ESO based anti-disturbance target tracking control for twin-screw unmanned surface vehicle

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Abstract: [Objectives] Focusing on the model uncertainties of unmanned surface vehicles (USVs) and unknown marine environmental disturbances, an anti-disturbance target-tracking control algorithm based on extended state observer (ESO) is proposed for twin-screw USVs. [Methods] At the kinematic level, a guidance law based on the principle of constant bearing is presented for USVs. At the kinetic level, aiming at model uncertainties and unknown disturbances, anti-disturbance control laws for surge velocity and yaw angular velocity based on ESOs are designed to eliminate the problems caused by model uncertainties and unknown marine environmental disturbances. Finally, the stability of the proposed controllers is analyzed via input-to-state stability and cascade theory. [Results] The results show that such a USV can effectively track the virtual target point using the proposed anti-disturbance target tracking controller. [Conclusions] The effectiveness of the proposed control algorithm is verified via experimental results.

Key words: unmanned surface vehicles (USV); extended state observer (ESO); target tracking; constant bearing guidance

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0 Introduction

In recent years, with the development of driverless technology, an unmanned surface vehicle (USV), as a miniaturized, intelligent, multi-purpose unmanned marine carrier platform, has attracted wide attention from scholars. In terms of motion scenarios, USVs can be used for trajectory, path and target tracking. Specifically, target tracking is of important application value in military and civilian fields [1]. The motion control of USVs is faced with some research difficulties including nonlinearity, model uncertainty, underactuation, and strong external disturbance. This brings challenges to effective and reliable target-tracking control of USVs. At present, many methods have been proposed for USV control, such as sliding mode control [2], robust control [3], fuzzy control [4], parameter adaptive control [5], neural-network-based control [6], disturbance observers [7], and extended state observers (ESOs) [8]. Traditionally, attitudes in USV motion are controlled by adjusting screw propellers and rudders. This method is more suitable for large ships. As rudder angles need to be frequently adjusted to control ship courses and attitudes, it is difficult to meet the high requirement of small USVs on mobility. In comparison, controlling velocity or courses by the same or different thrust from two screw propellers, twin-screw USVs can greatly improve mobility of USVs, enabling them to better adapt to working scenarios [9].
This paper studied anti-disturbance target-tracking control of twin-screw underactuated USVs with model uncertainties and unknown marine environmental disturbances. First, a mathematical model for the motion of a twin-screw underactuated USV was established, including kinematic and kinetic equations. In terms of kinematics, a target-tracking guidance law based on constant bearing (CB) was proposed. In terms of kinetics, control laws of surge velocity and yaw angular velocity were analyzed by input-to-state stability and cascade theory. Moreover, effectiveness of the anti-disturbance target-tracking control based on CB guidance was proved experimentally.

1 Mathematical model of USV

Fig. 1 shows a mathematical model for the motion of a twin-screw underactuated USV in the earth-fixed coordinate system $X_E-Y_E$ and the body-fixed coordinate system $X_B-Y_B$.

![Schematic diagram of plane motion of USV](image)

In the figure, $u$, $v$, and $r$ are the surge velocity, sway velocity, and yaw angular velocity of the USV in the body-fixed coordinate system $X_B-Y_B$, respectively; $x$, $y$, and $\psi$ are the $X_E$ coordinate, the $Y_E$ coordinate, and the yaw angle of the USV in the earth-fixed coordinate system, respectively; $f_1$ and $f_2$ are the thrust generated by left and right screw propellers, respectively; $B$ is the lateral wheelbase between the left and right screw propellers.

The kinematic model of the USV can be described by a nonlinear mathematical model with three degrees of freedom:

$$\eta = R(\psi)\nu$$

where $\nu = [u, v, r]^T$ is a velocity state vector of the USV: $\eta = [x, y, \psi]^T$ is a position state vector of the USV; $R(\psi)$ is a matrix of the USV in the earth-fixed and body-fixed coordinate systems.

