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AUV Plane Track Tracking Control Algorithm Based on Three Closed Loops

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Abstract. In order to solve the possible track deviation problem of autonomous underwater vehicle (AUV) in the course of linear track tracking, we developed a velocity three closed loop motion control algorithm combined with distance information, which is specially used for track tracking. This algorithm is based on line-of-sight guidance strategy and introduces a time-varying forward-looking distance to enhance the flexibility and response speed of the AUV. In the design of the control algorithm, we integrate the advantages of PID control, fuzzy PID control and parameter adaptive adjustment, so as to improve the adaptability and robustness of the algorithm. In particular, we use a range three closed loop speed control strategy, which means that the AUV dynamically adjusts its desired speed during sailing based on the real-time distance deviation from the end of the desired track segment. With this design, the AUV is able to slow down ahead of time and make low-speed turns, when necessary, effectively avoiding excessive course Angle adjustment. In addition, the parameter adjustment mechanism in the algorithm enables it to flexibly cope with various navigation conditions. In the case of large Angle turns, the AUV can still accurately travel along the intended track, significantly reducing the phenomenon of track deviation.

Keywords: Autonomous underwater vehicle, Tracking, Line of sight method, Triple closed loop control

1. Introduction

Autonomous underwater vehicle (AUV) in areas such as military, Marine resources exploration, environment monitoring and emergency rescue, and other key areas, both show the indispensable important role. With the expansion of application, the trajectory tracking capability of AUV has become an important factor affecting the efficiency and accuracy of its task execution. However, due to the complexity of underwater environment, interference uncertainty and the characteristics of AUV itself, trajectory tracking control becomes a very challenging problem. Track tracking is to obtain the expected heading from the position and expected route; By adjusting the steering Angle and motor speed, the control algorithm ensures that the AUV can enter smoothly from any starting position and sail stably along the expected track at the target speed according to the preset heading and speed requirements.

In the field of track tracking algorithms, the Line-Of-Sight (LOS) principle [1] presents a unique advantage in that its operation does not depend on any dynamic control model, achieving the principle independence of the algorithm. The desired heading obtained by this principle is determined only by the real-time position of autonomous underwater vehicle and the preset desired track. It is worth emphasizing that the LOS principle shows excellent robustness in the face of white noise, and its design parameters are extremely simple, only the core parameter of the forward-looking distance can be adjusted. LOS principle effectively simplifies the complex tracking error problem to a single course Angle error, thus achieving excellent convergence characteristics, and this advantage makes it widely adopted and applied in the field of track tracking control. Reference [2] proposes an improved line-of-sight method to coordinate the path tracking performance of AUVs with their ability to resist ocean current interference. In this method, the observer gain is dynamically adjusted by fuzzy control, and the error of state observer prediction and AUV speed regulation is compensated by the switch symbol function in sliding mode control, thus improving the tracking accuracy and anti-interference ability of the system. In order to better follow the path of sharp turns, Du Peizhou et al [3] proposed adaptive looking forward distance. By introducing auxiliary variables into the conventional line-of-sight guidance method and using an indirect adaptive disturbance observer to estimate the disturbance of the AUV motion, an improved LOS guidance law is designed to track the predetermined path more accurately.

In the category of control algorithms, PID and its optimization algorithms [4] are famous for their structural simplicity and excellent robustness and adaptability, which make them relatively less dependent on the specific model of the system. On the other hand, Chen Shili et al. [5] proposed an innovative double closed-loop control strategy to address the limitation of poor track tracking effect of autonomous underwater vehicle when turning at high speed. The strategy combines the loop of course control with the loop of speed control, and adjusts the steering speed of the loop according to the deviation Angle difference in the loop while adjusting the course. The experimental results show that compared with the conventional control algorithm, the double closed-loop control algorithm can achieve better track tracking control during AUV steering. With the vigorous development of computer technology, the advanced control theory system based on state space is becoming more and more mature. In this context, advanced control methods such as sliding mode control [6], fuzzy control [7], and comprehensive application of various control algorithms [8] came into being. These advanced control strategies show significant advantages over PID control under multiple operating conditions. However, they also face challenges such as high requirements for mathematical model accuracy, high computational complexity and difficult parameter tuning. At present, most research is still focused on the simulation level.

