of both sides of Lyapunov function, we obtain equation (17) as follows:

$$\dot{V}_3 = -k_1 z_e^2 - k_2\alpha_e^2 - \alpha_e u_0 \cos\theta_d \cos\theta_e q_e - \delta' + q_e\dot{q}_e. \tag{17}$$

Deriving both sides of equation (14), you can have:

$$\dot{q}_e = \dot{q} - \dot{q}_d = \frac{1}{m_{55}}\left[\left(m_{33} - m_{11}\right)uw - d_{55}q - \sum_{i\geq 2} d_{q^i}\left|q\right|^{i-1}q + \tau_q + \tau_{qq}\right] - \dot{q}_d. \tag{18}$$

According to the sliding mode structure, the sliding surface is define as $s = q_e$. To ensure that equation (17) is negative, take the control input τ_q as follows:

$$\begin{aligned}\tau_q &= m_{55}\left(-k_3 q_e + \dot{q}_d + \alpha_e u_0 \cos\theta_d \cos\theta_e\right) - \eta\,\text{sgn}(s) \\ &\quad - \left(m_{33} - m_{11}\right)uw + d_{55}q + \sum_{i\geq 2} d_{q^i}\left|q\right|^{i-1}q, \end{aligned} \tag{19}$$

where, $\eta \geq D > 0$, D is the upper bound of disturbance variable τ_{qq}.

When the model is uncertain and the interference is large, a large chattering is caused, and the gain η of switching term needs to be adjusted. If $s\dot{s}$ changes, the gain should also change. Therefore, in order to prevent chattering, a fuzzy switching rule is introduced, and a sharp change of the gain becomes less.

B. FUZZY RULE DESIGN

In order to eliminate the uncertain term τ_{qq} in equation (17), the gain η must be utilized to ensure that the existence of the sliding surface is satisfied. But the uncertain term is time-varying, so the gain need to be adjusted in real time.

Define a new gain as follows:

$$\eta' = \eta \cdot H(t). \tag{20}$$

Fuzzy rules obey two rules:

$$\begin{aligned}&\text{If } s\dot{s} < 0, \text{ then } \eta' \text{ increases}, \\ &\text{If } s\dot{s} > 0, \text{ then } \eta' \text{ decreases}. \end{aligned} \tag{21}$$

Combining equations (20) and (21), a fuzzy system is designed between $s\dot{s} < 0$ and $H(t)$. Define the fuzzy sets as:

$$s\dot{s} = \{NB, NM, ZO, PM, PB\}, \tag{22}$$
$$H(t) = \{NB, NM, ZO, PM, PB\}. \tag{23}$$

where, NB is negative big, NM is negative medium, ZO is zero, PM is positive medium, PB is positive big.

The fuzzy rules are designed as follows:

$$\begin{aligned}&\text{Rule1}: \text{If } s\dot{s} \text{ is } PB, \text{ then } H(t) \text{ is } PB, \\ &\text{Rule2}: \text{If } s\dot{s} \text{ is } PM, \text{ then } H(t) \text{ is } PM, \\ &\text{Rule3}: \text{If } s\dot{s} \text{ is } ZO, \text{ then } H(t) \text{ is } ZO, \\ &\text{Rule4}: \text{If } s\dot{s} \text{ is } NM, \text{ then } H(t) \text{ is } NM, \\ &\text{Rule5}: \text{If } s\dot{s} \text{ is } NB, \text{ then } H(t) \text{ is } NB, \end{aligned} \tag{24}$$

where, the input of the fuzzy system is $s\dot{s} < 0$, and the output is $H(t)$. The input and output membership functions of the fuzzy system are shown in Fig. 3–4.

The output obtained by using the fuzzy rule is substituted into equation (19), and the controller can be expressed as:

$$\begin{aligned}\tau_q &= m_{55}\left(-k_3 q_e + \dot{q}_d + \alpha_e u_0 \cos\theta_d \cos\theta_e\right) - \eta H(t)\,\text{sgn}(s) \\ &\quad - \left(m_{33} - m_{11}\right)uw + d_{55}q + \sum_{i\geq 2} d_{q^i}\left|q\right|^{i-1}q \\ &= m_{55}\left(-k_3 q_e + \dot{q}_d + \alpha_e u_0 \cos\theta_d \cos\theta_e\right) - \eta'\text{sgn}(s) \\ &\quad - \left(m_{33} - m_{11}\right)uw + d_{55}q + \sum_{i\geq 2} d_{q^i}\left|q\right|^{i-1}q. \end{aligned} \tag{25}$$