In the kinetics modeling, hydrodynamic damping of a USV during its sailing in water is usually of a linear form. In other words, there is a linear relationship between the resistance and velocity of the USV. Therefore, the kinetic equation of the USV is given by:

$$M \nu + C \nu + D \nu = \tau + \tau_d$$

where $M$ is a matrix of inertia mass of the USV; $C$ is a coefficient matrix of centripetal and Coriolis forces; $D$ is a matrix of hydrodynamic damping; $\tau$ is a vector of thrust and its moment of the USV; $\tau_d$ is a vector of disturbances to thrust and its moment.

A twin-screw USV is a typical underactuated system, with no force laterally. Therefore, its kinetic control input is $\tau = [f_1 + f_2, 0, B \cdot (f_1 - f_2)/2]^T$. In a towing test of the USV at a uniform velocity in still water, according to the linear regression equation, the thrust generated by screw propellers of the twin-screw USV is approximately linearly related to control voltage, namely, $f = kV$. Therefore, surge velocity and yaw angular velocity of the USV can be controlled by controlling the input voltage of DC motors on both sides of the USV. Suppose that the control voltage of motors on left and right sides is $V_L = \sigma_u + \sigma_r$ and $V_R = \sigma_u - \sigma_r$, respectively. Here, $\sigma_u$ and $\sigma_r$ are control voltage of surge velocity and yaw angular velocity, respectively. In the case of $\sigma_u > 0$ and $\sigma_r = 0$, or $\sigma_u < 0$ and $\sigma_r = 0$, the USV only moves forwards or backwards. In the case of $\sigma_u > 0$ and $\sigma_u = 0$, or $\sigma_u < 0$ and $\sigma_u = 0$, the USV only turns rightwards or leftwards. Therefore, the kinetic equation of the USV shown in Formula (2) can be rewritten as follows:

$$\begin{align*}
\dot{u} &= \frac{d_{11}}{m_1}u + \frac{d_{13}}{m_{13}}r + \frac{2k}{m_1} \sigma_u \\
\dot{r} &= \frac{d_{33}}{m_{33}}r + \frac{1}{m_{33}} \cdot \text{rad} + \frac{kB}{m_{33}} \sigma_r
\end{align*}$$

where $d_{11}$ and $d_{33}$ are damping coefficients, with $d_{11}, d_{13} \in D$; $m_1$ and $m_{33}$ are inertia mass constants, with $m_{11}, m_{33} \in M$; $k$ is a parameter of the relationship between input voltage of a DC motor and generated thrust; $\tau_{d1} \in \tau$ is a disturbance component in the direction of surge velocity; $\tau_{d3} \in \tau$ is a disturbance component in the direction of yaw angular velocity. From Formula (3), the motion of the USV can be controlled just by adjusting the control voltage $\sigma_u$ or $\sigma_r$. This realizes decoupled control of surge velocity and yaw angular velocity, thus simplifying the design of kinetic controllers of the twin-screw USV.
and solving the coupling between rotation and propulsion in motion control.

2 Controller design

2.1 Design of guidance laws in kinematics

The basic principle of CB guidance is to reduce line-of-sight rotation rates to zero, thus enabling follower ships to perceive and track targets in constant azimuths. Target tracking is to reduce the sight distance between a follower ship and a target to an expected value and keep it unchanged.

Define the position vectors of a follower ship and a target at a specific time as $\mathbf{p}(t) = [x(t), y(t)]^T$ and $\mathbf{p}_t(t) = [x_t(t), y_t(t)]^T$, respectively. Then, the velocity vectors of the follower ship and the target are $\dot{\mathbf{p}}(t) = \mathbf{p}_t(t) - \mathbf{p}(t)$, respectively. Let $\mathbf{u}_\text{max}$ be a vector of sight distance between the target and the follower ship. Then, the control target of CB guidance can be expressed as

$$\lim_{x \to \infty} \dot{\mathbf{p}}(t) = 0 \quad (4)$$

Fig. 2 shows velocity decomposition under the CB guidance law.

