

# A Lateral Error S-Plane Control for Path Tracking on Autonomous Underwater Vehicle

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**Abstract.** This research aims at the motion control on a certain torpedo-type underactuated AUV (Autonomous Underwater Vehicle), using the S (Sigmoid) plane control method to build the heading controller and speed controller, and analyzes the stability of them, then establishes a linear path tracking control system in horizontal plane. In order to improve the performance of the path tracking controller under a large initial disturbance, an asymptotic controller of the heading error is proposed. And to solve the curve path tracking, a curve path tracking controller with a feedforward control idea is proposed. The simulation shows that these two improved controllers have a satisfactory control effects and effectively improved the performance of underwater robot motion control.

## 1. Introduction

The motion of underwater vehicles has the characteristics of strong non-linearity, mutual coupling between multi-degrees of freedom, strong environmental disturbances, and it is difficult to obtain motion models. The underwater vehicle control methods commonly include: neural network control, fuzzy control, sliding mode control, etc. Liu Xuemin[1] proposed an underwater vehicle control method called S-plane, which integrates the idea of fuzzy control and proportional-integral-derivative (PID) control structure, with the advantages of simple structure, less parameters, easy adjustment, and convenient application. It is proved that the S-plane control method is suitable for underwater vehicle motion control[2].

This research uses S-plane control method to construct a lateral error linear path tracking controller, and analyzes the stability of the controller. In combination with the idea of feed-forward control, this linear path tracking controller is applied to the curve path tracking. This research analyzes and compares the control effects under different initial errors, and proves that the superiority of this kind of curve tracking with feed-forward thinking.

## 2. S-plane control



S-plane control stems from [3] the idea of fuzzy control, it uses a fuzzy control rule table to perform a nonlinear fitting, using a Sigmoid function to replace the fuzzy rule table. Then continuous expression of the S-plane control is obtained:

$$f = \frac{2}{1 + \exp(k_1 e + k_2 \dot{e})} - 1 + \Delta f \quad (1)$$

In the equation (1),  $k_1$ ,  $k_2$  are the control parameter,  $e$ ,  $\dot{e}$  are the control input, respectively indicate the error and the rate of change of error.  $f$  is the control output. To facilitate analysis of  $e$ ,  $\dot{e}$  through normalization, the range of  $f$  is  $[-1, +1]$ , indicates the negative maximum output to the positive output.  $\Delta f$  is the adjustment item to adapt environmental disturbances, factors such as buoyancy changes and currents are considered as fixed interference forces for a period of time. By adjusting the  $\Delta f$  to offset of S-plane, the control output is changed, so as to eliminate the fixed error. The two parameters of the S-plane controller can be adjusted by referring to the PD control [4].

The S-plane control method does not need a model of the control object, and the S-plane control method is actually a kind of non-linear PD control. Therefore, the S-plane control is very suitable for the underwater vehicle, which is nonlinear and difficult to obtain an accurate model [5].

### 3. Horizontal Linear path Tracking Controller

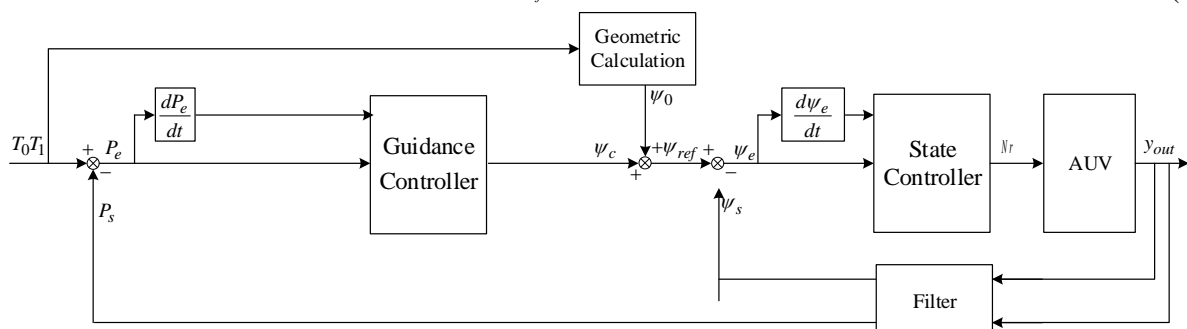
In the layered control system, the guidance law is an important component of the planning layer and plays an important role in the path tracking of the underactuated AUV [6]. For the path tracking control in the horizontal plane, the mechanism of the guidance control of the planning layer is: firstly, according to the geometric principle, the lateral error is obtained from the relative distance between the actual position and the target line; secondly, the control law is based on the Lyapunov stability method, according to the dynamic change of the error, calculate the appropriate target orientation by the S-plane controller, and finally the AUV's movement is converged to the target line [7].

