Research Article

Research on Heading Control of USV with the Lateral Thruster

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In order to solve the problem of low speed and stable course tracking of the small unmanned surface vessel (USV), the lateral thruster are added to the driving structure of the USV, and a backstepping control method is designed. By introducing the Lyapunov function, the course tracking error can converge to the region near the desired course and meet the transient and steady performance of the system at the same time. The adaptive control is applied to the lateral thrust control and the closed-loop system remains stable for a finite time. The Lyapunov direct method is used to prove the controller, which greatly simplifies the tedious parameter adjustment problem in traditional control. The simulation results show that the designed controller can make the USV track the specified value stably at low speed and meet the requirements of the USV heading robustness under dynamic conditions.

1. Introduction

The general selection of spray pump or hanging boat and heading speed depends on the pump or hanging angle adjustment and speed or air intake adjustment. At present, a lot of achievements have been made on the navigation control of underactuated USV [1, 2]; however, some problems are still found in the actual experiment. The underactuated small USV can adjust and track the desired course quickly under the condition of high speed, but the performance of accurate tracking control to the desired heading under the condition of low-speed is poor. A lateral thruster is a device that helps a ship turn. It is usually a propeller driven by an electric motor in a transverse pipe at the bow. It can drain water from one side to the other side and use the reaction force of water to help the ship turn. The size of side thrust is related to the flow rate per unit time in the groove. The higher the flow rate, the higher the side thrust. When the ship is near the dock or at low-speed, the rudder has little effect, and the maneuverability of the ship can be improved by using the side thruster. The general ship in the dock or canal moves in and out of the lock, through narrow channels and crowded waters; one is to slow down, and the other is to change the heading point often with the rudder. However, the slower the ship speed, the worse the rudder effect, which brings difficulties to the ship control.

Therefore, it is of great practical value to add the lateral push module to the driving structure. At the same time, in order to stabilize the heading at low-speed, the control research and design of the lateral thruster also have great challenges.

In recent years, many modern control theory methods have been widely used in the design of the navigation control system of the USV [3–5], including adaptive output-feedback control, adaptive fuzzy control [6], adaptive neural decentralized control [7], feedback fuzzy tracking control for discrete-time [8], and so on [9, 10]. Literature [11] studies static output-feedback tracking control problem for discrete-time nonlinear networked systems. Literature [12] studies the problem of adaptive fuzzy tracking control for a class of pure-feedback switched nonlinear systems with unknown gain. Literature [13] studies the adaptive tracking control problem for a class of uncertain nonlinear systems with unmodeled dynamics and disturbances, and literature [14] considers the issue of adaptive neural discrete tracking control for a class of output-constraint switched interconnected nonlinear systems with unknown backlash-like hysteresis control input. It is worth noting that the traditional controller tends to show asymptotic stability, and the setting of system parameters such as adjustment time and dynamic error often requires rich practical experience to meet the desired requirements [15]. When the condition of stable error is met, the adjustment time cannot be guaranteed theoretically. For the application
scenarios of this study, the USV faces a more hostile operating environment than the unmanned ground vehicle (UGV) and unmanned aerial vehicle (UAV), and under the condition of no power supply, the USV still faces the randomness of turning in place or spiraling motion, which also brings great pressure to the directional control at low-speed. At the same time, the complexity of parameter adjustment of the general nonlinear control means is not conducive to rapid application to the actual scene [16, 17].

In order to further solve the problem of high-precision directional control under low-speed navigation, this study combined the idea of backstepping control and finite time control to design a finite time tracking controller. Compared with the above literature, the main innovations of this paper are as follows:

1. Aiming at the heading control problem of USV under low-speed navigation, an adaptive control strategy of limited time is set. Different from the current situation that it is difficult to control the directional at low-speed under underdrive, the designer can specify the directional convergence time in advance according to the sea conditions or mission requirements and achieve the control performance of the controller.

2. In the process of controller design, the Lyapunov function is introduced to ensure that the designed adaptive controller can meet the directional error constraint and accurate tracking under the condition of low-speed sailing under the complicated external disturbance environment at sea.

The main contents of this paper are as follows: Firstly, the lateral thrust control model of unmanned vehicle is given. Then, a finite time adaptive lateral push controller is designed for an unmanned boat with limited speed by using the backstepping method, Lyapunov function, and adaptive control technology, and the error and time convergence of the designed directional controller are proved by using the Lyapunov direct method. Finally, the performance of the controller is analyzed by comparing other methods with simulation experiments.