Aiming at the situation that AUV are traveling at high speed and need to operate with large turning radius, we propose a path tracking control strategy of AUV using line-of-sight guidance principle, and by designing forward distance parameters that can change with time, the maneuvering flexibility of AUV is significantly enhanced. A pioneering speed function is proposed to correct the real-time variation of expected speed with distance deviation. In the course of AUV sailing, the speed heading controller realizes triple closed-loop control. The fuzzy theory combined with PID is used for the expected course Angle tracking controller. The proposed method has good adaptability to setting complex sailing trajectories and fast convergence speed. The proposed speed loop continuously adjusts the expected sailing speed, which effectively improves the maneuverability of AUV and saves AUV energy consumption.

2. Model introduction and problem description

2.1. Model introduction

The model studied has a maximum diameter of 19 cm, a length of 1.6 m, a mass of 37kg, a cruciform rudder, a single propeller, a maximum working depth of 100 m, an endurance of 10 h, and a maximum speed of 5 knots. As shown in Figure 1, The dynamic model is as follows.

$$M_{RB} \cdot \dot{v} + C_{RB} \cdot v + M_A \cdot \dot{v} + C_A \cdot v + D_V \cdot v + g\left(\eta\right) = \tau \tag{1}$$

In the formula, M_{RB} is the inertial matrix of the rigid body itself, is the adding velocity of the rigid body, v is the velocity of the rigid body, C_{RB} is the Coriolis force and the radial force matrix of the rigid body, M_A is the additional hydrodynamic inertia matrix, C_A is the additive mass matrix M_A to generate

Coriolis force matrix, D_V is the damping moment matrix, $g(\eta)$ is the generalized restoring force matrix, and τ is the controlling force matrix

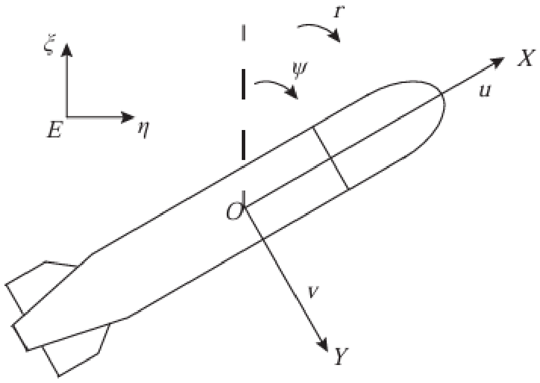


Figure 1. Schematic diagram of AUV plane coordinate system.

Considering the track tracking of the horizontal plane or a specific depth plane, the vertical and horizontal rudder of the cross-rudder act independently of each other, ignoring the AUV roll effect, the dynamic model of the horizontal plane can be established as follows:

$$\begin{cases}(m-X_{\dot{u}})\dot{u}=X_{|u|u}u|u|+(X_{vr}+m)vr+X_{rr}r^2+X_{prop}\\(m-Y_{\dot{v}})\dot{v}=Y_{|v|v}v|v|+(Y_{ur}-m)ur+Y_{ur}uv\\(I_z-N_{\dot{r}})\dot{r}-N_{\dot{v}}\dot{v}=N_{|v|v}v|v|+N_{|r|r}r|r|+N_{ur}ur+N_{uv}uv+N_{uu\delta_r}u^2\delta_r\end{cases} \tag{2}$$

Where, u, v and r are respectively the longitudinal, transverse linear velocity and yaw angular velocity of AUV in the satellite coordinate system XOY (the origin O is the center of buoyancy of AUV), and are respectively the acceleration corresponding to u, v and r, δ_r is the vertical rudder Angle; X_{prop} is the propeller thruster thrust; m is the AUV mass; I_z is the moment of inertia of AUV around the z axis. $X_{\dot{u}}$, $Y_{\dot{v}}$, $Y_{\dot{v}}$, $N_{\dot{v}}$, $N_{\dot{r}}$ is the additional mass, $X_{|u|u}$, $Y_{|v|v}$, $Y_{|r|r}$, $N_{|v|v}$, $N_{|r|r}$ is the damping force coefficient, X_{vr}, X_{rr}, Y_{ur}, Y_{uv}, N_{ur}, N_{uv} is the Coriolis force coefficient and N_{uu_r} is the rudder efficiency coefficient of the vertical rudder.

