Model-free Path Following Control of Unmanned Surface Vehicle Based on Adaptive Line-of-sight Guidance

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Abstract. A path following control scheme based on virtual transition line-of-sight (LOS) guidance law is proposed for model-free unmanned surface vehicle (USV). In the guidance part, an adaptive LOS circle radius based on the transition layer is designed to improve the convergence speed of USV. Aiming at reducing the overshoot of turning, a small angle transition steering strategy is proposed. In the heading and speed control part, the intelligent adaptive S-plane (IAS) heading controller and intelligent adaptive integral S-plane (IAIS) speed controller with strong robustness are designed respectively. In order to improve the following efficiency, a speed solver based on heading deviation and path point distance is designed. The effectiveness of the guidance strategy and the control algorithms of heading and speed proposed in this paper are verified by the comparative simulations.

1. Introduction

As one of the fields of marine equipment construction and an important part of the unmanned intelligent marine vehicles, USV has a very broad application prospect in both civil and military fields with its unique advantages [1]. In order to complete the task accurately and efficiently, there is a high demand for the ability of heading and speed and path following control of USV. At the same time, there are a large number of USVs and many types of USVs, so it is not realistic to establish accurate motion models for all USVs. Therefore, it has become a hot topic for scholars at home and abroad to explore an efficient USV path following scheme based on free-model [2].

In the indirect path following scheme of USV, the effect of path following control depends on the precision of guidance law largely, so it is very important to choose a precise and simple guidance algorithm, and line of sight method is very suitable. At first, the circle radius of line of sight method is a fixed value [3], and do not have self-adjusting ability, which reduces the convergence speed of USV. Liu T [4] designed a line of sight circle radius that can be changed adaptively, but it could not adapt to the path following of small corners well due to its small adjustment ability. Khaled [5, 6] further designed the exponential line of sight method, however, because of the introduction of the exponential function, the speed of solving the line of sight angle was reduced. Fossen et al. [7] designed the USV linear track following controller based on the line-of-sight method and anti-saturation PID control algorithm, and carried out the real boat verification on the lake, without considering the impact of external interference on USV.

From what has been discussed above, this paper adopts indirect control as USV path following scheme. On the one hand, an adaptive line-of-sight circle radius is designed, on the other, the angle
compensations based on heading deviation and path deviation are made for line-of-sight angle respectively. For heading and speed control, considering the difficulty of establishing accurate mathematical model for USV, the IAS heading controller and IAIS speed controller were designed. Finally, a series of comparative simulations are carried out to verify the algorithm proposed in this paper.

2. USV model
In this paper, the motion control of underactuated USV in horizontal plane is studied primarily, which has no direct lateral control input with only one rudder and one propeller [8]. The three degree of freedom model of USV is as follows [9]:

\[
\begin{align*}
\dot{x} &= u \cos \psi - v \sin \psi \\
\dot{y} &= u \sin \psi + v \cos \psi \\
\dot{\psi} &= r \\
\dot{u} &= N_u (v, r) - \frac{D_{11}}{M_{11}} u + \tau_u + d_u \\
\dot{v} &= X(u) r + Y(u) v + d_v \\
\dot{r} &= N_r (u, v, r) + \tau_r + d_r
\end{align*}
\]

(1)

\[
N_u (v, r) = \frac{1}{M_{11}} (M_{22} v + M_{23} r) r
\]

\[
X(u) = \frac{M_{23}^2 - M_{11} M_{33}}{M_{22} M_{33} - M_{23}^2} u + \frac{D_{33} M_{23} - D_{31} M_{23}}{M_{22} M_{33} - M_{23}^2} \\
Y(u) = \frac{(M_{22} - M_{11}) M_{33}}{M_{22} M_{33} - M_{23}^2} u - \frac{D_{31} M_{23} - D_{21} M_{23}}{M_{22} M_{33} - M_{23}^2} \\
N_r (u, v, r) = \frac{D_{22} M_{23} - D_{21} (D_{22} + (M_{22} - M_{11}) u)}{M_{22} M_{33} - M_{23}^2} v + \frac{M_{23} (D_{23} + M_{11} u) - M_{22} (D_{33} + M_{23} u)}{M_{22} M_{33} - M_{23}^2} r
\]

