Meng *et al*. *Complex Eng Syst* 2023;3:12
DOI: 10.20517/ces.2023.18

Complex Engineering Systems

Research Article

Open Access

Robust adaptive finite-time course tracking control of vessel under actuator attacks

Xiangfei Meng[1], **Guichen Zhang**[1], **Bing Han**[2,3]

[1]Merchant Marine College, Shanghai Maritime University, Shanghai 201306, China.
[2]Shanghai Ship and Shipping Research Institute Co., Ltd., Shanghai 201306, China.
[3]College of Physics and Electronic Information Engineering, Minjiang University, Fuzhou 350108, Fujian, China.

Correspondence to: Prof. Guichen Zhang, Merchant Marine College, Shanghai Maritime University, Shanghai 201306, China. E-mail: gczhang@shmtu.edu.cn

How to cite this article: Meng X, Zhang G, Han B. Robust adaptive finite-time course tracking control of vessel under actuator attacks. *Complex Eng Syst* 2023;3:12. http://dx.doi.org/10.20517/ces.2023.18

Received: 30 May 2023 **First Decision:** 19 Jun 2023 **Revised:** 15 Jul 2023 **Accepted:** 21 Jul 2023 **Published:** 26 Jul 2023

Academic Editors: Hamid Reza Karimi, Zhaojing Wu **Copy Editor:** Fanglin Lan **Production Editor:** Fanglin Lan

Abstract

This paper studies the course tracking control problem of unmanned surface vessels under the influence of uncertain dynamics, external unknown disturbances, constraints, and actuator attacks. In the design of the control scheme, adaptive technology is applied to approach the uncertain dynamics of the system, and a nonlinear finite-time disturbance observer is established to reconstruct the actuator attack signal and the unknown time-varying disturbances online. Combining disturbance compensation and adaptive technology, a finite-time course tracking control scheme is designed. The control scheme does not need to obtain the prior knowledge of the model in advance, and it has good robustness in the face of uncertain dynamics within the system, external disturbances, and actuator attacks. A rigorous stability analysis is provided for the control scheme based on the Lyapunov stability theory. Finally, the simulation shows that the proposed control scheme can effectively resist the influence of actuator attacks and external uncertain disturbances.

Keywords: Actuator attacks, course tracking, unmanned surface vessel, finite-time disturbance observer

1. INTRODUCTION

With the continuous development of marine economy, unmanned surface vessels (USV) have become the most economical and effective means of marine transportation and have received special attention in the field of marine engineering[1,2]. At the same time, the course tracking control of USV is a classic basic research topic, and many researchers have published important research results in this field. The goal of course tracking control is to overcome various internal and external disturbances and realize the high-precision tracking target course of USV[3,4]. In order to complete the control task, many control methods, such as neural networks (NNs), sliding modes, self-adaptation, event-triggered control (ETC), nonlinear feedback, and nonlinear decoration, are applied in the design of the control scheme[5].

In course tracking control, PID has been widely used in engineering because of its simple control structure and good control effect[6]. Witkowska *et al.*[7] combined backstepping and genetic algorithm to propose a course tracking control scheme. However, this scheme does not consider the disturbance of the environment. In addition, PID is in the face of disturbances, such as wind, waves, and currents. Its robustness also fails to meet further demands. In order to further solve the problem of external interference, Le *et al.*[8] combined PID and fuzzy logic control to develop an automatic driving scheme for surface vessels and verified the feasibility of the control scheme through simulation. Annamalai *et al.*[9] developed a robust USV adaptive course keeping control scheme combined with the gradient descent algorithm. Yang *et al.*[10] proposed a robust adaptive nonlinear control algorithm for ship steering based on the projection method and Lyapunov stability theory, which simultaneously solved the uncertain dynamics inside and outside the system. Li *et al.*[11] and Zhang *et al.*[12] combine Radial Basis Function NNs (RBFNNS) and dynamic surface control (DSC) technology to further discuss the problem of "differential explosion" in backstepping.