The kinematic model is

$$\begin{cases}\dot{x}=u\cdot\cos\psi-v\cdot\sin\psi\\\dot{y}=u\cdot\sin\psi+v\cdot\cos\psi\\\dot{\psi}=r\end{cases} \tag{3}$$

Where x and y represent the horizontal position coordinates of AUV in the geodetic coordinate system $\xi E\eta$ respectively, ψ is the yaw Angle, $\dot{x}$, $\dot{y}$, $\dot{\psi}$ is the first derivative of x, y, ψ respectively.

2.2. Problem Description

As shown in Figure 2, in the geodetic coordinate system $\xi E\eta$ plane, the desired straight path is formed by the eye point P_i (i=0, 1, 2). The real-time position of AUV is $P_t = (x_t, y_t)$, the coordinate points constituting the desired track segment are $P_k = (x_k, y_k)$ and $P_{k+1} = (x_{k+1}, y_{k+1})$, and the deviation of the vertical distance from AUV to the desired track is y_e(t).

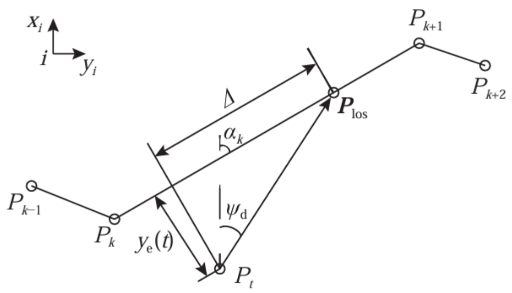


Figure 2. Principle of sight guidance.

The aim of AUV horizontal straight track tracking control is to design tracking algorithm and control algorithm to make AUV start from the initial position, reach the preset desired track, sail along the desired track at the desired speed, and minimize track overshoot during turning. The control objective is divided into the following two parts: 1) Control the AUV's sailing speed to maintain the desired sailing speed, that is $\lim_{t\to\infty}\left(v_t - v_d\right) = 0$. Where, v_t is the real-time sailing speed of AUV, v_d is the expected sailing speed of AUV. 2) The position of the control AUV converges to the desired track, and the deviation of the vertical distance between the real-time position and the expected track is 0, that is $\lim_{t\to\infty} y_e\left(t\right) = 0$. Wait for the AUV to finish sailing along the current desired path P_kP_{k+1}, and when the distance difference from the end point of this segment (P_{k+1} (x_{k+1}, y_{k+1})) is less than R, the AUV will track the next segment P_{k+1} P_{k+2}, this process is called cutting the desired path. The principle of AUV switching the desired track is as follows: (R is a constant, usually an integer multiple of the AUV length is selected or the design is based on the turning performance). AUV continuously tracks multiple target points, and the navigation task is completed when all the desired track segments are completed.

3. Design of track tracking control algorithm

3.1. Adaptive forward distance line of sight guidance

Line of sight guidance algorithm is a common and effective guidance strategy, which is widely used in track tracking. A LOS algorithm based on forward looking distance is adopted in this study. In this method, the position error is converted to course error, and the AUV is approximated to the target track by adjusting the combined velocity direction of the AUV so that it always points to the LOS vector point P_{los} on the desired track. In geodetic coordinate system, the course Angle of the desired track is defined as the Angle between the desired track and the vertical axis of the geodetic coordinate system. The heading Angle is calculated by the four-quadrant arctangent, the origin is the Angle between the starting position, the ray pointing to the point (y, x) and the positive direction of the X-axis. The course Angle of the desired track is determined by the two adjacent points P_k and P_{k+1}

$$\alpha_k = a\tan 2(y_{k+1} - y_k, x_{k+1} - x_k) \tag{4}$$

The vertical deviation from AUV real-time position P_t=(x_t, y_t) to desired track P_k, P_{k+1} is $y_e(t)$.