The guidance controller uses the lateral distance error  $P_e$  as the control input to calculate the compensation heading angle  $\psi_c$ . So that the reference angle of the AUV is:

$$\psi_{ref} = \psi_o + \psi_c(P_e) \quad (2)$$

The error of the heading angle  $\psi_e$  can be calculated by the reference heading angle  $\psi_{ref}$  and the real heading angle  $\psi_s$

$$\psi_e = \psi_{ref} - \psi_s \quad (3)$$



**Figure 1.** Structure of horizontal straight line tracking control system

The structure of the complete linear path tracking control system in horizontal plane is shown in Figure 1. It is a single input single output (SISO) system. The compensation heading angle  $\psi_c$  of the guidance control part is a function of the error  $P_e$ .

### 4. Speed Controller Stability Analysis

First, we designed the S-plane speed controller. The speed control is actually the control of the position change rate, and the angle control is the position control. Let the desired speed be  $u$ , and the speed deviation and the change rate of speed deviation are:

$$\begin{cases} e_u = u_{\text{ref}} - u \\ \dot{e}_u = \dot{u}_{\text{ref}} - \dot{u} \end{cases} \quad (4)$$

The discrete form is:

$$f = \sum k \left[ \frac{2}{1 + \exp(-k_p e_u - k_d \dot{e}_u)} - 1 \right] \quad (5)$$

Where  $k$  is the integration step size.

The S-plane speed controller is derived from the S-plane position controller and can directly use the parameters of the S-plane position controller. In theory, the stability problem can only be qualitatively analyzed[8].

Under the homing and reclamation mission, the AUV usually performs a cruise control during the tracking of the trajectory,  $u = u_{\text{ref}}$ . The overcome resistance is  $F$ , and the controller output is expressed as  $f_0 = F / F_{\text{max}}$ .

Set  $s = -k_p e_u - k_d \dot{e}_u$ , the Lyapunov function is:  $V(s) = \frac{1}{2} s^2$ , so,  $\dot{V}(s) = s \dot{s}$ ,

When  $f > f_0$ ,  $\dot{s} > 0$ ; when  $f < f_0$ ,  $\dot{s} < 0$ , So,  $\text{sgn}(\dot{s}) = \text{sgn}(f - f_0)$ .

There are:

$$\text{sgn}(\dot{V}) = \text{sgn}[s \cdot (f - f_0)] = \text{sgn}[s \cdot (\int k \dot{f} dt - f_0)] \quad (6)$$

because of  $s \cdot \dot{f} < 0$ ,  $s \cdot (\int k \dot{f} dt - f_0)$ , When  $k$  is big enough,  $\text{sgn}[s \cdot (\int k \dot{f} dt - f_0)] = \text{sgn}[s \cdot \dot{f}] < 0$ , So  $V(s)$  is gradually stable[9].

## 5. Linear path tracking with asymptotic control

The path tracking control will face an unstable tracking control condition when the initial steering angle error is greater than  $\pi/3$ , and even the path convergence time will rise sharply and even lose control of the AUV. In multi-interference oceans, the heading of AUV sometimes suffers from the ocean currents disturbances, which are accompanied by lateral errors. If the AUV's heading error from the target line is  $70^\circ - 90^\circ$ , it will lose control stability, and such a control system is not suitable of operating in a varied marine environment. Therefore, an improved method is proposed in which the idea of progressive control is used to control the error of the heading angle of AUV. In the simulation, it is shown that when the initial heading angle error is less than  $\pi/8$ , the peak value of the error of the AUV was extremely small, and the convergence time was also small. In this way,  $\pi/8$  is considered as the threshold value of the error of the heading angle. When the absolute value of AUV heading angle error is greater than  $\pi/8$ , the target heading is considered as the  $\pi/8$  offset on the target line direction of the AUV heading angle, and the magnitude of the lateral error  $P_e$  has no change. When the AUV heading angle error is less than  $\pi/8$ , it need not change the value of the heading angle error. In this way, the error of the heading angle at the input of the controller is always limited to  $\pi/8$  or less. A long-term convergence process is decomposed into several short-term convergence processes, achieving stable control and quicker time convergence.