![Fig. 2 Velocity assignment associated with CB guidance](image)

According to Fig. 2, we have

$$\dot{\mathbf{u}}(t) = \dot{\mathbf{u}}(t) + \mathbf{u}_\text{max} \frac{\dot{\mathbf{p}}(t)}{\sqrt{(\dot{\mathbf{p}}(t))^2 + \delta_p^2}} \quad (5)$$

where $\mathbf{u}_\text{max}$ is maximum approaching velocity of the follower ship along the line-of-sight direction, $\mathbf{u}_\text{max} > 0$; $\delta_p$ is an anti-collision constant, $\delta_p > 0$. Therefore, the CB-based kinematic guidance law is as follows:

$$\begin{cases}
\dot{u}_s = \sqrt{(\dot{x}(t))^2 + (\dot{y}(t))^2} \\
\psi_s = \text{atan2}(\dot{y}(t), \dot{x}(t))
\end{cases} \quad (6)$$

where $u_s$ is expected velocity of the USV; $\psi_s$ is an expected course angle of the USV, satisfying $\psi_s \in (-\pi, \pi]$. As the kinetics fails to directly control courses, a virtual control law is designed as follows.

$$r_s = K_r \dot{\psi}_s \quad (7)$$

where $r_s$ is expected angular velocity of the USV; $\dot{\psi}_s = \psi_s - \psi$ is a course-tracking error; $K_r$ is a gain constant.

2.2 Design and stability analysis of surge-velocity controller

Without the consideration of motor characteristics, a response model of surge velocity of the twin-screw USV is given by

$$\dot{u}_s = f_s + b_v \sigma_u \quad (8)$$

where $f_s$ is an uncertainty term in the direction of surge velocity; $b_v$ is a control gain. Following assumptions are made for the design and stability analysis of an ESO subsystem.

Assumption 1: The derivative of $f_s$ is bounded and satisfies $|\dot{f}_s| < f_s$, where $f_s > 0$ is a constant.

Affected by model uncertainties and unknown environmental disturbances, $f_s$ in Formula (8) is unknown. In order to estimate the unknown term, we design a first-order linear ESO as follows.

$$\begin{cases}
\dot{\hat{u}} = -\beta_{u1} (\hat{u} - u_s) + f_s + b_v \sigma_u \\
\dot{\hat{f}} = -\beta_{u2} (\hat{u} - u_s)
\end{cases} \quad (9)$$

Where $\hat{u}$ and $\hat{f}$ are estimated values of $u$ and $f_s$, respectively; $\beta_{u1}$ and $\beta_{u2}$ are gains of the observer.

Define the following estimation errors: $\hat{u} = \hat{u} - u_s$, $\hat{f} = \hat{f} - f_s$. Then, error dynamic equations of the first-order ESO are given by

$$\begin{cases}
\dot{\hat{u}} = -\beta_{u1} \hat{u} + \hat{f} \\
\dot{\hat{f}} = -\beta_{u2} \hat{u} - f_s
\end{cases} \quad (10)$$

Let $E_1 = [\hat{u}, \hat{f}]^T$. Then, the ESO subsystem shown in Formula (10) is written into the following matrix form:

$$\dot{E}_1 = A_1 E_1 - B_1 f_s \quad (11)$$

where $A_1 = \begin{bmatrix} -\beta_{u1} & 1 \\ \beta_{u2} & 0 \end{bmatrix}$, $B_1 = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$.

As $A_1$ is a Hurwitz matrix, there exists a positive definite matrix $P_1$ which satisfies the following inequality:

$$A_1^T P_1 + P A_1 \leq -e_a I \quad (12)$$

where $e_a \in \mathbb{R}$ is a constant greater than zero; $I$ is a three-dimensional diagonal unit matrix.

According to Formula (8), in order to offset disturbances in the direction of surge velocity, we design a self-anti-disturbance control law of surge velocity as follows:

$$\sigma_u = \frac{1}{b_v} [\xi_u (u_s - \hat{u}) - \hat{f}_s] \quad (13)$$

where $\xi_u$ is a kinetic gain. Let $\hat{u}_s = \hat{u} - u_s$ be a tracking error of surge velocity. By taking the derivative of $\hat{u}_s$ and substituting Formula (13) into the derivative, we can obtain the dynamic equation of tracking errors as follows:
\[ \dot{u} = -\xi \dot{u} - \beta \ddot{u} \]  

1) Stability analysis of the ESO subsystem.