(2)

Where \(x, y, \psi\) represent the position and the heading angle in geodetic coordinate system of USV, respectively. \(u, v, r\) represent the longitudinal velocity, lateral velocity and the heading of angular velocity, respectively. \(d_u, d_v, d_r\) are interference force and torque. \(\tau_u\) is thrust force and \(\tau_r\) is torque. \(M_{11}, M_{22}, M_{23}, M_{32}, M_{33}, D_{11}, D_{22}, D_{23}\) and \(D_{32}\) are the hydrodynamic coefficient of USV.

3. Improved LOS guidance law design
The effectiveness of the indirect path following scheme of USV depends largely on the accuracy of the guidance. The guidance algorithm can calculate a real-time LOS angle to guide USV to converge to the desired path [10]. In this paper, an adaptive LOS circle radius guidance strategy based on transition layer is proposed for USV way-point following from the perspective of simplicity and practicality. Defining the coordinates of waypoints \(P_1, P_2, \ldots, P_{k-1}, P_k, P_{k+1}, \ldots, P_n\), \(P_k (x_k, y_k)\) is the kth coordinate, and \(P_{LOS} (x_{LOS}, y_{LOS})\) is the coordinate of LOS. \(R_{min}\) is the minimum LOS circle radius. \(R_i\) and
\( R_k \) represent the circle radius of the transition layer and the switching circle radius of the \( k \)th expected path point, respectively. \( y_e \) is the path deviation.

In the process of following the expected path, the reference position of LOS angle is calculated as follows:

\[
(x_{LOS} - x)^2 + (y_{LOS} - y)^2 = R^2
\]

\[
y_{LOS} - y_{k+1} = \frac{y_k - y_{k+1}}{x_k - x_{k+1}} = \tan \alpha_{k-1}
\]  

\( R \) is the LOS circle radius, and \( \psi_{LOS} \), the LOS angle of USV tending to the desired path, is calculated as follows:

\[
\psi_{LOS} = \arctan\left(\frac{y_{LOS} - y}{x_{LOS} - x}\right) = \alpha_{k-1} + \arctan\left(\frac{y_e}{\Delta}\right)
\]  

USV is sailing toward the reference point constantly with the guidance of the LOS angle, and gradually converging to the expected path. When approaching the next way point \( P_k \), USV is judging whether to follow the next linear path unit by comparing with the radius \( R_k \) [11].

In the classical LOS, the LOS circle radius \( R \) is a constant value, so the speed of convergence become slower greatly. Aiming to elimination the phenomenon, an adaptive LOS circle radius guidance strategy based on transition layer is proposed for path following. The adaptive LOS circle radius is designed as follows:

\[
R = \begin{cases} 
|y_e| > R_{min} + \delta & \text{if } |y_e| > R_{min} + \delta \\
R_{min} + \delta + \delta \tanh\left[k_1\left(|y_e| - R_{min} - \delta\right)\right] & \text{if } R_{min} - \delta < |y_e| \leq R_{min} + \delta \\
R_{min}, & \text{if } |y_e| \leq R_{min} - \delta 
\end{cases}
\]  

Where \( \delta \) and \( k_1 \) represent the thickness of transition layer and the coefficient, respectively.