$$y_e(t) = (y_t - y_k)\cos\alpha_k - (x_t - x_k)\sin\alpha_k \tag{5}$$

Define the distance from the AUV's real time position on the desired track to the line-of-sight point P_{los} as the forward-looking distance Δ, then the output expected heading Angle is:

$$\psi_d = \alpha_k - a\tan 2(y_e(t), \Delta) \tag{6}$$

It can be seen from the above that the choice of forward-looking distance Δ will affect the size of the expected course Angle. When Δ is large, the vector point selection is far away, and the AUV will slowly approach the desired route. With the decrease of Δ, the speed of AUV convergence to the desired route will be accelerated, but it is easy to produce shock, overshoot and instability. Considering that when the AUV is far away from the desired track, the first thing is to approach the desired track quickly to reduce the lateral error, so a small forward-looking distance should be selected. When the AUV is near the expected track, a larger forward-looking distance should be selected to make the AUV slowly approach the expected track and minimize overshoot. Therefore, vertical distance ye(t) is introduced and simple time-varying forward-looking distance is adopted:

$$\Delta = (\Delta_{\max} - \Delta_{\min})\exp(-\lambda y_e^{\,2}(t)) + \Delta_{\min} \tag{7}$$

In the formula, $\Delta_{\min}$ and $\Delta_{\max}$ are the design forward looking distance respectively, which are generally selected as integer multiples of L; λ is the design factor.
The principle of AUV switching the expected trajectory:

$$(x_t - x_{k+1})^2 + (y_t - y_{k+1})^2 < R^2 \tag{8}$$

The linear distance between the AUV's current position and the target expected aircraft point is calculated. When the linear distance is less than the switching circle radius, the target track point is switched. Thus, the AUV can approach the desired route smoothly, effectively reduce the overshoot of position error, and realize the AUV tracking multiple target points to complete all the desired track segments.

3.2. Controller design

The LOS guidance algorithm has been used to convert position control into heading Angle control, and then the entire control target becomes heading control and speed control. The flow chart of the control algorithm is shown in Figure 3.

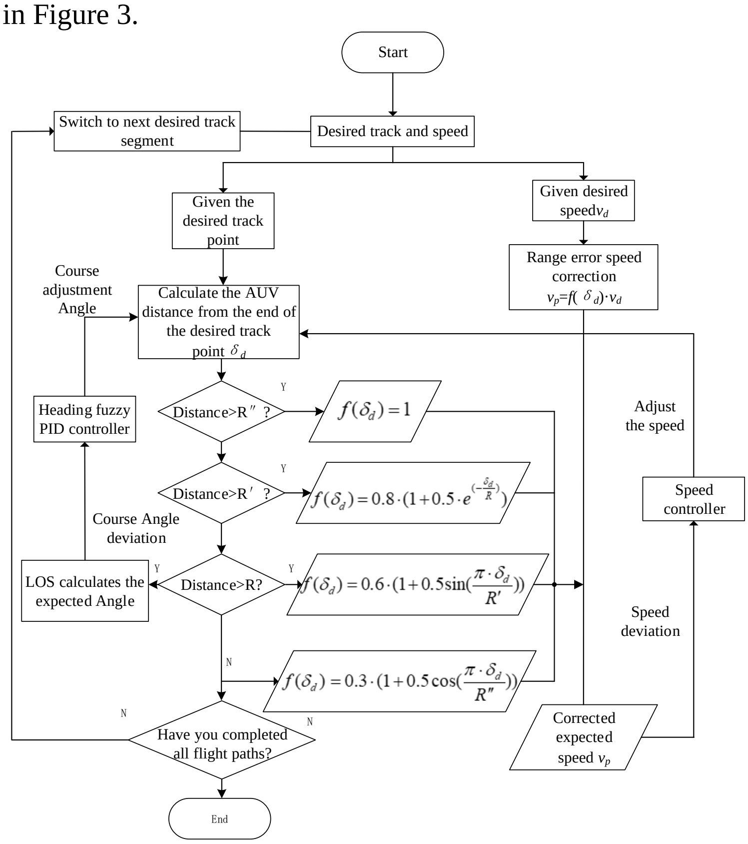


Figure 3. AUV distance three closed loop path tracking algorithm diagram.