Stability of the ESO subsystem in Formula (11) is given by Lemma 1.

Lemma 1: Under the condition that Assumption 1 is satisfied, the ESO subsystem with a state of \( E \) and an input of \( f \) shown in Formula (11) is input-to-state stable.

Proof: Construct a Lyapunov function as follows:\[ V = \frac{1}{2} E^T P E \]  

Taking a derivative of Formula (15) yields \[ V = E^T P \left( A E - B f \right) = \]  

\[ -\frac{\varepsilon}{2} E^T E + \frac{1}{2} E^T P B f \leq \]  

\[ -\frac{\varepsilon}{2} \| E \|^2 + \frac{1}{2} \| P B f \| \| f \| \]  

From \[ \| E \| \geq \frac{2 \| P B f \| \| f \|}{\varepsilon_1 \tilde{b}_1} \]  

we have \[ V_{11} \leq \frac{\varepsilon}{2} \left( 1 - \tilde{b}_1 \right) \| E \|^2 \]  

where \( 0 < \tilde{b}_1 < 1 \). As can be seen, the ESO subsystem shown in Formula (11) is input-to-state stable, and there exists a class \( \mathcal{KL} \) function \( \alpha \) and a class \( \mathcal{K}_\sigma \) function \( \gamma \) to make the following condition satisfied:

\[ \| E_{1} (t) \| \leq \alpha_{1}(E_{1}(t), \| B \| ) + \gamma_{1}(\| f \| ) \]  

where \[ \gamma_{1}(s) = \frac{\tilde{b}_1}{s} \], \( \gamma_{1}(s) = \frac{\tilde{b}_1}{s} \) and \( \gamma_{1}(s) = \frac{\tilde{b}_1}{s} \).

2) Stability analysis of the control subsystem.

The stability of the control subsystem in Formula (14) is given by Lemma 2.

Lemma 2: The control subsystem with a state of \( \dot{u} \) and an input of \( \ddot{u} \) shown in Formula (14) is input-to-state stable.

Proof: Construct a Lyapunov function as follows:

\[ V_{2} = \frac{1}{2} \dot{u}^2 \]  

Taking a derivative of Formula (15) yields \[ V_{2} = \dot{u} \dot{u} \]  

Substituting Formula (14) into Formula (21) yields \[ V_{2} - \dot{u} (\epsilon \dot{u} - \beta \ddot{u} + \beta \dot{u} + \beta \ddot{u} - \beta \dot{u} \ddot{u} \leq \]  

\[ -\epsilon \dot{u}^2 + \beta \dot{u} \| \ddot{u} \| \| \ddot{u} \| \]  

From \( \tilde{u} > \beta \| \ddot{u} \| \) we have \[ V_{2} \leq \epsilon \| 1 - \tilde{b}_2 \| \| \ddot{u} \| \]  

where \( 0 < \tilde{b}_2 < 1 \). Therefore, the control subsystem in Formula (14) is input-to-state stable, and there exists a class \( \mathcal{KL} \) function \( \alpha \) and a class \( \mathcal{K}_\sigma \) function \( \gamma \) to make the following condition satisfied:

\[ \| \dot{u} \| \leq \alpha_{2}(\ddot{u}(t), \| B \| ) + \gamma_{2}(\| \ddot{u} \| ) \]  

where \( \gamma_{2}(s) = \frac{\tilde{b}_2}{s} \).

3) Stability analysis of cascaded ESO and control subsystems.

The ESO subsystem in Formula (11) and the control subsystem in Formula (14) are considered as a cascade system:

\[ \Sigma_{\alpha} : \dot{u} = \alpha u + f \]  

\[ \Sigma_{\beta} : \ddot{u} = -\beta_1 \ddot{u} + \beta_2 \ddot{u} \]  

\[ \ddot{f} = -\beta_2 \ddot{u} - \frac{\ddot{f}}{s} \]  

Stability of the cascade system of the ESO-based surge-velocity controller, composed of \( \Sigma_{\alpha} \) and \( \Sigma_{\beta} \), is given by Theorem 1.