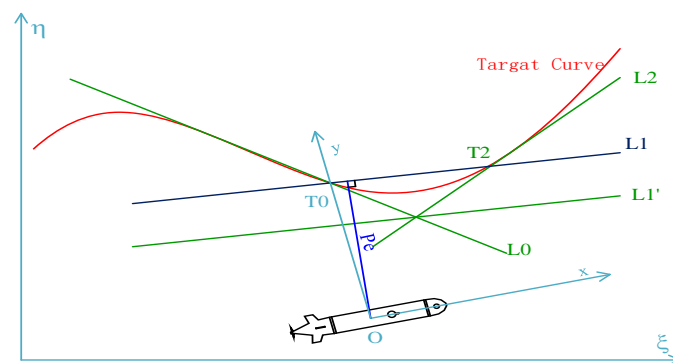
## 6. Curve path tracking control

For the sake of simplifying the problem, it was decided not to change the linear guidance controller and the state controller, and the linear tracking controller was applied to the curve tracking. A curved path tracking method is proposed to change the tracked target straight line in real time as the curve curvature changes. As shown in the Figure 2, the tracking target is selected as the hypothesis line TOL1,

and the lateral error between the actual position of the AUV and the hypothesis line T0T1 is obtained as the current control error. The solution of the arbitrary curve lateral error  $P_e$  is shown in Figure 2.

As shown in Figure 2, the AUV is at point O and the tracking target curve is C. First, a perpendicular line is made in the x direction of the vertical AUV, intersecting with the target curve C at a point T0, and the slope of the curve C at the point of the tangent line L0 is  $k_0$ ; the idea of introducing the feedforward control takes into account the next change trend of the curve, along with the target curve C, taking a point T2 of 1m-10m after T0, we can also find the slope  $K_2$  of C at this point's tangent line L2, and then weighting the two to obtain  $k_1$ , that is:

$$k_1 = (k_2 + k_3) / 2 \quad (7)$$



**Figure 2.** Horizontal position error of arbitrary curves

Then use  $k_1$  as the slope to make a straight line through T0, and find a point T1 on this straight line. Think of this straight line as the straight line traced at that moment. The advantage of this consideration is that it takes into account both the distance and the error of the current position from the target curve C, and the trend of the next trend of the curve. This allows the AUV to approach the target curve C faster, and the precision of the follow-up curve motion of AUV is greatly improved.

In practical tasks, when  $k_1$  is determined, different control effects can be achieved by changing the weights of  $k_2$  and  $k_3$ , that is:

$$k_1 = (c_2 \cdot k_2 + c_3 \cdot k_3) \cdot (c_2 + c_3)^{-1} \quad (8)$$

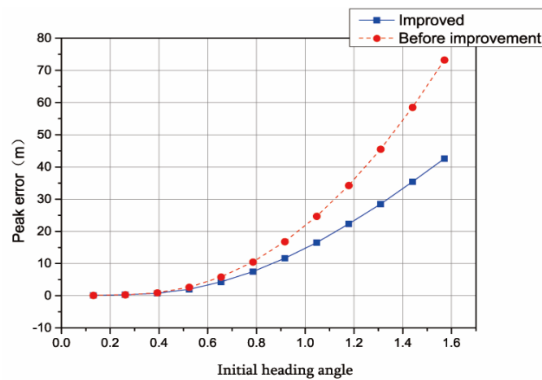
The simulation shows that changing the weights  $c_2$  and  $c_3$  will have a certain impact on the quality of the path tracking. Therefore, in the actual situation, the values of  $c_2$  and  $c_3$  should be reasonably determined according to the characteristics of the path.