When we choose the membership function of the variables, the low-resolution fuzzy set is used in the region with large error, and the higher-resolution fuzzy set is selected in the region with less error, which can achieve better control precision and better control effect. According to the characteristics of input variables and output variables, the range of input and

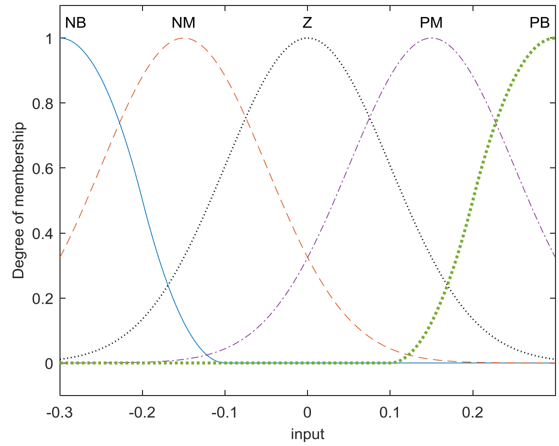

FIGURE 3. Membership function of input.

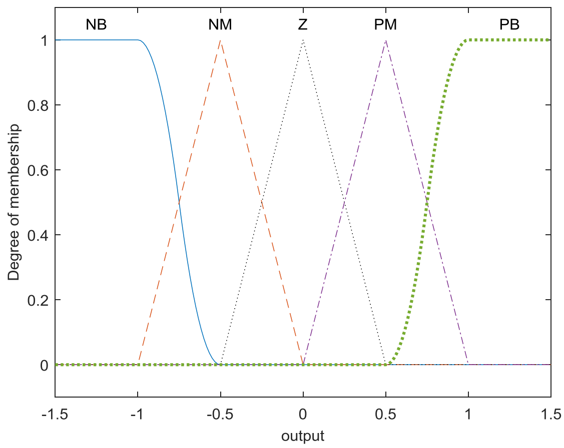

FIGURE 4. Membership function of output.

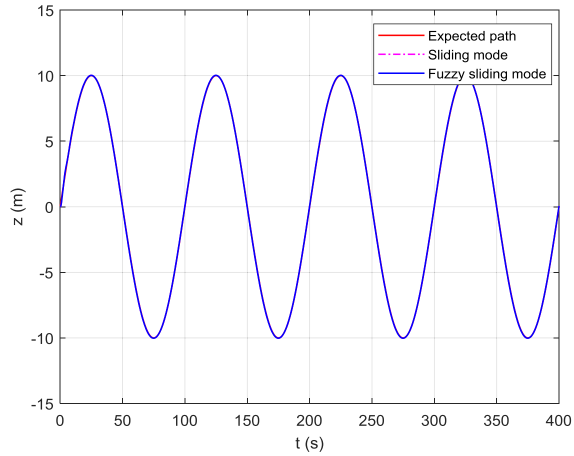

FIGURE 5. Depth control response curve of UUV.

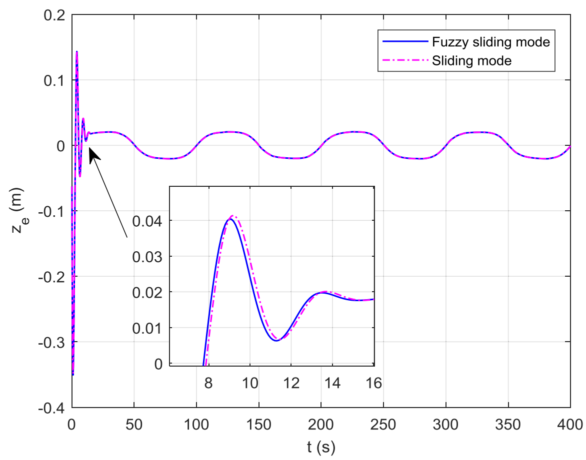

FIGURE 6. Depth error curve of UUV.

output of the fuzzy system are defined from -0.3 to +0.3 and from -1.5 to +1.5, respectively.