Theorem 1: In view of the surge velocity of the USV in Formula (8), under the condition that Assumption 1 is satisfied, the surge-velocity ESO in Formula (9) and the surge-velocity control law in Formula (13) make the cascade system composed of \( \Sigma_{\alpha} \) and \( \Sigma_{\beta} \) be input-to-state stable.

Proof: Lemmas 1 and 2 have been proved. If the subsystem \( \Sigma_{\alpha} \) has a state of \( \dot{u} \) and an input of \( \ddot{u} \), it is input-to-state stable. If the subsystem \( \Sigma_{\beta} \) has a state of \( \ddot{u} \) and \( \ddot{f} \) and an input of \( \ddot{f} \), it is input-to-state stable. According to the theorem of globally uniformly asymptotic stability, for the entire closed-loop system of surge velocity, if its state is \( \dot{u} \) and \( \ddot{f} \), and its external input is \( \ddot{f} \), the system is input-to-state stable. In other words, there exist a class \( \mathcal{KL} \) function \( \alpha \) and a class \( \mathcal{K} \) function \( \phi \) to make \( E_{2}(t) \) satisfy the following condition:

\[ E_{2}(t) \leq \alpha \| E_{2}(0) \| \| t \| + \phi \| \ddot{f} \| \]  

where \( E_{2} = \left[ \ddot{u}, \dot{u}, \ddot{f} \right] \). Due to the bounded external input \( \ddot{f} \), the error signal \( E_{2} \) is bounded.

2.3 Design and stability analysis of yaw-angular-velocity controller

Without the consideration of motor characteristics, a response model of yaw angular velocity of the twin-screw USV is given by

\[ \dot{r} = f_{r} + b \sigma \]  

where \( f \) is an uncertainty term in the direction of yaw angular velocity; \( b \) is a control gain. Following assumptions are made for design and stability analysis of the ESO subsystem.
Assumption 2: The derivative of $f_r$ is bounded and satisfies $|f_r' - f_r| < f_r^*$, where $f_r'$ is a constant and $f_r^* > 0$.

Affected by model uncertainties and unknown environmental disturbances, $f_r$ in Formula (27) is unknown. In order to estimate the unknown term, we design a first-order linear ESO as follows:

\[
\begin{align*}
\dot{r} &= -\beta_1 (r - \hat{r}) + \hat{f}_r, \\
\dot{\hat{f}_r} &= -\beta_2 (f_r - \hat{f}_r),
\end{align*}
\]

(28)

where $\hat{r}$ and $\hat{f}_r$ are estimated values of $r$ and $f_r$, respectively; $\beta_1$ and $\beta_2$ are gains of the linear state observer.

Define the following estimation errors: $\hat{r} = \hat{r} - r$ and $\hat{f}_r = \hat{f}_r - f_r$. Then, combining Formulas (27) and (28) can yield error dynamic equations of the ESO as follows:

\[
\begin{align*}
\dot{\hat{r}} &= -\beta_1 \hat{r} + \hat{f}_r, \\
\dot{\hat{f}_r} &= -\beta_2 \hat{f}_r - \hat{f}_r,
\end{align*}
\]

(29)

Let $E_1 = [\hat{r}, \hat{f}_r]^T$. Rewrite Formula (29) into the following matrix form:

\[
E_1 = A_2 \dot{E}_1 - B_2 \dot{f}_r,
\]

(30)

where $A_2 = \begin{bmatrix} -\beta_1 & 1 \\ 0 & -\beta_2 \end{bmatrix}$ and $B_2 = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$.

As $A_2$ is a Hurwitz matrix, there exists a positive definite matrix $P_2$ which satisfies the following condition:

\[
A_2^T P_2 + P_2 A_2 \leq -\varepsilon I_2,
\]

(31)

where $\varepsilon \in \mathbb{R}$ is a constant greater than zero.