In practice, there is often the challenge of controlling signal transmission, which can lead to channel overload[13]. This problem is more prominent in many control systems, especially when long-distance transmission is required or when operating under harsh environmental conditions[14]. Factors such as bandwidth limitations, signal delays, and others all bring great challenges to the reliability of the control scheme. ETC adopts an event-driven approach, which triggers the controller to send a control signal only when the system state reaches a certain condition[15]. This means that signals are only sent when adjustments or corrective control actions are required, saving communication bandwidth. Zhang *et al.*[16] combined ETC technology and proposed a heading tracking fault-tolerant control (FTC) scheme. This scheme effectively improves bandwidth efficiency and saves computing resources.

In theoretical research, nonlinear feedback[17] and nonlinear decoration[18] have also been widely used in course tracking control. In Ref.[19], a course tracking control algorithm is designed by establishing the error driving function to address unknown time-varying disturbance, uncertain ship model parameters, and input saturation. Zhang *et al.*[20] introduced a nonlinear function of heading error in the feedback loop to replace the heading error itself and designed an improved compact backstepping controller based on the Lyapunov candidate function. Zhang *et al.*[21] adopted PID technology, introduced a bipolar sigmoid function, and designed a nonlinear feedback algorithm. Finally, the effect of the algorithm is analyzed using the theory of closed-loop gain shaping. Cao *et al.*[22] proposed an active disturbance rejection control algorithm based on nonlinear feedback to solve the problems of external disturbance, internal model uncertainty, and rudder angle energy input in the process of ship course keeping.

Robustness is an important performance index of the ship control system, which plays a vital role in ensuring the safe and effective operation of the ship[23]. FTC technology is widely used in the field of ship control because of its good control effect. Compared with traditional control methods, FTC techniques focus on achieving the control objectives of the system within a predetermined finite time. Through the research of the above reference, this paper designs a USV robust adaptive finite-time course tracking control scheme under actuator attacks. The main contributions of this paper are as follows:

(1) Using the features of adaptive online approximation and high reconstruction accuracy of nonlinear finite-time disturbance observer (NFTDO), a robust adaptive tracking control scheme based on depth information robust adaptive method is developed. The scheme not only overcomes internal and external uncertainties but also effectively resists the impact of actuator attacks.

(2) The FTC technology is introduced to further improve the control performance of the course tracking system so that the errors of the system can be converged within a finite time. Compared with traditional control schemes, the steady-state performance and transient response of the system are improved.

2. PROBLEM FORMULATION AND PRELIMINARIES

The nonlinear ship course tracking mathematical model can be expressed in the following form[24]:

$$\ddot{\psi} + \frac{1}{T}F(\dot{\psi}) = \frac{K}{T}\delta + \xi + \partial \tag{1}$$

where T and K are the maneuverability index of the ship, respectively. ξ is the unknown environmental disturbances. ∂ is the actuator attack signal. $F(\dot{\psi}) = a\dot{\psi} + b\dot{\psi}^3$ is a nonlinear function of $\dot{\psi}$, where a and b are constants.

Let $x_1 = \psi, x_2 = \dot{\psi} = r, u = \delta$, and then it can be obtained from Eq. (1)

$$\dot{x}_1 = x_2 \tag{2}$$

$$\dot{x}_2 = \theta^T f(x_2) + \omega u + \xi + \partial \tag{3}$$

$$y = x_1 \tag{4}$$

where $y \in R$ is the output of the system, u is the control input of the system, $\omega = \frac{K}{T}$, $f(x_2) = [-x_2, -x_2^3]^T$, $\theta = \left[\frac{a}{T}, \frac{b}{T}\right]^T$.

Assumption 1 The external environment disturbances ξ and the actuator attack signal ∂ are unknown and bounded; that is, there is a constant a greater than 0, s satisfying $|\xi| \le \xi_d, |\partial| \le \partial_d$.

