Intelligent Path-following Control of Unmanned Surface Vehicles Based on Improved Line-of-sight Guidance

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Abstract. For the way point-based path following control of under-actuated unmanned surface vehicle (USV), a new adaptive compensation line-of-sight (LOS) guidance law and speed solver are proposed, and the fuzzy heading control and integral S-plane speed control are designed. The path following control scheme is based on the separation control, and a speed control is added to improve the overall control structure. For adaptive compensation LOS guidance law, confirm the optimal circle radius of the adaptive LOS method first, and then the angle compensation of heading deviation of navigation is conducted for the LOS angle solved by adaptive LOS method, which is used to guide the USV to approach the desired path with the optimal improved LOS angle. Considering the rapidness of path following, a speed solver is designed according to the distance between the two path points, which can calculate the optimal desired speed of the USV in real time. The experimental results testify the effectiveness and superiority of the proposed guidance strategy, the speed solver and the control strategies.

1. Introduction

The unmanned surface vehicle (USV) is a small surface vehicle that can navigate autonomously and accomplish corresponding tasks. In recent years, with the continuous exploitation of marine resources and the rapid development of marine defense technology, the USV, as an important marine intelligence equipment, has played an important role in fields such as seabed surveying and mapping, the inspection of offshore platforms and offshore wind power plants, marine environment monitoring, and offshore investigation and defense [1]. To complete the task accurately and efficiently, considering the under-actuated of USV and the influence of complex and changeable marine environment on its maneuverability, the requirement for the USV’s function of following the preset desired path is getting higher. Therefore, exploring a simple, accurate and efficient USV path following method has become a research focus of domestic and foreign scholars [2].

The current path following control of USV can be divided into direct control and indirect control. Direct control will receive the heading errors and track errors of USV simultaneously, and convert them into the control command output of rudder angle. Indirect control can be divided into two nested rings, the outer ring path guidance and the inner ring heading control. The indirect control scheme is more...
widely used because of its relative separation of the path guidance and heading control, which is conducive to the modularization development of hardware and software, and is convenient for engineering implementation. The performance of indirect path following depends largely on the guidance law. The LOS method is widely used in the design of USV path following guidance system for its simplicity and efficiency.

Initially, the LOS radius of LOS-based path following is a fixed value [3]. Although the form is simple, both the convergence speed and the following accuracy are low. Later, Liu T et al. [4] used a variable LOS radius, so that there was always an intersection between the LOS and the path, but the adjustment range of the variable radius was small, and the path adaptability of the small bending angle was lower. Fossen et al. [5] proposed proportional LOS and Khaled [6] et al proposed exponential LOS. Although the exponential LOS method effectively improves the convergence of the LOS angle, the solution speed of LOS angle is reduced due to the introduction of the exponential function and Lambert W function. Fossen et al. considered the disturbance of ocean current to the motion model, studied the path following control of USV, but did not consider the asymmetry of the USV model [7].

Based on the above analysis, this paper chooses the indirect control scheme as the basis. For the guidance system, the adaptive improvement is conducted for the traditional LOS first, and then the angle compensation of heading deviation and deviation distance of navigation for the adaptive LOS is carried out. In the process of heading and speed control, since the non-linearity, uncertainty and complexity of the USV model, it is difficult to establish an accurate mathematical model, and the heading fuzzy controller and the speed integral S-plane controller are designed. To track the desired path quickly, a speed solver is added to transmit the best desired speed calculated in real time to the speed controller.

2. Unmanned surface vehicle path following control scheme

The path following control scheme of USV consists of two parts: one is the cascade control composed of the outer ring of path guidance and the inner ring of heading control; the other is the speed solver and controller. The overall framework is shown in Figure 1.

The outer ring of path guidance is used to compare the position information of USV received by the GPS with the desired path, calculate the path deviation, calculate the desired target heading $\psi_r(k)$, and transmit it to the inner ring of heading control to guide the USV to the direction of eliminating the path deviation.