According to Formula (27), in order to offset disturbances in the direction of yaw angular velocity, we design a self-anti-disturbance control law of yaw angular velocity as follows:

\[
\sigma_r = \frac{1}{\hat{r}_e} |\xi_r (r - \hat{r}) - \hat{f}_r|,
\]

(32)

where $\xi_r$ is a kinetic gain. Let $\dot{r}_e = \hat{r} - r$, $\dot{f}_e$ be a tracking error of yaw angular velocity. By taking the derivative of $\dot{r}_e$ and substituting Formula (32) into the derivative, we can obtain the dynamic equation of tracking errors as follows:

\[
\dot{\hat{r}}_e = -\xi_r \dot{r}_e - \beta_1 \hat{r}_e
\]

(33)

Thus, the controller design for the entire closed-loop system is completed, and Fig. 3 shows the controller structure.

1) Stability analysis of the ESO subsystem.

The stability of the ESO subsystem in Formula (30) is given by Lemma 3.

Lemma 3: Under the condition that Assumption 2 is satisfied, the ESO subsystem with a state of $E_1$ and an input of $f_r$ shown in Formula (30) is input-to-state stable.

Proof: Construct a Lyapunov equation as follows:

\[
V_3 = \frac{1}{2} E_1^T P_2 E_3
\]

(34)

By taking a derivative of $V_3$ and combining Formula (30), we have

\[
V_3 = E_2 \cdot \frac{1}{2} P_2 \left( A_2 E_1 - B_2 f_r \right) \leq -\frac{\varepsilon_3}{2} |E_1|^2 + ||E_3|| ||P_2 B_2|| \|f_r\|
\]

(35)

From

\[
||E_3|| \geq \frac{2 ||P_2 B_2|| \|f_r\|}{\varepsilon_3 \theta_1}
\]

(36)

we have

\[
V_3 \leq -\frac{\varepsilon_3}{2} (1 - \theta_1) ||E_1||^2
\]

(37)

where $0 < \theta_1 < 1$. Therefore, the ESO subsystem in Formula (30) is input-to-state stable, and there exist a class $\mathcal{K}$ function $\alpha_3$ and a class $\mathcal{K}$ function $T_3^*$ to make $E_1(t)$ satisfy the following condition:

\[
||E_3(t)|| \leq \alpha_3 (E_3(t_0), t - t_0 + T_3^* ||f_r||)
\]

(38)

where

\[
T_3^* (s) = \frac{2 \sqrt{l} (P_2)}{s} \sqrt{2 (P_2) ||E_3||}
\]

2) Stability analysis of the control subsystem.

The stability of the control subsystem in Formula (33) is given by Lemma 4.

Lemma 4: The control subsystem with a state of $\dot{r}_e$ and an input of $\hat{r}$ shown in Formula (33) is input-to-state stable.

Proof: Construct a Lyapunov equation as follows:

\[
V_4 = \frac{1}{2} \dot{r}_e^2
\]

(39)

By taking a derivative of $V_4$ and combining Formula (33), we have

\[
V_4 = \dot{\dot{r}}_e (-\xi_r \dot{r}_e - \beta_1 \dot{r}_e) = -\xi_r \dot{r}_e^2 - \beta_1 \dot{r}_e \dot{r}_e \leq -\xi_r \dot{r}_e^2 + \beta_1 \dot{r}_e \dot{f} / ||f||
\]

(40)

From $\dot{r}_e > \beta_1 \|\hat{f}_r\| / (\xi_r \theta_3)$, we have

\[
V_4 \leq -\xi_r (1 - \theta_3) ||\dot{r}_e||
\]

(41)

where $0 < \theta_3 < 1$. Therefore, the control subsystem in Formula (33) is input-to-state stable, and there exist a class $\mathcal{K}$ function $\alpha_4$ and a class $\mathcal{K}$ functions $\gamma_4$ to make $\dot{r}_e$ satisfy the following condition:

\[
||\dot{r}_e|| \leq \alpha_4 (\dot{r}_e (t_0), t - t_0 + \gamma_4 (||\dot{r}_e||)
\]

(42)

where

\[
\gamma_4 (s) = \frac{\beta_1}{\xi_r \theta_3 s}
\]
3) Stability analysis of cascaded ESO and control subsystems.