4. The improvement of steering strategy

It is found that, through a lot of experiments, when USV has a small angle steering, that is, when the steering angle is less than 90°, it can smoothly transition to the next track unit with a small overshoot, but when it has a large angle steering, that is, when the steering angle is greater than or equal to 90°, if the USV still follows the original path with the LOS guidance law, there will be a large overshoot. In order to solve this phenomenon, this paper will improve USV's large angle steering strategy in path following [12], and the improvement idea is as follows: three small steering angles are used to transfer one large steering angle, as shown in figure 1. When the turning angle of USV is less than 90°, it still sails according to the guidance law of the original desired path, otherwise, it navigates according to the improved virtual path guidance law.
Figure 1. The transition strategy of large angle turning

Where $P_{k-1}$, $P_k$ and $P_{k+1}$ are the actual path points, the coordinates are $(x_{k-1}, y_{k-1})$, $(x_k, y_k)$ and $(x_{k+1}, y_{k+1})$ respectively. Supposing that USV is turning along $\angle P_{k-1}P_kP_{k+1}$, in order to reduce the overshoot during turning, selecting two suitable virtual turning points A and C on the path $P_{k-1}P_k$ and path $P_kP_{k+1}$ firstly, the coordinates are $(x_A, y_A)$ and $(x_C, y_C)$ respectively, so that they form an isosceles triangle $\triangle APK$, and $AP = PC$, then take the center point B as the intermediate transition point of virtual turning points A and C, the coordinates are $(x_B, y_B)$, and the coordinates calculation methods of virtual turning points A, B and C will be as follows. Finally, when USV makes a large angle turn according to the original path point $P_{k-1}$, $P_k$ and $P_{k+1}$, it can now make a small angle transition turn according to $P_{k-1}$, A, B, C and $P_{k+1}$, reducing the overshoot caused by USV following the original path greatly.

The pre-steering distance of the USV is related to the angle at which it is to be turned and the current speed. Therefore, taking into account all factors, the pre-steering distance of the USV is designed as follows:

$$l_{AP} = l_{PC} = \lambda \left\{ 2 - \exp \left[ \left( \frac{v_n^2}{\sigma_\theta^2} + \frac{v_n^2}{\sigma_v^2} \right) \right] \right\} L_{OA}$$

(6)

Where $\lambda$ is the coefficient of gyration, $l_{AP}$ is the distance of $AP$, $l_{PC}$ is the distance of $PC$, $\theta_n = \frac{\theta}{180}$ is the normalization of steering angle, $v_n = \frac{v}{v_{\max}}$ is the normalization of speed, $\sigma_\theta$, $\sigma_v$ are adjustable parameters, $L_{OA}$ is the length of USV.

The coordinate calculation of virtual turning points A, B and C are as following:

If $x_k - x_{k-1} = 0$,

$$x_d = x_{k+1} = x_k, y_d = y_k - \mu l_{AP}$$

(7)

If $y_k - y_{k-1} = 0$,

$$x_d = x_k - \Theta l_{AP}, y_d = y_{k-1} - y_k$$

(8)

If $x_k - x_{k-1} \neq 0$, $y_k - y_{k-1} \neq 0$,
\( x_{t+1} = x_t - \Theta \frac{I_{ap}}{I_{p,i}} (x_t - x_{t-1}) \), \( y_{t+1} = y_t - \Theta \frac{I_{ap}}{I_{p,i}} (y_t - y_{t-1}) \) \( (9) \)

If \( x_{k+1} - x_k = 0 \),
\( x_c = x_{k+1} = x_k, \ y_c = y_{k+1} = y_k + \Theta \frac{I_{pc}}{I_{p,c}} \) \( (10) \)

If \( y_{k+1} - y_k = 0 \),
\( x_c = x_k + \Theta \frac{I_{pc}}{I_{p,c}}, \ y_c = y_{k+1} = y_k \) \( (11) \)

If \( x_{k+1} - x_k \neq 0, \ y_{k+1} - y_k \neq 0 \),
\( x_c = x_k + \Theta \frac{I_{pc}}{I_{p,c}} (x_{k+1} - x_k), \ y_c = y_k + \Theta \frac{I_{pc}}{I_{p,c}} (y_{k+1} - y_k) \) \( (12) \)

After the coordinates of virtual turning points \( a \) and \( C \) are determined, the coordinates of point \( B \) can be obtained:
\( x_B = \frac{x_A + x_C + x_k}{3}, \ y_B = \frac{y_A + y_C + y_k}{3} \) \( (13) \)

If \( x_{k+1} > x_k \) or \( x_k > x_{k-1} \), \( \Theta = 1 \), otherwise, \( \Theta = -1 \). If \( y_{k+1} > y_k \) or \( y_k > y_{k-1} \), \( \mu = 1 \), otherwise, \( \mu = -1 \).