Assumption 2 The reference course y_d is smooth guideable, and $\dot{y}_d$ and $\ddot{y}_d$ are available.

Assumption 3 Both model parameters θ and ω are unknown.

Lemma 1[25] For system $x = u_c + \xi$, where u_c is the control input, ξ is the external unknown and bounded disturbances, satisfying $\left|\dot{\xi}\right| \le \xi_d$, and ξ_d is a positive definite constant. If there are parameters λ_1, λ_2, λ_3 satisfying $0 < \lambda_3 < 1, \lambda_1, \lambda_2, \lambda_3 > 0$, and then the disturbance observer shown in Eq. (4) can converge in a finite time.

$$\begin{cases} \dot{\hat{x}} = u_c + \hat{\xi} \\ \dot{\hat{\xi}} = \lambda_1 sig^{\lambda_3}(\pi) + \lambda_2 \int \left[sig^{\lambda_3}(\pi)\right] dt \end{cases} \tag{5}$$

where $\hat{x}$ and $\hat{\xi}$ are estimates of x and ξ, $\pi = x - \hat{x}$, $sig^{\lambda_3}(\pi) = |\pi|^{\lambda_3}\mathrm{sgn}(\pi)$.

Lemma 2[26] Assuming that there is a positive definite Lyapunov function $V(x)$: $\Omega_0 \to R$ and any scalars $a > 0$, $b > 0$, and $0 < \kappa < 1$, such that the inequality $\dot{V}(x) + aV(x) + bV^{\kappa}(x) \le 0$ holds, then the system is finite-time stable, and its adjustment time satisfies:

$$T \le \frac{1}{a(1-t)} \ln \frac{aV^{1-\kappa}(x_0) + b}{b} \tag{6}$$

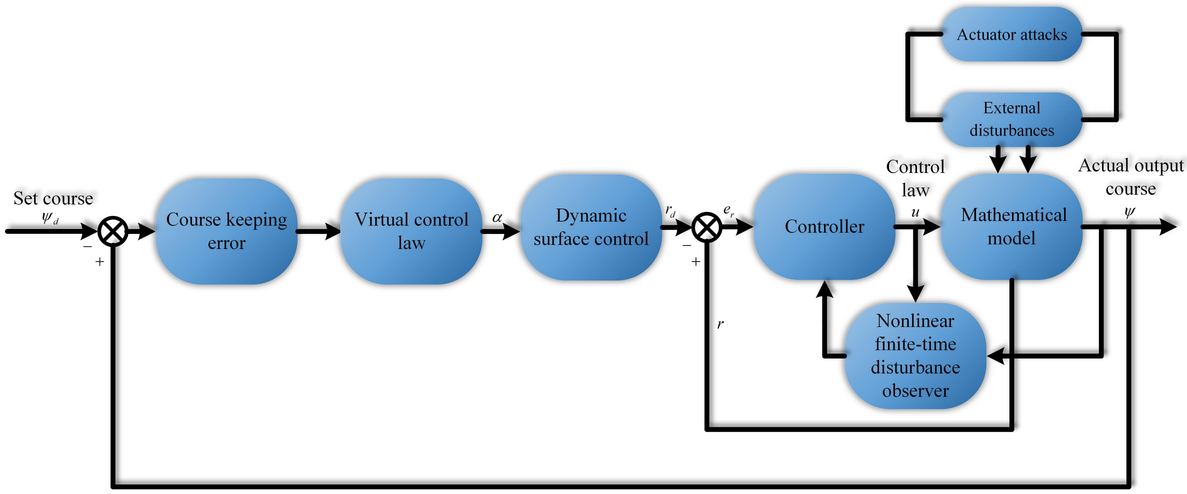

Figure 1. The designed procedure of control law.

where $V(x_0)$ is the initial value of $V(x)$.

3. CONTROL DESIGN AND STABILITY ANALYSIS

The designed procedure of control law is shown in Figure 1. First, define the error variable

$$e_\psi = \psi - \psi_d \tag{7}$$

$$e_r = r - r_d \tag{8}$$

where ψ_d is the reference course, and r_d is the virtual control variable.