The ESO subsystem in Formula (30) and the control subsystem in Formula (33) are considered as a cascade system:

\[
\Sigma_1: \begin{align*}
\dot{\hat{r}} &= -\zeta \hat{r} - \beta_1 \hat{r} \\
\dot{\tilde{r}} &= \beta_1 \hat{r} + \tilde{f}
\end{align*}
\]

\[
\Sigma_2:\begin{align*}
\dot{\hat{f}} &= -\beta_2 \hat{f} + \dot{f}
\end{align*}
\] (43)

The stability of the cascade system of the ESO-based yaw-angular-velocity controller, composed of \(\Sigma_1\) and \(\Sigma_2\), is given by Theorem 2.

Theorem 2: In view of the yaw-angular-velocity of the USV in Formula (27), under the condition that Assumption 1 is satisfied, the yaw-angular-velocity ESO in Formula (28) and the yaw-angular-velocity control law in Formula (32) make the cascade system composed of \(\Sigma_1\) and \(\Sigma_2\) be input-to-state stable.

Proof: Lemmas 3 and 4 have been proved. If the control subsystem \(\Sigma_1\) has a state of \(\hat{r}\) and an input of \(\hat{r}\), it is input-to-state stable. If the ESO subsystem \(\Sigma_2\) has a state of \(\hat{r}\) and \(\tilde{f}\) and an input of \(\tilde{f}\), it is input-to-state stable. According to the theorem of globally uniformly asymptotic stability, for the entire closed-loop system of yaw angular velocity, if its state is \(\hat{r}, \hat{f}, \tilde{f}\), and its external input is \(\tilde{f}\), the system is input-to-state stable, and there exist a class \(\mathcal{K}_L\) function \(\sigma\) and a class \(\mathcal{K}\) function \(\phi\) to make \(E_4(\dot{t})\) satisfy the following condition:

\[
\|E_4(\dot{t})\| \leq \sigma(\|E_4(0)\|, t) + \phi(\|f_t\|)
\] (44)

where \(E_4 = [\hat{r}, \hat{r}, \tilde{f}, \tilde{f}]^T\). Due to the boundedness of the external input \(f_t\), the error signal \(E_4\) is bounded.

3 Test results

Two CSICST-DH01 USVs shown in Fig. 4 were tested to verify the effectiveness of the ESO-based CB-guided anti-disturbance target-tracking control method. The USVs were equipped with global positioning modules, electronic compasses, motion processing units, Freescale single-chip microcomputers, brushless DC motors, electronic velocity governors, wireless communication modules, and power supplies.

Controller parameters in this test were set as follows: \(u_{\text{max}} = 0.7\) m/s, \(\delta_p = 4\), \(\beta_{u1} = 1\), \(\beta_{u2} = 0.25\), \(\beta_{r1} = 1\), \(\beta_{r2} = 0.25\), \(\xi = 2\), \(\varepsilon_r = 0.5\), \(h_u = 1\), \(h_r = 1\).

In order to avoid collision between the follower ship and the target ship, according to the coordinate translation principle, the follower ship tracked a virtual target point near the target ship. The position of the virtual target point in \(X_E-Y_E\) is as follows [14]:

\[
p_v(t) = p_v(t) + R'(\psi)q
\] (45)

where \(p_v(t)\) is the position of the virtual target point; \(q\) is a position-offset vector, and \(q = [-2, -2]^T\) in this test; \(R'(\psi)\) is a rotation matrix, satisfying

\[
R'(\psi) = \begin{bmatrix}
\cos \psi & -\sin \psi \\
\sin \psi & \cos \psi
\end{bmatrix}
\] (46)

Figs. 5-7 show the test results of surge-velocity control. From Fig. 5, for a given expected velocity signal, both ESO-based estimated velocity and actual velocity of the USV can stabilize to the expected value in a short time. From Fig. 6, under the surge-velocity control law in Formula (13), velocity tracking errors of the USV stabilize at about 0 in a steady state. Fig. 7 shows disturbances to the USV in transient and steady states. Specifically, in a steady state, the disturbance is basically constant, which is consistent with the actual situation. This indicates the effectiveness of the surge-velocity ESO in Formula (9).