C. STABILITY ANALYSIS

Substituting the controller designed in this paper into the dynamic model of UUV, and combining with equation (16), we can obtain:

$$\dot{V}_3 = -k_1 z_e^2 - k_2 \alpha_e^2 - k_3 q_e^e - \eta' \operatorname{sgn}(s) s + q_e \tau_{qq} - \delta'. \tag{26}$$

Define $\gamma = [z_e, \alpha_e, q_e]^T$, and the Lyapunov function candidate V_3 can be express as:

$$2V_3 = \|\gamma\|^2. \tag{27}$$

Combining with formulas (16) and (19), it is known as:

$$\dot{V}_3 \le -2\lambda V_3 - \delta', \tag{28}$$

where, $\lambda = \min\{k_1, k_2, k_3\}$.

Due to the boundedness of δ', according to the comparison principle in [46], we can obtain:

$$V_3 \le V_3(0)\, e^{-2\lambda t} - \frac{\delta'}{2\lambda}, \tag{29}$$

$$\|\gamma(t)\| \le \|\gamma(0)\|\, e^{-\lambda t} - \sqrt{\frac{\delta'}{\lambda}}. \tag{30}$$

Therefore, the closed-loop trajectory tracking error can converge to a compressed bounded set near zero by adjusting the gain λ, that is, the system is globally asymptotically stable.

IV. SIMULATION

In order to verify that the fuzzy switching gain based backstepping sliding mode controller designed in this paper can realize the accurate trajectory tracking control of UUV under the external disturbance. The simulation experiment is carried out by MATLAB, and the traditional sliding mode control method is compared in this simulation. The simulation results are shown in Fig. 5–11.

The parameters of the two sliding mode controllers in equations (19) and (25) are the same, and the control gains are selected as: $k_1 = 1, k_2 = 1, k_3 = 10, \eta = 15$.

Set the longitudinal speed u of the underactuated UUV is $u_0 = 1m/s$, the initial position is $z_0 = 0$, the initial attitude angle is $\theta = 0$. The UUV model parameters are: $m_{11} = 200$,

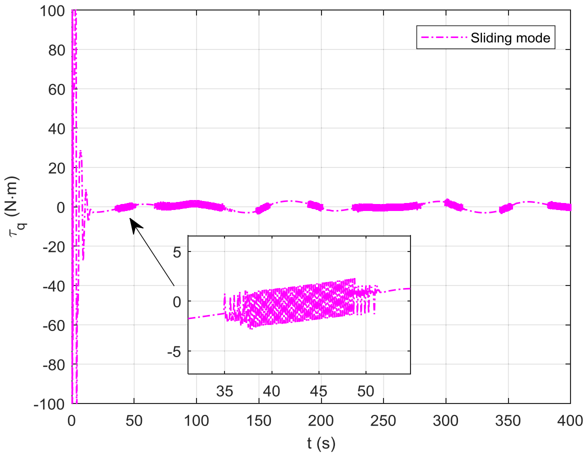

FIGURE 7. Depth control action τ_q of UUV.

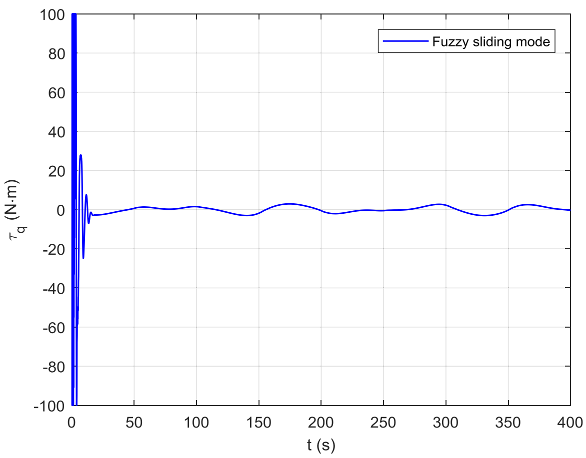

FIGURE 8. Depth control action τ_q of UUV.

$m_{33} = 250$, $m_{55} = 70$, $d_{33} = 50$, $d_{55} = 100$, $d_{w^2} = 200$, $d_{q^2} = 100$. Disturbance variables are $\tau_{ww} = 1\sin(0.01t)$ and $\tau_{qq} = 1\sin(0.01t)$.