Define the following virtual control variables

$$\alpha = -\gamma_{11} e_\psi - \gamma_{12} sig^{\gamma_{13}}\left(e_\psi\right) - \gamma_{14} \int \left[sig^{\gamma_{13}}\left(e_\psi\right)\right] dt + \dot{\psi}_d \tag{9}$$

where γ_{11}, γ_{12}, γ_{13}, and γ_{14} are positive definite parameters.

Then, using the following DSC technique, we can obtain the derivative of the virtual control

$$\gamma_r \dot{r}_d + r_d = \alpha \tag{10}$$

where γ_r is a positive definite parameter.

Taking the derivative of Eq. (6), we can get

$$\dot{e}_r = F(x_2) + \omega u + \xi_\partial - \dot{r}_d \tag{11}$$

where $F(x_2) = -\frac{a}{T}x_2 - \frac{b}{T}x_2^3$, $\xi_\partial = \xi + \partial$.

According to Eq. (9), it can be further obtained

$$\dot{\hat{e}}_r = \hat{F}(x_2) + \omega u + \hat{\xi}_\partial - \dot{r}_d \tag{12}$$

where $\hat{F}(x_2)$ and $\hat{\xi}_\partial$ are estimated values of $F(x_2)$ and ξ_∂, respectively.

Define a new variable $\beta = e_r - \hat{e}_r$, and according to Lemma 1, we can get

$$\hat{\xi}_\partial = \gamma_{31}\beta + \gamma_{32} sig^{\gamma_{33}}(\beta) + \gamma_{34}\int [sig^{\gamma_{33}}(\beta)]\, dt \tag{13}$$

where γ_{31}, γ_{32}, γ_{33}, and γ_{34} are positive definite parameters, and $0 < \gamma_{33} < 1$.

The design control law is as follows

$$\begin{cases} u = \omega^{-1}\kappa \\ \kappa = -\gamma_{21}\hat{e}_r - \gamma_{22} sig^{\gamma_{23}}(\hat{e}_r) - \gamma_{24}\int [sig^{\gamma_{23}}(\hat{e}_r)]\, dt - \hat{\xi}_\partial + \dot{r}_d - e_\psi - \hat{F}(x_2) \\ \dot{\hat{F}}(x_2) = \varepsilon_1 \left[\beta - \varepsilon_2 \hat{F}(x_2)\right] \end{cases} \tag{14}$$

where γ_{21}, γ_{22}, γ_{23}, γ_{24}, ε_1, and ε_2 are positive definite parameters.

Construct the Lyapunov function as follows

$$V = \frac{1}{2}{e_\psi}^2 + \frac{1}{2}\hat{e}_r^2 + \frac{1}{2}\beta^2 + \frac{1}{2}\tilde{F}^2(x_2) \tag{15}$$

where $\tilde{F}(x_2) = \bar{F}(x_2) - \hat{F}(x_2)$. $\tilde{F}(x_2)$, $\hat{F}(x_2)$, and $\bar{F}(x_2)$ are the estimated error, estimated value, and upper bound of $F(x_2)$, respectively.

Deriving Eq. (13) and substituting Eqs. (7)-(12), one can get

$$\begin{aligned} \dot{V} \le\ & e_\psi \left[-\gamma_{11}e_\psi - \gamma_{12}|e_\psi|^{\gamma_{13}}\mathrm{sgn}(e_\psi) - \gamma_{14}\int \left[|e_\psi|^{\gamma_{13}}\mathrm{sgn}(e_\psi)\right] dt\right] \\ & + \hat{e}_r\left[-\gamma_{21}\hat{e}_r - \gamma_{22}|\hat{e}_r|^{\gamma_{23}}\mathrm{sgn}(\hat{e}_r) - \gamma_{24}\int [|\hat{e}_r|^{\gamma_{23}}\mathrm{sgn}(\hat{e}_r)]\, dt\right] \\ & + \beta\left\{-\gamma_{31}|\beta|^{\gamma_{33}}\mathrm{sgn}(\beta) - \gamma_{32}\int [|\beta|^{\gamma_{33}}\mathrm{sgn}(\beta)]\, dt + \xi_\partial\right\} \\ & + \varepsilon_2\tilde{F}(x_2)\hat{F}(x_2) + e_\psi\alpha_e \end{aligned} \tag{16}$$