As shown in Figure 4, in order to improve the robustness of heading control and adapt to the step expected signal brought by track segment switching, PID parameters are dynamically adjusted by fuzzy rules, so that the control system can flexibly adjust the control strategy according to real-time errors and error changes. When the error e(t) and the error change rate Δe(t) are different combinations, the fuzzy controller outputs the corresponding k_p, k_i and k_d values. By adjusting these outputs, the controller adaptively adjusts the response and optimizes the dynamic performance of the system. The traditional

PID guarantees the completion of the control. Combining traditional PID and fuzzy PID, the weight function is designed:

$$U(u_c,u_{cf})=\frac{\sin(\ln(u_c+1))+u_c^{\frac{1}{3}}\cdot e^{\cos(u_{cf})}}{u_c^{0.5}+u_{cf}^{0.5}}\cdot(1+\frac{\sin(u_c)}{1+u_{cf}^{2}}) \quad (9)$$

Where, u_c is the control output of PID controller, u_{cf} is the control output of fuzzy PID, and $U(u_c,u_{cf})$ is the final controller output after weighting the use weight function.

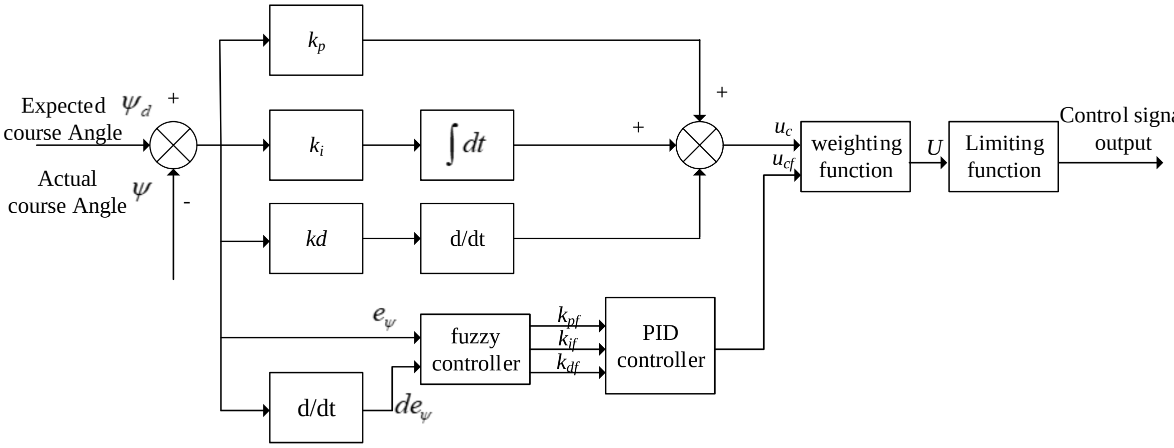


Figure 4. AUV heading controller design.

The underwater vehicle is sailing on a predetermined trajectory, and if the speed is large, the AUV will produce a large trajectory overshoot when switching the desired trajectory. Therefore, a speed controller based on the desired point distance is designed, as shown in Figure 5. During AUV sailing, the target speed is turned in real time according to the distance difference between AUV and the end of the desired track segment; When the AUV is about to switch the desired track, the expected speed is reduced, which makes the AUV switch the track at low speed and reduces the track overshoot. When the course change is complete, accelerate to the desired speed.

The input variables of course loop controller is expected course Angle and real course Angle, and the output is rudder Angle of steering gear. The input to the speed loop controller is the desired and actual speed of the AUV, as well as the position deviation δ_d from the end of the desired track segment. The relationship between the design position deviation and the speed loop input target speed is

$$v_p = f\left(\delta_d\right)\cdot v_d \quad (10)$$

Where: v_p is the corrected expected speed adjusted with the change of position deviation, that is, the expected target value of the final speed loop; The coefficient $f\left(\delta_d\right)$ is a function of the set deviation δ_d .