The inner ring of heading control compares the actual heading collected by the electronic compass with the desired heading, and obtains the heading deviation signal. Then, through the heading controller, a command is obtained to transmit the rudder angle to the steering gear, which makes the USV turn in the direction of reducing the heading deviation.
The speed controller is used to control the speed of USV. Firstly, the speed solver calculates the optimal desired speed according to the maximum speed and the distance between the USV and the two paths. Namely, when the USV turns, the speed is reduced in advance; when the USA travels along the desired path in a straight line, the speed is increased. The speed controller compares the desired speed with the actual speed of USV to obtain the speed deviation $\Delta v(k)$. Then, through the speed controller, the speed control command is calculated and transmitted to the motor, and the speed of USV is indirectly controlled by controlling the speed of the propeller.

3. Mathematical model of the USV motion

Through analyzing the horizontal motion of USV, it can be concluded that the position and the heading angle in geodetic coordinate system $\{E\}$ can be expressed as $\eta = [x, y, \psi]^T$, and the longitudinal velocity, transverse velocity, and heading angular velocity in hull coordinate system $\{B\}$ can be expressed as $v = [u, v, r]^T$, then the three-degree of freedom kinematics equation and the dynamic asymmetric model of the USV horizontal plane can be expressed as:

$$\begin{align*}
\dot{\eta} &= J(\psi)v \\
M\dot{v} + C(v)v + D(v)v &= Bf + d
\end{align*}$$

(1)

Where $J(\psi) \in \mathbb{R}^{3 \times 3}$ represents the rotation matrix of the USV from the hull coordinate system $\{B\}$ to the geodetic coordinate system $\{E\}$, $M \in \mathbb{R}^{3 \times 3}$ represents inertial matrix, $C(v) \in \mathbb{R}^{3 \times 3}$ represents the coriolis force and centripetal force matrix, $D \in \mathbb{R}^{3 \times 3}$ represents the damping force matrix and $B \in \mathbb{R}^{3 \times 2}$ represents the actuator configuration matrix, which are respectively defined as:

$$J(\psi)=\begin{bmatrix}
\cos \psi & -\sin \psi & 0 \\
\sin \psi & \cos \psi & 0 \\
0 & 0 & 1
\end{bmatrix}$$

(2)

$$M=\begin{bmatrix}
m_{11} & 0 & 0 \\
0 & m_{22} & m_{23} \\
0 & m_{32} & m_{33}
\end{bmatrix}$$

(3)

$$C(v)=\begin{bmatrix}
0 & 0 & -m_{22}v-m_{23}r \\
0 & 0 & m_{11}u \\
m_{22}v+m_{23}r & -m_{11}u & 0
\end{bmatrix}$$

(4)

$$D=\begin{bmatrix}
d_{11} & 0 & 0 \\
0 & d_{22} & d_{23} \\
0 & d_{32} & d_{33}
\end{bmatrix}, B=\begin{bmatrix}
h_{11} & 0 \\
0 & h_{11}
\end{bmatrix}$$

(5)

Where $m_{11}, m_{22}, m_{23}, m_{33}, d_{11}, d_{22}, d_{23}$ and $d_{32}$ are the hydrodynamic coefficient of USV. $f=[f_u, f_r]^T$ is the input of the controller, where $f_u$ is the propeller thrust, $f_r$ is torque of the rudder angle, and $d=[d_u, d_r, d_d]^T$ is interference force/torque caused by winds, waves and currents.
Since the USV studied in this paper is only equipped with one rudder and one propeller, and has no lateral direct control input, it is an under-actuated system [8]. For the USV [9] with symmetrical port and starboard, the coordinate center of the hull can be converted to get $M^{-1}Bf = [\tau_u, 0, \tau_r]^T$, where $\tau_u$ and $\tau_r$ are control force and control torque, respectively. Similarly, the transformed external environment interference item can also be defined as $M^{-1}d = [d_u, d_v, d_r]^T$. The component form of the under-actuated USV model can be expressed as:

$$\begin{align*}
\dot{x} &= u \cos \psi - v \sin \psi \\
\dot{y} &= u \sin \psi + v \cos \psi \\
\dot{\psi} &= r \\
\dot{u} &= N_u(v, r) - \frac{d_{1u}}{m_1} u + \tau_u + d_u \\
\dot{v} &= X(u)r + Y(u)v + d_v \\
\dot{r} &= N_r(u, v, r) + \tau_r + d_r
\end{align*}$$

(6)