where $\alpha_e = r_d - \alpha$. There exists a constant λ_α greater than zero, which satisfies $|\alpha_e| \le \lambda_\alpha$ [27]. According to Assumption 2 and Lemma 1, we can get A=B, where λ_{ξ_∂} is a constant greater than zero. Then

$$\beta\left\{-\gamma_{31}\beta - \gamma_{32}|\beta|^{\gamma_{33}}\mathrm{sgn}(\beta) - \gamma_{34}\int [|\beta|^{\gamma_{33}}\mathrm{sgn}(\beta)]\, dt + \xi_\partial\right\} \le -\gamma_{31}\beta^2 - \gamma_{32}|\beta|^{\gamma_{33}+1} + \beta\lambda_{\xi_\partial} \tag{17}$$

Substituting Eq. (15) into Eq. (14), one can get

$$\begin{aligned} \dot{V} \le & -\left(\gamma_{11} - \tfrac{1}{4}\right){e_\psi}^2 - \gamma_{12}|e_\psi|^{\gamma_{13}+1} - \gamma_{21}\hat{e}_r^2 - \gamma_{22}|\hat{e}_r|^{\gamma_{23}+1} - \gamma_{31}\beta^2 - \gamma_{32}|\beta|^{\gamma_{33}+1} + \beta\lambda_{\xi_\partial} \\ & + \varepsilon_2\tilde{F}(x_2)F(x_2) - \varepsilon_2\tilde{F}^2(x_2) + {\lambda_\alpha}^2 \end{aligned} \tag{18}$$

Using Young's inequality, we can get $\varepsilon_2\tilde{F}(x_2)F(x_2) \le \frac{1}{4}\varepsilon_2\tilde{F}^2(x_2) + \varepsilon_2 F^2(x_2)$, $\frac{1}{4}\varepsilon_2\left|\tilde{F}(x_2)\right| \le \frac{1}{4}\varepsilon_2\tilde{F}^2(x_2) + \frac{\varepsilon_2}{16}$. In addition, for arbitrary variables δ_m, δ_n, and arbitrary real numbersℓ_1, ℓ_2 ℓ_3, satisfy $|\delta_m|^{\ell_1}|\delta_n|^{\ell_3} \le \frac{\ell_1}{\ell_1+\ell_3}\ell_2|\delta_m|^{(\ell_1+\ell_3)} + \frac{\ell_3}{\ell_1+\ell_3}\ell_2^{-\frac{\ell_1}{\ell_3}}|\delta_m|^{(\ell_1+\ell_3)}$ [28]. So $-\frac{\varepsilon_2}{4}\left|\tilde{F}(x_2)\right|^2 \le -\frac{\varepsilon_2}{2(\varepsilon_2+1)}\left|\tilde{F}(x_2)\right|^{\varepsilon_2+1} + \frac{\varepsilon_2(1-\varepsilon_2)}{4(\varepsilon_2+1)}$. Then, one can get