5. Controllers design

In this paper, heading and speed controllers are designed respectively. Because it’s so difficult for USV to establish accurate motion model, aiming at this characteristic of USV, this paper designs IAS heading controller and IAIS speed controller. These two controllers can not only realize the USV motion control effectively without model, but also have simple structure and are easy to operate in engineering implementation.

5.1. Heading controller design

The S-plane controller is designed by using the input and output information of the system directly, which doesn’t be limited by the accurate system model. It is an efficient nonlinear control method. Therefore, based on the S-plane control algorithm, an intelligent self-tuning S-plane heading controller is designed, and the expression is as follows:

\[ f = \frac{2.0}{1.0 + \exp \left(- \left[k_1^* + k_2^* \cdot f_a (e, \dot{e}) \right] e - \left[k_1^* + k_2^* \cdot f_b (e, \dot{e}) \right] \dot{e} \right)} - 1.0 \] \( (14) \)

Where, \( k_1^* \) and \( k_2^* \) are base-value, \( k_\alpha \) and \( k_\beta \) are coefficients of adjustment function, \( f_a (e, \dot{e}) \) and \( f_b (e, \dot{e}) \) are adjustment function.

In this paper, the self-tuning function is constructed by using heading deviation and deviation rate of change. Compared with the traditional design method, the function is more adaptive. The expression is as follows:
5.2. Speed controller design

According to the characteristics of USV speed control, an IAIS speed controller is designed based on the IAS controller by adding the integration link. The expression is as follows:

\[
\begin{align*}
    f_a(e, \dot{e}) &= \frac{|e|^2 + |\dot{e}|}{|e|^2 + |\dot{e}|^2 + 1} \\
    f_\beta(e, \dot{e}) &= \frac{|e|^2 + |\dot{e}|}{|e|^2 + |\dot{e}|^2 + 1}
\end{align*}
\]

(15)

5.2. Speed controller design

According to the characteristics of USV speed control, an IAIS speed controller is designed based on the IAS controller by adding the integration link. The expression is as follows:

\[
    f = \int k \left[ \frac{2.0}{1.0 + \exp\left\{-\left[k_1^* + k_\alpha \cdot f_a(e, \dot{e})\right]e - \left[k_2^* + k_\beta \cdot f_\beta(e, \dot{e})\right]\dot{e}\right\} - 1.0} \right] dt
\]

(16)

Where, \(k\) is integral step, \(k_1^*\) and \(k_2^*\) are base-value, \(k_\alpha\) and \(k_\beta\) are coefficients of adjustment function, \(f_a(e, \dot{e})\) and \(f_\beta(e, \dot{e})\) are adjustment function.

6. Speed Solver Design

In the study of USV path tracking, the tracking speed is usually set to a fixed value, which reduces the tracking quality and operation efficiency, so a joint speed solver based on course deviation and path point distance is designed. The solver based on the deviation of heading angle and considering the distance from the next path point calculates an optimal expected speed and transmits it to the speed controller in real time. When the USV is turning, the speed will be reduced in advance to ensure the accuracy of the path following, and when the USV enters the stable straight line tracking phase, the expected speed will increase. The design form can be expressed as:

\[
v_d = v_{\text{max}} \left\{ \alpha \left[ \exp\left(-\frac{(\psi_d - \psi_0)^2}{\sigma^2}\right) \right] + \beta \left[ 1 - \exp\left(-\frac{\Delta l^2}{\sigma^2}\right) \right] \right\}
\]

(17)

Where, \(v_d\) is the expected speed of the USV, and \(v_{\text{max}}\) is the maximum speed of the USV. \(\alpha\) and \(\beta\) represent the weight of the heading deviation function and the distance function of the waypoint respectively, and \(\alpha + \beta = 1\). \(\Delta l\) is the distance of USV to the next waypoint. \(\sigma_\psi\) and \(\sigma_l\) represent the adjustment coefficients.