In order to make the AUV speed decrease gradually when it turns, without damaging the overall mechanical properties of the AUV and complicating the problem, the expected speed of the design correction changes with the change of distance deviation. The specific correction functions are as follows. R″, R′ and R are all constants, and R is R in the principle of same track renewal, which depends on the design of turning radius; When the deviation of AUV from the end of the expected track segment is greater than R″, it indicates that AUV is far away from the end of the expected track segment and will not switch course for the time being. At this time, the expected speed does not change, $f\left(\delta_d\right)$ = 1.0, that is, $v_p = v_d$. When the deviation of AUV from the end of the desired track segment is less than or equal to R″, it indicates that the AUV is ready to switch the desired track. At this time, the speed should be reduced to make the AUV turn at a low speed. The expression of coefficient $f\left(\delta_d\right)$ is as follows

$$f(\delta_d)=\begin{cases}\mathbf{1} & |\delta_d|>R'';\\ 0.8\cdot(1+0.5\cdot e^{(-\frac{\delta_d}{R})}), & R'<|\delta_d|<R''\\ 0.6\cdot(1+0.5\sin(\frac{\pi\cdot\delta_d}{R'})) & R<|\delta_d|<R''\\ 0.3\cdot(1+0.5\cos(\frac{\pi\cdot\delta_d}{R''})) & |\delta_d|<R\end{cases} \tag{11}$$

It can be seen from the above that the course speed controller forms a three closed-loop control during AUV navigation; During the course of steering, the steering system $f(\delta_d)$ gradually decreases from 1, the steering ends, and the steering speed is adjusted back to 1. The speed ring constantly adjusts the desired speed to achieve "turning to low-speed sailing and straight high-speed sailing".

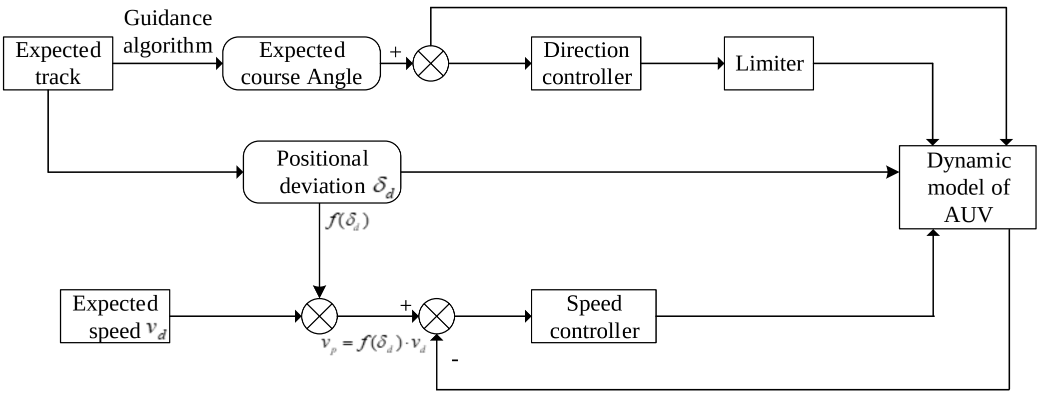


Figure 5. Design of AUV speed controller combined with range deviation.

4. Simulation results and analysis

In order to verify the effectiveness of the proposed algorithm, the linear track tracking control simulation of the AUV model was carried out based on MATLAB/Simulink software. AUV model parameters are shown in reference [9]. The initial state of AUV is: x = 0, y = 0, u = 0, v = 0, ψ = 0, r = 0. Plan multi-angle flight paths, and add common Z-shaped flight paths: given the target point coordinates (unit: m) are A (0,0), B (300,0), C (0, -300), D (300, -300) (m), and give the expected speed of 2.5m /s.For the design of the tracking algorithm, the minimum forward looking distance Δ_{min} = 6m, the maximum forward looking distance Δ_{max} = 16m, the track updating principle R = 3.0, the deviation of the prepared deceleration distance R″ and R′ are 30 and 10 respectively.

Table 1. The coefficient of Angle PD controller and Speed PID controller for Angle double closed loop control.