$$\begin{aligned} \dot{V} \le & -\left(\gamma_{11} - \tfrac{1}{4}\right){e_\psi}^2 - \gamma_{12}|e_\psi|^{\gamma_{13}+1} - \gamma_{21}\hat{e}_r^2 - \gamma_{22}|\hat{e}_r|^{\gamma_{23}+1} - \left(\gamma_{31} - \tfrac{1}{4}\right)\beta^2 - \gamma_{32}|\beta|^{\gamma_{33}+1} + \left|\lambda_{\xi_\partial}\right|^2 \\ & - \tfrac{1}{4}\varepsilon_2\left|\tilde{F}(x_2)\right|^2 - \tfrac{\varepsilon_2}{2(\varepsilon_2+1)}\left|\tilde{F}(x_2)\right|^{\varepsilon_2+1} + \tfrac{\varepsilon_2(1-\varepsilon_2)}{4(\varepsilon_2+1)} + \tfrac{1}{2}\varepsilon_2|F(x_2)|^2 + {\lambda_\alpha}^2 \\ \le & -\vartheta_1 V - \vartheta_2 V^{\frac{1}{2}} + \Xi \end{aligned} \tag{19}$$

where $\vartheta_1 = \min\left\{\left(2\gamma_{11} - \frac{1}{2}\right), 2\gamma_{21}, \left(2\gamma_{31} - \frac{1}{2}\right), \frac{1}{2}\varepsilon_2\right\}$, $\vartheta_2 = 2^{\frac{\gamma+1}{2}}\min\left\{\gamma_{12}, \gamma_{22}, \gamma_{32}, \frac{\varepsilon_2}{2(\varepsilon_2+1)}\right\}$, $\Xi = \left|\lambda_{\xi_\partial}\right|^2 + \frac{1}{2}\varepsilon_2 F^2(x_2) + {\lambda_\alpha}^2 + \frac{\varepsilon_2(1-\varepsilon_2)}{4(\varepsilon_2+1)}$.

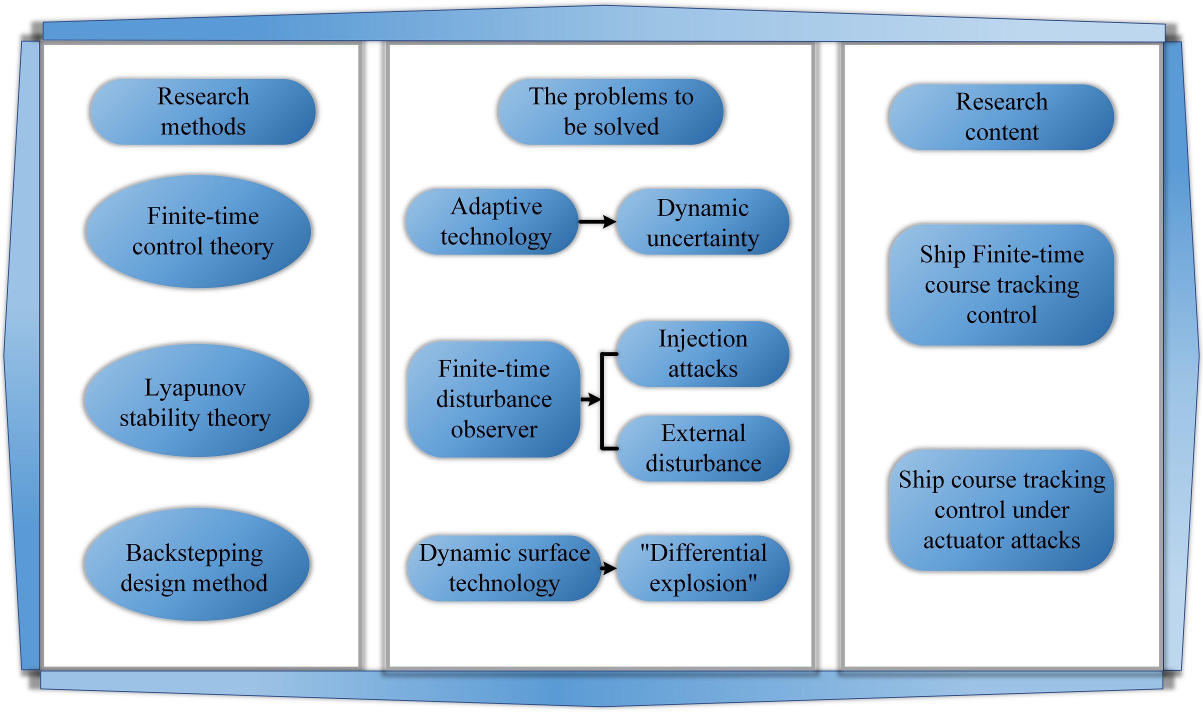

Figure 2. Research methodology and main design steps.