Figs. 8-10 show the test results of yaw-angular-velocity control. From Fig. 8, for a given expected velocity signal, both ESO-based estimated angular
velocity and actual yaw angular velocity can stabilize to the expected value in a short time. From Fig. 9, under the yaw-angular-velocity control law in Formula (32), angular-velocity tracking errors of the USV stabilize at about 0° in a steady state. Fig. 10 shows that the disturbance to the USV is basically constant in a steady state, which is consistent with the actual situation. This indicates the effectiveness of the yaw-angular-velocity ESO in Formula (28).

Figs. 11-14 show the test results of yaw-angular-velocity control. Fig. 11 shows the actual trajectories of the follower ship (red line) and the target ship (blue line). From the figure, the follower ship has stabilized to the position of the virtual target point set by Formula (45). Fig. 12 shows tracking errors between the follower ship and the virtual target point. From the figure, under the proposed CB guidance law in Formula (6), the USV gradually converges to the virtual target point, with tracking errors stabilizing at about 0 m. From Figs. 13 and 14, with the decrease in tracking errors, the courses and velocity of the follower ship and the virtual target point tend to be the same. There were water weeds randomly distributed in the lake of this test. When the follower ship passed through dense water weeds at 75 s, the weeds were wound onto its screw propellers, resulting in increased errors. From the guidance law in Formula (6) and the control law in Formula (13), once the surge velocity starts to increase, the control input $\sigma_u$ of surge velocity also increases, and thus the propellers rotate faster. After getting rid of the weeds, the USV continued to catch up with the target, restoring its tracking state to a steady one.
4 Conclusions

In view of target tracking of twin-screw USVs, this paper proposed a method of ESO-based CB-guided anti-disturbance target-tracking control. Firstly, a motion model of a twin-screw USV was established in $X_E$-$Y_E$ and $X_B$-$Y_B$ coordinate systems. Then, a target-tracking control law based on CB guidance was proposed in terms of the kinematics, and ESO-based surge-velocity and yaw-angular-velocity control laws were proposed in terms of the kinetics. Thus, model uncertainties of the USV and problems caused by unknown environmental disturbances can be overcome. With the input-to-state stability and cascade theory, stability of the proposed controllers was proved. Finally, effectiveness of the proposed anti-disturbance target-tracking control method was verified experimentally.

References


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某型无人艇综合健康管理系统分析

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摘 要：[目的] 为确保无人艇(USV)航行安全，降低维修保障费用，推行高效的维修保障模式，开展无人艇综合健康管理(IVHM)系统分析。[方法] 根据某型无人艇的功能结构，对若干关键设备和船体展开故障模式、影响及危害度分析(FMECA)；基于运维需要，分析无人艇IVHM系统的功能需求，以设计其系统框架，并提出设计该系统所需的关键技术；采用基于智能体仿真模型评估无人艇主题任务的成功性，分析保障资源需求。[结果] 将设备故障参数和功能性参数作为输入，建立了基于智能体的IVHM系统模型，为USV的任务成功性评估和保障资源需求分析提供了推理依据。[结论] 研究结果可为此类IVHM系统的设计提供思路。

关键词：无人艇; 综合健康管理系统; 智能体仿真

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基于扩张状态观测器的双桨推进无人艇抗干扰目标跟踪控制

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摘 要：[目的] 针对无人艇(USV)的模型不确定性和未知海洋环境扰动，提出一种基于扩张状态观测器(ESO)的双桨推进无人艇抗干扰目标跟踪控制算法。[方法] 在运动学层级，设计基于平行接近制导原理的目标跟踪制导律；在动力学层级，针对模型不确定性未知环境扰动，设计基于ESO的纵荡速度和艏摇角速度自抗扰控制律，以减小模型不确定性和环境扰动的影响；最后，通过输入状态稳定性分析和级联定理分析所提控制器的稳定性。[结果] 实验结果表明，基于所提的自抗扰目标跟踪控制方法能使跟踪船有效地跟踪虚拟目标点。[结论] 研究成果可为无人艇在环境扰动下的目标跟踪提供参考。

关键词：无人艇; 扩张状态观测器; 目标跟踪; 平行接近制导