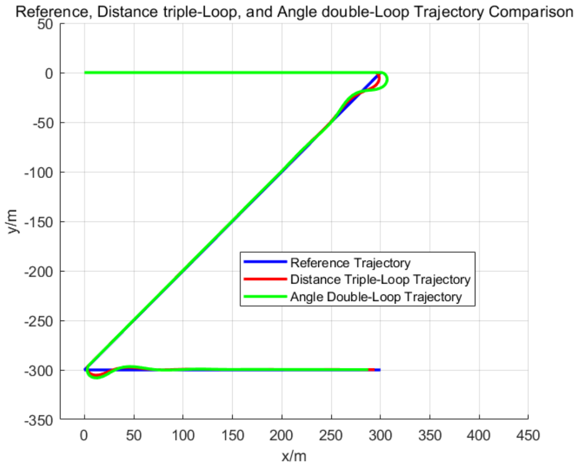
	k_p	k_i	k_d
Angle PD controller	0..017	/	0.89
Speed PID controller	8.34	0.19	19.189

The heading Angle deviation double closed-loop PID control algorithm proposed in literature [5] and the distance deviation self-adaption fuzzy PID control algorithm proposed in this study (distance triple closed-loop) were respectively used for simulation. For angular double closed-loop control, the coefficients of the rudder Angle PD controller are shown in Table 1.

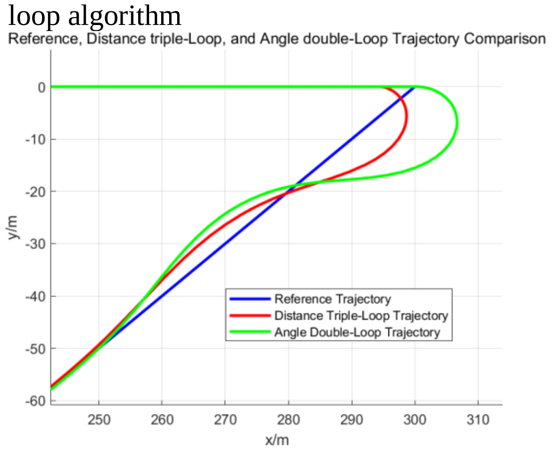
For distance triple closed-loop control, The fuzzy rules used in fuzzy theory are shown in Table 2, The parameter design of traditional PID controller is consistent with that of Angle double closed loop.

Table 2. Table of fuzzy rules.

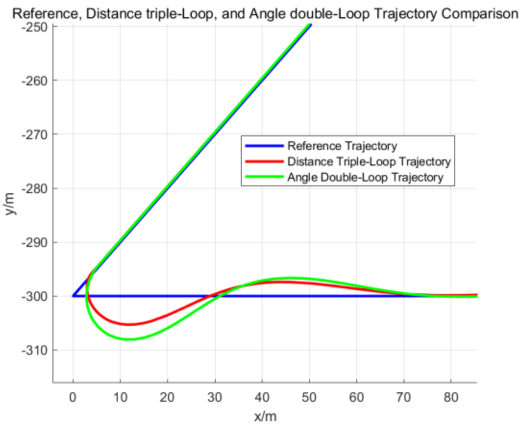
U		*EC*						
		NB	NM	NS	ZO	PS	PM	PB
E	NB	PB	PB	PB	PB	PM	ZO	ZO
	NM	PB	PB	PB	PM	PM	ZO	ZO
	NS	PB	PM	PM	PS	ZO	NS	NM
	ZO	PM	PM	PS	ZO	NM	NM	NM
	PS	PS	PS	ZO	NM	NM	NM	NB
	PM	ZO	ZO	NM	NM	NB	NB	NB
	PB	ZO	NS	NB	NB	NB	NB	NB



(a) Comparison of track tracking curves between Angle double closed loop and distance triple closed loop algorithm



(b) The tracking curve at coordinates (300, 0)



(c) The tracking curve at coordinates (0, −300)

Figure 6. Comparison of track tracking simulation results between Angle double closed loop and distance triple closed loop.