## 7. Simulation

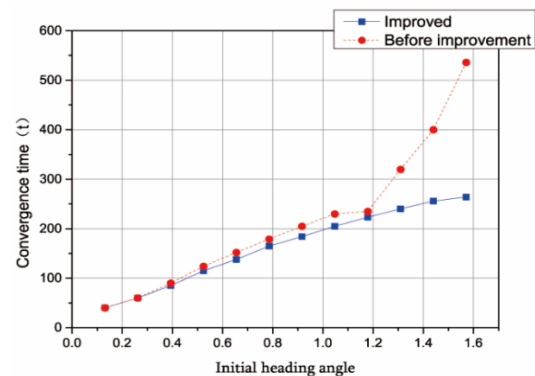
### 7.1 Linear path tracking asymptotic control

The initial position of the AUV is set on the target straight line, and the initial steering angle is changed to compare the different control effects of the S-plane controller and the improved progressive error S-plane controller. When the lateral error  $P_e < 0.5\text{m}$ , the AUV converges on the target path.

It is shown in Figure 3. and Figure 4. that the improved linear tracking controller has greater advantages in rejecting a large initial heading errors, and the convergence time and the convergence distance are approximately linearly positively correlated with the initial heading angle error.



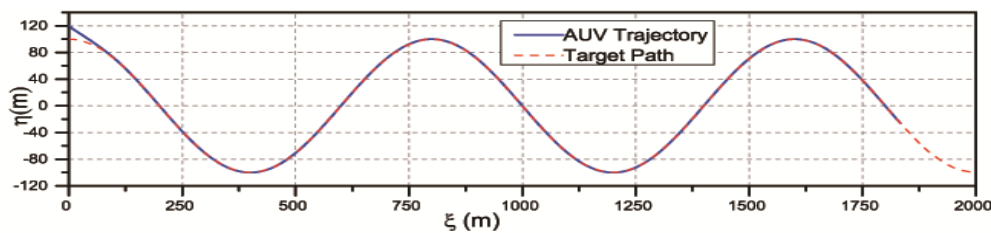
**Figure 3.**Comparison of error peaks before and after improvement



**Figure 4.**Comparison of convergence time before and after improvement

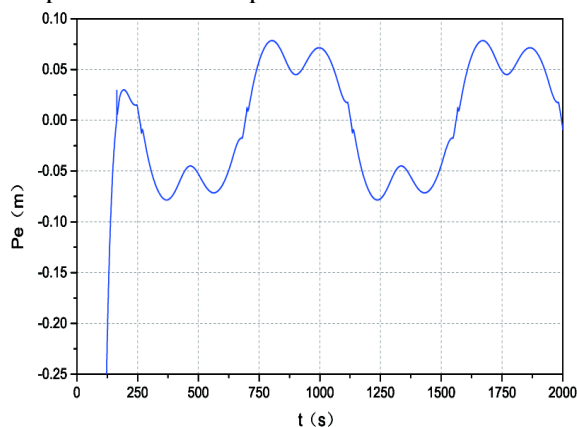
### 7.2 Curve path tracking control

The curve path has an amplitude of 100 m and a period of 800 m. The initial position of the AUV is selected to be (0, 120) and the initial angle of the direction is 0, the simulation time is set to 2000s. Take the guidance controller parameters  $k_1 = 2$ ,  $k_2 = 55.2$ , state controller  $k_1 = 0.1$ ,  $k_2 = 0.02$ . The following is an image of the AUV along the set cosine curve and the image of the lateral error  $P_e$ :