Where

$$\begin{align*}
N_u(v, r) &= \frac{1}{m_1} (m_{22}v + m_{23}r)r \\
X(u) &= \frac{m_{23}^2 - m_{11}m_{33}}{m_{22}m_{33} - m_{23}^2} u + \frac{d_{33}m_{23} - d_{23}m_{33}}{m_{22}m_{33} - m_{23}^2} \\
Y(u) &= \frac{(m_{22} - m_{11})m_{23}^2}{m_{22}m_{33} - m_{23}^2} u - \frac{d_{23}m_{32} - d_{32}m_{23}}{m_{22}m_{33} - m_{23}^2} \\
N_r(u, v, r) &= \frac{d_{23}m_{33} - m_{22}(d_{32} + (m_{22} - m_{11})u)}{m_{22}m_{33} - m_{23}^2} v + \frac{m_{22}m_{33} - m_{23}^2}{m_{22}m_{33} - m_{23}^2} r
\end{align*}$$

(7)

$N_u(v, r)$, $X(u)$, $Y(u)$ and $N_r(u, v, r)$ are continuous smooth functions.

4. Design of adaptive compensation los guidance law

4.1. Design of adaptive radius LOS guidance law

The guidance system of USV provides a reference heading angle for the heading control system in real time to guide the USV towards the desired path [10]. Based on the practicability, this paper proposes a transition layer-based guidance strategy of adaptive LOS radius for way point following, as shown in Figure 2. Define a series of way point coordinates, $P_1$, $P_2$, ..., $P_{k-1}$, $P_k$, $P_{k+1}$, ..., $P_n$. $P_k(x_k, y_k)$ is the kth coordinate, $P_{LOS}(x_{LOS}, y_{LOS})$ is position coordinate of LOS, $\alpha_{k-1}$ is azimuth of the desired path, $R_{LOS}$ is the
minimum LOS radius, \( R_e \) is the LOS radius of the transition layer, \( R_k \) is the circle radius of the desired path point after the \( k \)th switching, \( y_e \) is the deviation distance of navigation and \( \Delta > 0 \) is the visibility distance.

\[
\begin{align*}
\alpha_{k-1} = & \frac{y_{LOS} - y_{k-1}}{x_{LOS} - x_{k-1}} = \frac{y_k - y_{k-1}}{x_k - x_{k-1}} = \tan \alpha_{k-1} \\
\psi_{LOS} = & \text{arctan}\left(\frac{y_{LOS} - y}{x_{LOS} - x}\right) = \alpha_{k-1} + \text{arctan}\left(-\frac{y_e}{\Delta}\right)
\end{align*}
\]

**Figure 2.** Adaptive LOS guidance law

On the straight line connecting two adjacent path points, the reference position of the LOS method can be obtained by the following equations:

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

Where \( R \) is the LOS radius centered on the USV. The steering angle \( \psi_{LOS} \) of the USV towards the desired path is calculated by the projection algorithm:

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

Under the guidance of the LOS angle, the USV moves to the reference point continuously, and then gradually converges to the desired path. When it approaches the next path point \( P_k \), whether the USV enters the next straight path can be judged through comparing with the set conversion radius [11].

In the traditional line-of-sight method, the design of the LOS radius \( R \) is generally fixed [3], and the convergence speed is slow. To solve this problem, a new and transition layer-based adaptive LOS radius guidance strategy is proposed in this paper. The circular radius design scheme of the guidance strategy LOS is as follows:
\[ R = \begin{cases} R_{\text{min}}, & |y_e| \leq R_{\text{min}} - \delta \\ R_{\text{min}} + \delta \frac{2.0}{1.0 + \exp[-k_i(\min - R_{\text{min}} - \delta)]}, & R_{\text{min}} - \delta < |y_e| \leq R_{\text{min}} + \delta \\ |y_e| > R_{\text{min}} + \delta & \end{cases} \] (10)

Where, \( \delta \) is the thickness of transition layer and \( k_i \) is the adjustable coefficient. When the deviation distance of navigation \( |y_e| > R_{\text{min}} + \delta \), the USV converges to the desired path with the current minimum visibility distance; when the deviation distance of navigation \( |y_e| \leq R_{\text{min}} - \delta \), the USV towards to the desired path with a minimum inscribed circle radius \( R_{\text{min}} \); when \( R_{\text{min}} - \delta < |y_e| \leq R_{\text{min}} + \delta \), the LOS radius \( R_e \) can transit smoothly between \( R_{\text{min}} \) and \( R_{\text{min}} + \delta \).