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From the track tracking curve in Figure 6(a), it can be seen that both of the closed-loop control algorithms can make the AUV achieve better tracking control effect in the entire track tracking process, and the actual track can converge to the desired track well. From the track tracking curve at the corner of Figure 6(b), it can be seen that the tracking control effect of the three-closed-loop fuzzy PID control algorithm with distance deviation is greatly improved when turning at a large Angle at (0, −300), the actual track switching is smoother, and the overshoot is significantly reduced. The maximum overshoot is 6.0 m. In Figure 6(c), it can be seen that near the (0, −300) expected point, the method used in this paper still tracks the expected trajectory with a smaller tracking error. AUV speed variation of the two control algorithms is shown in Figure 7. As can be seen from the figure, both control algorithms can reduce AUV speed when switching the desired track, and the distance deviation double closed-loop algorithm can make AUV slowdown in advance, turn at a smaller speed, and reduce track overshoot. The output value of AUV steering gear rudder Angle is shown in Figure 8. We can see that the change of heading Angle of distance three closed loop is slightly smaller than that of Angle double closed loop, which can reduce unnecessary manoeuvrings and improve resource utilization in practical engineering applications.

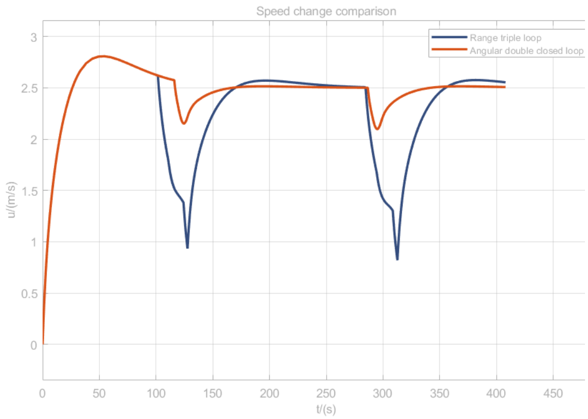

Figure.7. Speed change comparison of angle double closed loop and distance triple closed loop algorithm.

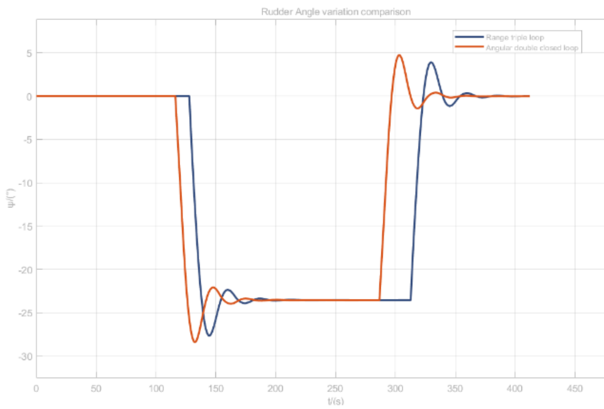

Figure.8. Comparison of actual heading Angle variation between Angle double closed loop and distance triple closed loop algorithm.

5. Conclusion

Aiming at the problem of track overshoot of autonomous underwater vehicle (AUV) during the course of plane track tracking, an AUV control algorithm was developed to reduce track overshoot effectively. The main conclusions are as follows:

(1) Obtain the expected course through the line-of-sight guidance method of time-varying forward-looking distance, and convert the discrete expected point path tracking into the output of the expected course Angle.

(2) Introduce the fuzzy control algorithm to adjust the PID parameters, and combine the traditional PID control method to design the weight function to adapt to various sailing conditions, and design the course speed as a three-loop control. By adjusting the distance deviation between the AUV and the end of the desired track, the speed of the AUV is reduced in advance, so that it slows down to a lower speed when turning, so as to reduce the overshoot of the track during the turning process.

(3) For typical AUV models, compared with the double closed-loop PID algorithm with the deviation of course Angle, the simulation results show that, the proposed three-distance closed-loop algorithm has better track tracking control effect, and can effectively reduce track overshoot in the course of turning at large angles.

(4) The plane linear tracking control algorithm designed in this study focuses on track tracking at horizontal plane or a specific depth plane, and depth control is planned to be introduced in the future.

The problem of track overshoot reduction in AUV track tracking in three-dimensional space is also studied.

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