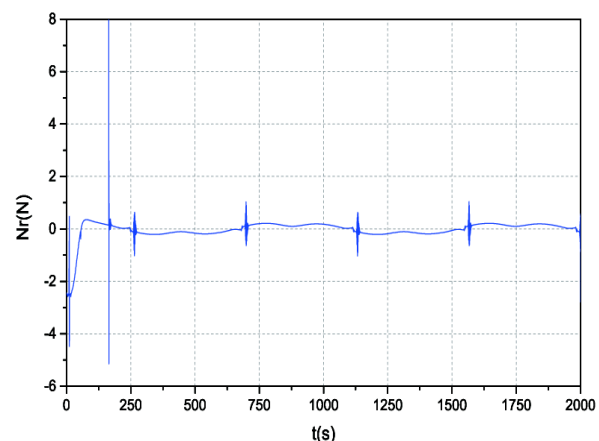


**Figure 5.** Path tracing of a cosine curve

In Figure 5, Figure 6. and Figure 7, it is shown that the S-plane controller has a very low error in tracking the curve. The lateral distance error varies from -0.1m to 0.1m. At the same time, the turning torque  $N_r$  of the AUV is also changing smoothly, which also shows that the S-plane controller under the parameters is adapted to control the motion of the AUV.



**Figure 6.**Horizontal Positional Errors of Cosine Curve Tracking  $P_e$

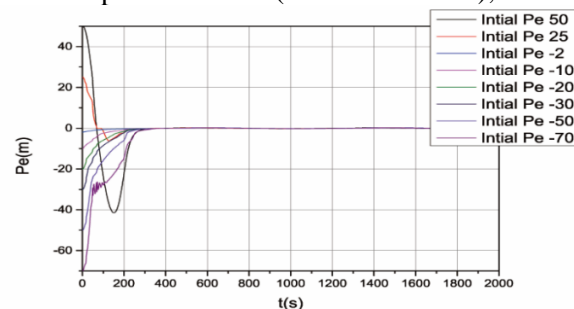


**Figure 7.**Turning moment tracked by the cosine curve  $N_r$

### 7.3 Curve simulation for different lateral errors

Different initial lateral position errors are selected to research the characteristics and applicability of the curve path tracking system. The following is the result of changing the simulation of a set of initial lateral positions. Figure 8. is the variation of the lateral positional error  $P_e$  of the AUV at different initial positions:

It can be seen from Figure8. that when tracing arbitrary curves, the initial lateral position is from (0,50) to (0,170), and after a certain period of time (about 150s-300s), it will converge to almost zero.



**Figure 8.** Tracking lateral error of cosine curve path at different initial positions track

## 8. Conclusion

Practice has proved that the S-plane control method is an effective method for path tracking of underwater vehicle. In this paper, the S-plane control method is used to design a linear path tracking system, and the stability of the controller and speed controller is analyzed. Aiming at the instability at a large initial heading angle error for S-plane controllers, a method of progressive heading angle error control was proposed, so that in the simulation, the convergence time and convergence distance were reduced. Aiming at the curve tracking task, a curve tracking method with feedforward idea is proposed. The simulation results show that this curve tracking method can track the curve and can complete convergence under different initial lateral errors.

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## Reference

- [1] Liu, X. M., & Yu-Ru, X. U. (2001). S control of automatic underwater vehicles. *Ocean Engineering*.
- [2] Yue-Ming, L. I., Pang, Y. J., & Wan, L. (2012). Adaptive s plane control for autonomous underwater vehicle. *Journal of Shanghai Jiaotong University*, 1, 482 - 489.
- [3] YANUSHEVSKY R. Modern Missile Guidance[M]. CRC Press, 2008.
- [4] SIOURIS G M. Missile Guidance and Control Systems[M]. New York: Springer-Verlag New York, Inc., 2004.
- [5] SPEARMAN M L. Historical development of worldwide guided missiles[C]. In: AIAA 16th Aerospace Sciences Meeting, Huntsville, Alabama, USA. 1978.
- [6] LIN C L, SU H W. Intelligent control theory in guidance and control system design: An overview[C]. Proceedings of the National Science Council. 2000,24: 15-30.
- [7] MIZUTANI A, CHAHL J S, SRINIVASAN M V. Motion camouflage in dragonflies[J]. Nature, 2003, 423(6): 604.
- [8] DRIELS M. Linear Control Systems Engineering[M]. Columbus, Ohio: McGraw-Hill, 2000.
- [9] YE L, YONGJIE P, LEI W. Stability analysis on speed control system of an autonomous underwater vehicle[J]. China Ocean Engineering, 2009, 23(2): 345-350.