7. Simulation Results

7.1. Heading control simulation

In order to verify the effectiveness of the IAS heading controller, which will be compared with S-plane controller. The initial heading of the USV is 2° and the speed is 2 m/s. \(k_1^* = 2.5\), \(k_2^* = 3\). The controller input adopts 60° step signal. The results are shown as Figure 2- Figure 3.
According to the comparison between figure 2 and figure 3, it can be intuitively seen that the USV with the IAS heading controller can converge to the desired heading at a faster speed with almost no overshoot with the disturbance force. However, the control effect of S-plane is poor, the USV is affected by external force interference obviously, and has a large overshoot and weak robustness.

7.2. Speed control simulation
In order to verify the effectiveness of the IAIS speed controller, which will be compared with integral S-plane controller. The initial heading of the USV is 2°. k=0.02, k₁=2.5, k₂=3. The controller input adopts 2 m/s step signal. The results are shown as Figure 4- Figure 5.

![Figure 4. 1.25m/s speed control](image)

![Figure 5. Thrust curve](image)

It can be intuitively seen that USV with the IAIS speed controller can quickly converge the desired speed, and there is almost no overshoot in the whole process. The robust performance is strong. The speed of the integral S-plane controller has a large overshoot at the beginning stage. After reaching the stable state, the speed will fluctuate with the change of external interference.

7.3. Path following simulation
Three schemes are adopted in path tracking test, which are recorded as scheme 1, scheme 2 and scheme 3 respectively. The scheme 1 includes basic LOS, S-plane heading controller and integral S-plane speed controller. The scheme 2 includes improved LOS, IAS heading controller and IAIS speed controller, and the scheme 3 adds speed solver on the basis of the scheme 2, in which the speed in the scheme 1 and scheme 2 is set as 1.25m/s. The initial state of USV is \( [x(0), y(0), \psi(0)]^T = [31m, 2m, 30^\circ]^T \), \( R_{\text{min}} = 3m \), \( k_1 = 2 \), \( k_2 = k_3 = 3 \), \( R_i = 2m \), \( \delta = 1m \), \( \sigma_{\psi} = \sigma_i = 0.3 \), \( L_{\text{ox}} = 1.25m \), \( k_p = 30 \), \( \alpha = 0.7 \), \( \beta = 0.3 \), \( v_{\max} = 2.5 m/s \), and the way-points coordinates are \( P_1 = (40, 20) \), \( P_2 = (110, 110) \), \( P_3 = (110, 40) \), respectively. The results are shown as Figure 6- Figure 9.
According to the comparison in figure 6, it can be intuitively seen that during the whole following process, scheme 2 and scheme 3 have better following effect and smaller overshoot compared with scheme 1, because when there is heading deviation and path distance of USV, the improved LOS guidance law is more sensitive than the basic LOS guidance law. At the same time, the improved LOS guidance law makes real-time compensation for the desired heading on the basis of the basic LOS guidance law, so that USV can converge to the expected heading faster. In Scheme 3, since the speed solver is added, it takes less time to complete the following of the same path. Figure 9 shows the speed change in the following process. When USV is about to arrive at the following path, it will reduce the speed in advance actively and converge on the expected path smoothly. When it is stable along the expected path, the speed of USV will be adjusted according to the deviation of the heading and the distance from the next path point and gradually increase, so as to complete the following of the linear path unit quickly.

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