4.2. Design of LOS angle compensator with adaptive radius

In this paper, the path following is indirectly realized by the way of heading control. Although this method is effective, it cannot converge to the desired path quickly. To reach the desired path faster, the S-plane heading angle compensator based on heading deviation of navigation is designed in this paper.

The heading deviation-based compensation angle refers to the correction of the current desired heading angle based on the deviation between the actual heading angle and the adaptive LOS angle during the process in which the USV navigates to the desired target point. The larger the deviation value, the greater the compensation angle. Following the desired path, the USV can converge to the desired path more quickly. The heading deviation-based compensator is designed as follows:

\[ \begin{align*}
\Delta \psi &= \psi_{\text{LOS}} - \psi_r \\
\psi_r &= k_p \left[ \frac{2.0}{1.0 + \exp(-k_2 \Delta \psi)} - 1.0 \right]
\end{align*} \] (11)

Where \( \Delta \psi \) is heading angle deviation, \( \psi_r \) is the actual heading of USV, \( \psi_H \) is heading compensation angle, \( k_i \) is the maximum steering rudder angle of the USV in actual navigation and \( k_i \) is the adjustable coefficient of compensator.

In summary, the desired LOS angle is calculated first by applying the transition layer-based adaptive LOS method, and then compensating the LOS angle based on the heading deviation and the deviation distance of navigation. Finally, the actual desired heading of the USV is as follows:

\[ \psi_d = \psi_{\text{LOS}} + \psi_H \] (12)

5. Design of speed solver

According to the distance between the front and back path points, the speed solver can calculate the optimal desired speed, and then transfer it to the speed controller. After the USV entering the new straight path and remaining stable, the deviation between the actual heading and the path azimuth is small, and the distance from the next path point is far. The speed will gradually increase to the maximum speed to follow the path; When the USV is turning fast, the speed will be reduced in advance to ensure that the USV can enter next path unit smoothly. The speed solver is designed as:
\[ v_d = v_{\text{max}} \left( \frac{2.0}{1.0 + \exp(-k_1 \Delta l)} - 1.0 \right) \]  

(13)

Where \( v_d \) is the desired speed of USV; \( v_{\text{max}} \) is the maximum speed of USV; \( \Delta l \) is the distance from the next path point; \( k_1 \) are the adjustable coefficients.

6. Controllers design

There are two controllers in this paper, one is heading controller and the other is speed controller. In actual navigation, the parameters of the USV model are complex and uncertain, which decide it is difficult to establish an accurate mathematical model. However, fuzzy control and S-plane control can not only achieve effective control of complex and nonlinear systems, but also have simple structure and can be applied in engineering. Therefore, this paper adopts fuzzy control method to design the heading controller of USA, and adopts S-plane control method to design the speed controller.

6.1. Heading fuzzy controller

The heading fuzzy controller includes four parts: the fuzzy input variable, the establishment of fuzzy rules, the fuzzy reasoning and the defuzzification of the output variable [12].

6.1.1. Fuzzy and fuzzy rules

The heading fuzzy controller of USV uses the heading deviation \( E \) and the heading deviation rate \( EC \) as the input language variables of the fuzzy controller, and the heading torque \( \tau \) is treated as the output language variables. The basic domain of defined variables including: heading deviation angle \( E \) is \([-180^\circ, 180^\circ]\), the variation rate of heading \( EC \) is \([-3^\circ/s, 3^\circ/s]\), and the yawing torque \( \tau \) is \([-1.5 \text{Nm}, 1.5 \text{Nm}]\). Define the quantification domain of fuzzy variable as: heading deviation angle \( E \) is \([-3, 2, 1, 0, 1, 2, 3]\), the heading deviation angle \( EC \) is \([-3, 2, 1, 0, 1, 2, 3]\) and yawing torque \( \tau \) is \([-3, 2, 1, 0, 1, 2, 3]\); Define fuzzy subset as \{NB, NM, NS, ZO, PS, PM, PB\}, where the elements represent negative large, negative medium, negative small, zero, positive small, positive medium and positive, respectively. The membership functions of fuzzy subset uses positive trigonometric function. According to the steering experience of USV, the control rules are as follows.