According to Eq. (17), it can be obtained

$$\dot{V} \leq -\iota\vartheta_1 V - (1-\iota)\,\vartheta_1 V - \vartheta_2 V^{\frac{1}{2}} + \Xi \tag{20}$$

where $0 < \iota < 1$. If $V > \frac{\Xi}{\iota\vartheta_1}$, then

$$\dot{V} \leq -\iota\vartheta_1 V - (1-\iota)\,\vartheta_1 V - \vartheta_2 V^{\frac{1}{2}} \tag{21}$$

According to Lemma 2, V falls in the residual set $\Omega_V = \left\{V : V \leq \frac{\Xi}{\iota\vartheta_1}\right\}$, and the stabilization time is

$$T \leq \frac{4}{(1-\iota)\,\vartheta_1} \ln\left[\frac{(1-\iota)\,\vartheta_1 V^{\frac{1}{2}}(0) + \vartheta_2}{\vartheta_2}\right] \tag{22}$$

where $V_{(0)}$ is the initial value of V.

Remark 1 The basic theory of control design is backstepping. As shown in Figure 1, both virtual control and controller design phases introduce finite-time techniques. At the same time, a finite-time disturbance observer is further introduced to compensate for actuator attacks and external disturbances. This ensures that the response speed and steady state of the system are improved compared to the traditional adaptive scheme.

4. SIMULATION

This paper takes the Dalian Maritime University practice ship "Yulong" as the test object for simulation research[19]. The main parameters are shown in Table 1.

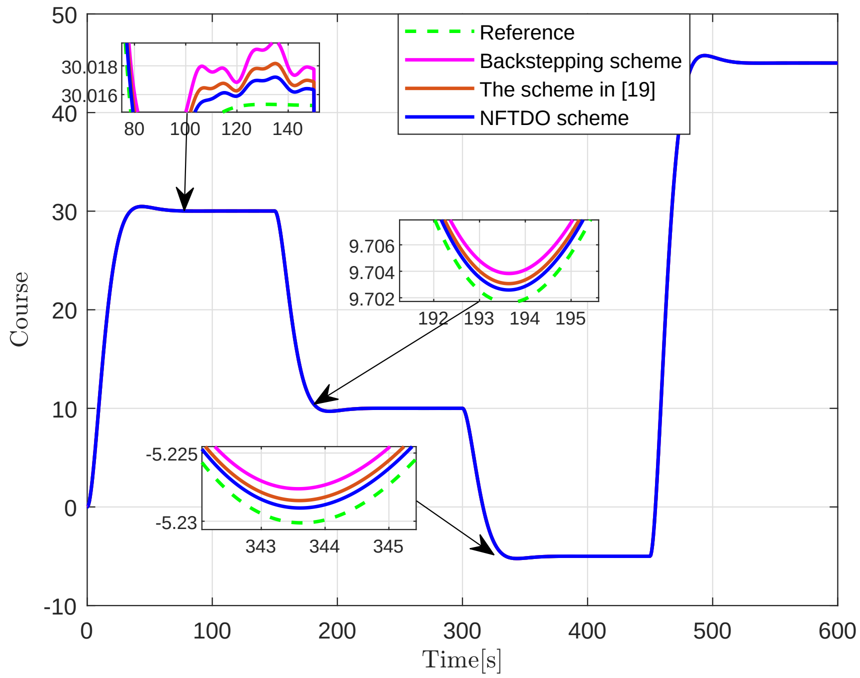

Figure 3. Course-keeping.