2. USV Sailing Motion Model

When a ship sails at a certain speed on the water surface, the power needed to overcome the hull resistance is called effective power. When the ship type is given, hull resistance is only a function of the ship speed \(v\) under certain external conditions [18]. The simplified calculation of hull frictional resistance can be achieved by

\[
R_f = \frac{v \cdot L_w}{y},
\]

\[
C_f = \frac{0.075}{(\lg R_e - 2.0)^2},
\]

\[
R_f = (C_f + C_a) \frac{1}{2} \rho v^2 S,
\]

where \(R_e\) is the Reynolds number, and in fixed ship types and moving media, the Reynolds number is only related to the hull velocity. When the hull moves in a fluid medium, it is subjected to three kinds of resistance, namely, frictional resistance, viscosity resistance, and boom resistance [19]. For low-speed boats, frictional resistance accounts for 70% to 80% of all resistance, viscoelastic resistance praises more than 10% of all resistance, and boom resistance is very small [20]. The object of this study is the control of the heading in the low-speed sailing state, so the boom resistance is ignored. The part of \(C_f\) in the formula represents frictional resistance, and the part of \(C_a\) represents the viscosity resistance. \(v\) is the ship’s speed, \(L_w\) is the waterline length, \(\gamma\) is the dynamic viscosity, \(S\) is the wet area, \(\rho\) is the density of the fluid medium, in model calculation, and \(C_a\) is generally taken as a constant, i.e., \(C_a = \Delta C_f = 0.4 \times 10^{-4}\) [21].

Hypothesis 1. The USV is a rigid body with uniform medium. During navigation, the dynamic viscosity and wet area of fluid medium are fixed constants.

Hypothesis 2. For the \(\lg R_e\) term in formula (1), although the size of \(R_e\) varies with the speed, the Reynolds number in practical application scenarios is as high as \(10^6\), so in the case of small speed variation, there is little change in \(\lg R_e\); therefore, it is assumed that the viscous resistance coefficient \(C_f\) is a constant for this research object.

On the premise of the above hypothesis, the resistance to USV motion can be simplified as

\[
R_f = kv^2,
\]

where \(k\) is a fixed constant related to hull parameters and fluid media. The formula (2) shows that the USV resistance is a function of velocity and nonlinear.

3. Controller Design

Aiming at the USV under low-speed navigation, the designated time adaptive controller is designed by combining the backstepping method and the designated time synchronization control method, and by introducing the Lyapunov function of nonlinear system synchronization, the system can satisfy the state constraints during operation.

In the process of adjustment of the bow direction, in a short period of time, think is in a state of balance and stable in the USV, which is a propeller mounted on the front side of the ship; therefore, it can be considered that the rigid body ship with uniform overall mass only receives a lateral thrust first, as shown in Figure 1; in this study, the lateral input force \(F\) is the input, and heading Angle \(\Phi\) is the output.

Through simple force analysis, the following formula can be listed:

\[
F - R_f = \frac{1}{2} mL\Phi,
\]

where \(M\) is the hull mass, and \(L\) is the distance from the side thruster installation point to the stern.
Substituting into (2) and simplifying, we get
\[ F = \frac{1}{2} mL\dot{\phi} + kL^2 \dot{\phi}^2. \] (4)

Set the lateral thrust as input \( u \) and set the state variable as follows:
\[
\begin{align*}
    x_1 &= \phi, \\
    x_2 &= \phi, \\
\end{align*}
\] (5)

According to (4), the following formula of state can be listed:
\[
\begin{align*}
    \dot{x}_1 &= x_2, \\
    \dot{x}_2 &= -\frac{2kL}{m}x_2^2 + \frac{2}{mL}u. \\
\end{align*}
\] (6)

In order to facilitate the subsequent calculation, let \( a = -2kL/m, b = mL \), and then the above formula can be expressed as
\[
\begin{align*}
    \dot{x}_1 &= x_2, \\
    \dot{x}_2 &= ax_2^2 + bu. \\
\end{align*}
\] (7)

During the voyage, the desired heading angle is \( x_{1d} \). In order to achieve feedback control, the error is introduced as
\[ e = x_{1d} - x_1. \] (8)

Set the Lyapunov function as
\[ V_1 = \frac{1}{2} e^2. \] (9)

It is obvious that \( V_1 \geq 0 \), then take the derivative of (9), then plug in (7) and (8), and after simplification, one gets
\[
\begin{align*}
    \dot{V}_1 &= e \cdot \dot{e} \\
    &= e \cdot (\dot{x}_{1d} - \dot{x}_1) \\
    &= e \cdot (\dot{x}_{1d} - x_2). \\
\end{align*}
\] (10)

From formula (10), it can be seen that if \( x_2 = x_{1d} + k_1 e \), where \( k_1 > 0 \), then the condition that \( \dot{V}_1 \) is negative definite can be satisfied, according to the idea of backstepping method, and it is necessary to control the intermediate variable \( x_2 \) by controlling the input \( u \) and then the output \( x_1 \) by controlling the intermediate variable \( x_2 \). Define a new variable \( x_{2d} = x_{1d} + k_1 e \); meanwhile, a new error signal \( \delta \) is introduced
\[ \delta = x_{2d} - x_2. \] (11)

Substituting (11) into (10), we can obtain
\[ \dot{V}_1 = e(-k_1 e + \delta). \] (12)

Taking the derivative to \( \delta \) and plugging into equation (7), we get
\[
\begin{align*}
    \dot{\delta} &= \dot{x}_{2d} - \dot{x}_2 \\
    &= \dot{x}_{1d} + k_1 \dot{e} - ax_2^2 - bu. \\
\end{align*}
\] (13)