| \( \tau \) | NB | NM | NS | ZO | PS | PM | PB |
|-----|-----|-----|-----|-----|-----|-----|-----|
| NB | NB | NB | NM | NM | NM | ZO | ZO |
| NM | NB | NB | NM | NM | NM | PB | PB |
| NS | NB | NB | NM | NM | PS | PB | PB |
| ZO | NB | NB | NM | ZO | PM | PB | PB |
| PS | NB | NB | NS | PM | PM | PB | PB |
| PM | NB | NB | PM | PM | PM | PB | PB |
| PB | ZO | ZO | PM | PM | PM | PB | PB |

6.1.2. The integral S-plane controller of speed

The basic S-plane controller integrates the ideas of fuzzy control and PD control. It has simple structure and strong robustness, and has been successfully applied in the offshore tests of multi-type AUV and USV. However, for the basic speed control of USV, the basic S-plane controller cannot eliminate the steady-state error of the speed control. Therefore, an improved integral S-plane controller is proposed, and the formula is as follows:
\[ \tau_u = \int k \left[ \frac{2.0}{1.0 + \exp(-k_4 \Delta v - k_5 \Delta v)} - 1.0 \right] dt \] (14)

Where \( \tau_u \) is the propulsive force of USV; \( k \) is the integral step; \( k_4 \) and \( k_5 \) are the adjustable coefficients; \( \Delta v \) and \( \Delta \dot{v} \) are the speed deviation and the deviation variation rate of USV, respectively.

7. Vehicle test and result analysis

7.1. Construction of Experimental Platform

This paper adopts “KV-1” USV as the test platform, and the host computer is developed on the VC 6.0 MFC platform, as shown in figure 3. “KV-1” is a single O-type boat, as shown in figure 4. The boat is made of fiberglass reinforced plastic (FPR) technology. Its length, width and height are about 1.2 meters, 0.32 meters and 0.29 meters, respectively. Its processing module is STM32F103 microcontroller with ARM Cortex-M3 as core. It is equipped with three-axis gyroscope, three-axis accelerometer, three-axis magnetometer, GW-GNB110 global positioning system, E15 wireless communication system and HLK-RM04 WIFI communication system. In the experiment, USV sends its attitude angle, position and other information to the host computer through the wireless communication system. After the experiment, the test data are processed and analyzed by MATLAB.
7.2. Test in Songhua River

To verify the effectiveness and efficiency of the path following control algorithm based on adaptive compensation line-of-sight method, team members conducted a series of field tests in Songhua River, as shown in Figure 5. A series of tests of two schemes are conducted for the comb scanning path commonly used in engineering. The first scheme is the corresponding algorithm proposed in this paper, and the second scheme uses the traditional LOS guidance plus S-plane heading and speed controller. The speed solver uses the algorithm of this paper, and the test result is shown in Figure 6.

![Test in Songhua River](image)

**Figure 5. Test in Songhua River**

![Comparison of path following results with different guidance laws](image)

**Figure 6. Comparison of path following results with different guidance laws**

It can be concluded from Figure 6 that the path following effect of USV is intuitively. Although both guidance laws can effectively guide the USV to navigate in accordance with a predetermined trajectory, the adaptive compensation line-of-sight method designed in this paper has better inflection performance and more accurate path following and maintenance ability. After switching paths, it can converge to the desired path at a faster speed. During the whole following process, only a slight adjustment occurs at the third inflection point, and the transition in other places is smooth and stable. Due to the efficiency
and superiority of the path following method proposed in this paper, the following effect of the first scheme is better than the second scheme.

8. Conclusion
In this paper, the path following and control problem of under-actuated USV is studied. A new adaptive compensation line-of-sight guidance law and a desired speed solver are proposed. The fuzzy heading controller and integral S-plane speed controller are designed. The adaptive compensation line-of-sight method can effectively solve the problems of slow convergence speed and low following accuracy in the traditional guidance law; The speed solver can calculate the optimal desired speed in real time, which significantly shortens the time required to complete the path following; The fuzzy heading controller and the integral S-plane speed controller can effectively control the heading and the speed of the USV. The experiment verifies the effectiveness and superiority of the path following control strategy proposed in this paper.

Acknowledgments
This work was funded in part by the National Natural Science Foundation of China under Grant U1713205 and 51809062, and in part by the Fundamental Research Funds for the Central Universities 3072019CFM0106 and 3072019CFG0101.

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