The trajectory tracking curve of UUV and the expected attitude angle are chosen as:

$$\begin{cases} z_d = 10\sin(0.02\pi t), \\ \theta_d = -\arcsin\left(\dot{z}_d / u_0\right). \end{cases} \tag{31}$$

It can be seen from Fig. 5 that under the traditional sliding mode control and fuzzy sliding mode control the UUV can track the desired deep dive path very well, and the error of using fuzzy sliding mode control is smaller than the traditional method in Fig. 6, but the difference is not obvious. By comparing Fig. 7 and Fig. 8, it can be clearly seen that the control input has large chattering in the traditional sliding mode, and in the sliding mode controller designed in this paper the control input only has chattering at the initial stage, but then there is almost no chattering. We can see the prominent feature of the designed controller is that the chattering is smaller than the traditional sliding mode controller proposed in some other literatures. Fig. 9 reflects the change in the attitude angle of the deep dive of UUV. It can be seen that the two curves have the same trend and the difference is not obvious. Fig. 10 reflects the change in pitch, and the two curves change almost the same. The UUV's heave curves in Fig. 11 are also the same, and the curve of the backstepping

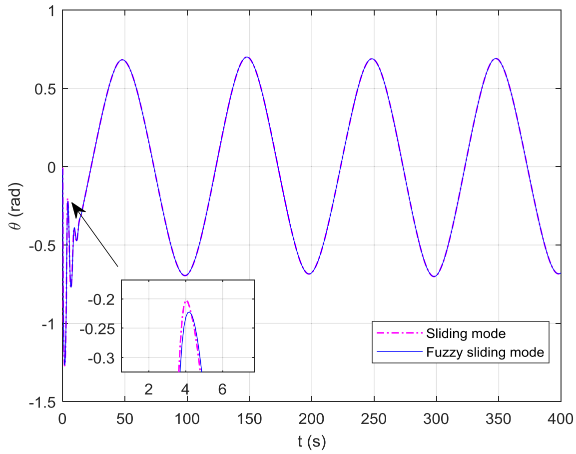

FIGURE 9. Attitude angle response curve of UUV.

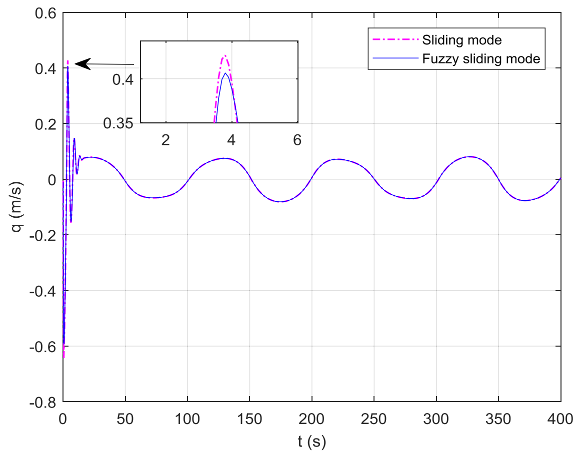

FIGURE 10. Pitch velocity of UUV.

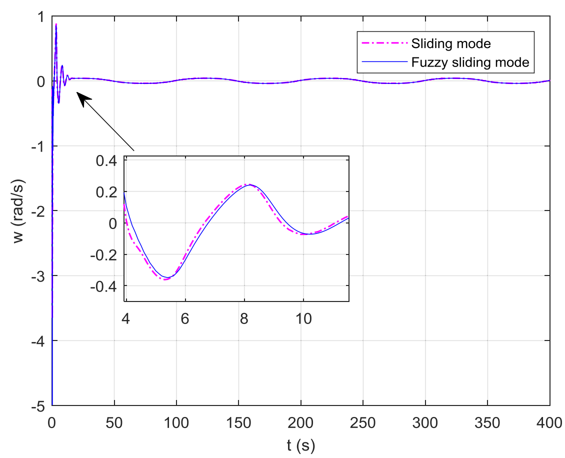

FIGURE 11. Heave velocity of UUV.

sliding mode control method by using fuzzy switching gain is more smooth, which is superior to the traditional sliding mode control.

V. CONCLUSION

In this paper, for the trajectory tracking in diving plane control problem of underactuated UUV, considering the existence of time-varying interference, a sliding mode control method with fuzzy switching gain is designed in combination with backstepping method. By using the backstepping method to select the Lyapunov functions, the virtual control variable is introduced to solve the singular value problem that can be caused by the traditional backstepping method. The fuzzy rule of sliding mode control gain is designed. Then the backstepping sliding mode controller based on fuzzy switching gain is given. The stability of the closed-loop tracking system is proved by Lyapunov theory and comparison principle. Finally, apply the controller proposed in this paper to the UUV motion model and simulate by MATLAB software. The experimental results verify that the controller designed in this paper can guarantee the UUV accurately track the expected path in the presence of time-varying interference and effectively eliminate the chattering in the traditional sliding mode control method, which indicates that the controller has high tracking accuracy and better robustness.

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