Construct a new Lyapunov function as
\[ V_2 = V_1 + \frac{1}{2} \delta^2. \] (14)

Obviously, \( V_2 \geq 0 \), then take the derivative of (14) and substitute in (12)
\[
\begin{align*}
    \dot{V}_2 &= \delta \cdot \dot{\delta} + e \cdot \dot{\delta} - k_1 e^2 \\
    &= \delta (\dot{\delta} + e) - k_1 e^2. \\
\end{align*}
\] (15)

When \( \delta + e = -k_2 \delta \), where \( k_2 > 0 \), it satisfies the condition that \( \dot{V}_2 \) is negative definite so that
\[ \dot{\delta} = -k_2 \delta - e. \] (16)

By substituting (11) and (13) into the above equation, we can obtain that input \( u \) should satisfy
\[
\begin{align*}
    u &= e + \frac{1}{b} \dot{x}_{1d} + \frac{k_1}{b} \dot{e} - \frac{a}{b} x_2^2 + \frac{k_2}{b} \delta. \\
\end{align*}
\] (17)

Two error variables \( e \) and \( \delta \) are tested, according to equations (8), (11), and (16), the following linear state space expressions can be listed:
\[
\begin{align*}
    \dot{e} &= -k_1 e + \delta, \\
    \dot{\delta} &= -e - k_2 \delta. \\
\end{align*}
\] (18)

It is not difficult to conclude that the eigenvalues of the eigen matrix of the state space have only negative real parts, so it satisfies the asymptotic stability condition, namely, \( \lim_{t \to \infty} x \to 0 \), \( \lim_{t \to \infty} \delta \to 0 \). Therefore, it is proved that the above control model meets the requirements of system stability.
4. Simulation Experiments

In order to verify the simulation effect of the controller, as shown in Figure 2, the following simulation experiment process is designed.

According to the control system and state equation described in the previous section, as shown in Figure 3, the following simulation model was built on the Matlab platform in this study.
It is worth mentioning that the derivation of heading in actual navigation is based on the definition of derivation, and finite difference is used for derivation calculation. However, for the convenience of system calculation, the continuous sine function is used as the change of expected heading. The meaning mapped to the actual navigation is when the speed of the USV is constant, it moves in a circle. When the speed of the USV is uniform, the spiral forward motion is carried out.

In this section, the performance of the designed controller is simulated and analyzed. The motion model of the low-speed sailing USV is taken as the object. The USV parameters are as follows: the initial heading angle of the USV is set as 50°, and the tracking heading instruction is a sinusoidal signal with amplitude of 360, and the frequency is 1 rad/s.

In order to demonstrate the effectiveness of the proposed method in this study, this section studies the change curves of system state and output under ideal loads and loads with interference terms. The method in this paper is compared and analyzed with literature [5]. The controller parameters selected in the experiment are shown in Table 1.

Simulation results are shown in Figures 4–9. Figures 4–7 are heading tracking curves and corresponding error curves, respectively. It can be seen that the adaptive backstepping controller designed in this study can track the desired heading in a limited time, ensure that the heading error meets the constraints of Lyapunov function, and realize the convergence of the system in a short time, with high steady-state performance and transient performance. In contrast, the nonlinear saturated PID control method given in literature [5] has a large-tracking error in the tracking control of the heading angle on this application object, and the addition of differential terms poses a great challenge to the realization of specific control input. At the same time, in the process of simulation experiment, it is
quite difficult to adjust PID parameters, and it requires a lot of trial and error and a lot of energy to obtain the ideal-tracking effect. The adaptive backstepping controller designed in this study can achieve good-tracking control effect without complex parameter design. Figures 8 and 9 show the heading output curve of the adaptive backstepping controller with interference terms, demonstrating the robustness of the controller.

In order to better present the comparison between the method in this paper and literature [5], the absolute value of error is selected to evaluate the performance index as

\[ \varepsilon = \int_0^t |e(t)| \, dt. \]  (19)

Let \( t = 50 \), taking the integral of the absolute value of error (50 s), the error integral of adaptive backstepping controller and nonlinear saturated PID controller can be calculated to be 275.747 and 695.610, respectively. By comparison, it can be seen that the proposed method has less input burden on the controller and greatly improves the tracking performance of the system compared with the nonlinear saturated PID controller.

5. Conclusion

This paper analyzes the problem that the directional control of the USV is not accurate enough under low-speed navigation, adds the side push controller, and then studies and analyzes the heading control under low-speed navigation by using the backstepping nonlinear control theory and adaptive method.

In the simulation environment, the backstepping control strategy greatly simplifies the difficulty of controller parameter adjustment and improves the practicability of the system. Through the analysis of the designed evaluation function, the heading tracking speed of the proposed controller is more than twice that of the nonlinear PID method. Based on the proof of control stability and the simulation results of the interference term, the controller designed in this study can realize the heading tracking control of the system with limited unknown disturbances and meet the requirements of system robustness.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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