Table 1. Ship particulars of the ship "Yu Long"

Length between perpendiculars (LBP)	L(m)	126
Molded breadth	b(m)	20.8
Molded draught	d(m)	8.0
Rudder area	$A_R(m^2)$	18.8
Block coefficient	C_b	0.681
Trial speed	V/Kn	15

The relevant parameters used for simulation are $K = 0.478$, $T = 216$, $a = 1$, $b = 30$, $\gamma_{11} = 0.15$, $\gamma_{12} = 0.08$, $\gamma_{13} = 0.5$, $\gamma_{14} = 0.003$, $\gamma_{21} = 0.1$, $\gamma_{22} = 0.05$, $\gamma_{23} = 0.5$, $\gamma_{24} = 0.001$, $\gamma_r = 0.01$, $\varepsilon_1 = 0.1$, and $\varepsilon_2 = 0.01$. The time-varying disturbances and actuator attack signal are set as $\xi = [1 + 0.3\sin(0.25t) + 0.15\cos(0.6t)]$, $\partial = 0.15 + 0.1\sin(0.2t)$.

Figure 2, Figure 3, Figure 4 and Figure 5 show the USV under the influence of time-varying disturbances and actuator attacks, the NFTDO control scheme designed in this paper, the scheme in Ref. [19], and the ship course tracking effect of the traditional Backstepping control scheme.

The control scheme in Ref. [19] is as follows:

$$\begin{cases} \alpha = -k_1 \Phi\left(e_\psi\right) + \dot{\psi}_d \\ u = -k_2 e_r - c_2 \hat{\Theta} \zeta\left(Z\right) \Phi\left(e_r\right) \\ \dot{\hat{\Theta}} = c_2 \zeta^2\left(Z\right) \Phi^2\left(e_r\right) - \sigma \hat{\Theta} \end{cases} \tag{23}$$

where k_1, k_2, c_2, and σ are positive definite parameters.

It can be seen from Figure 3 that both the NFTDO control scheme designed in this paper and the comparative scheme have completed the heading tracking task, but the dynamic adjustment performance of the scheme in

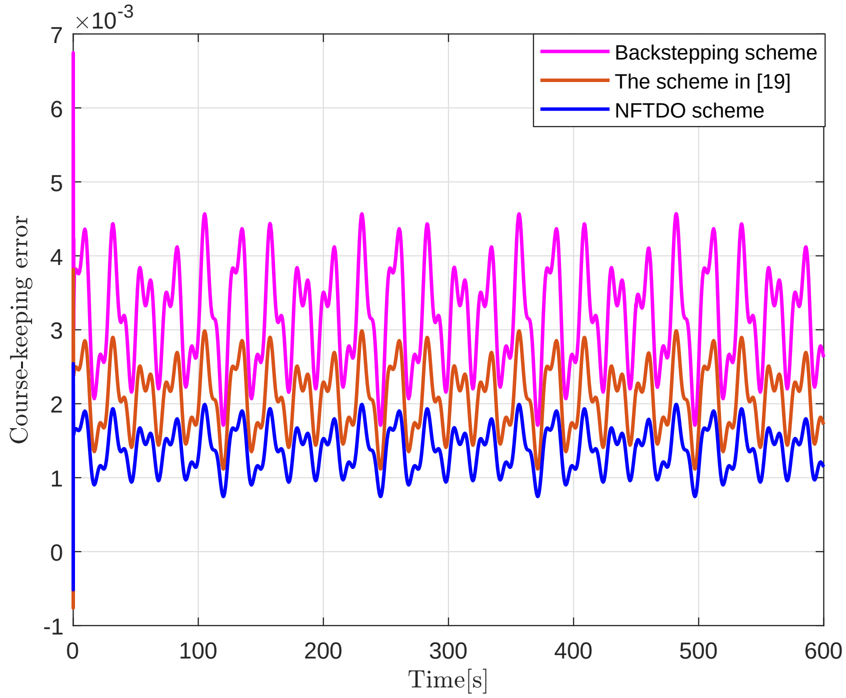

Figure 4. Course-keeping error.

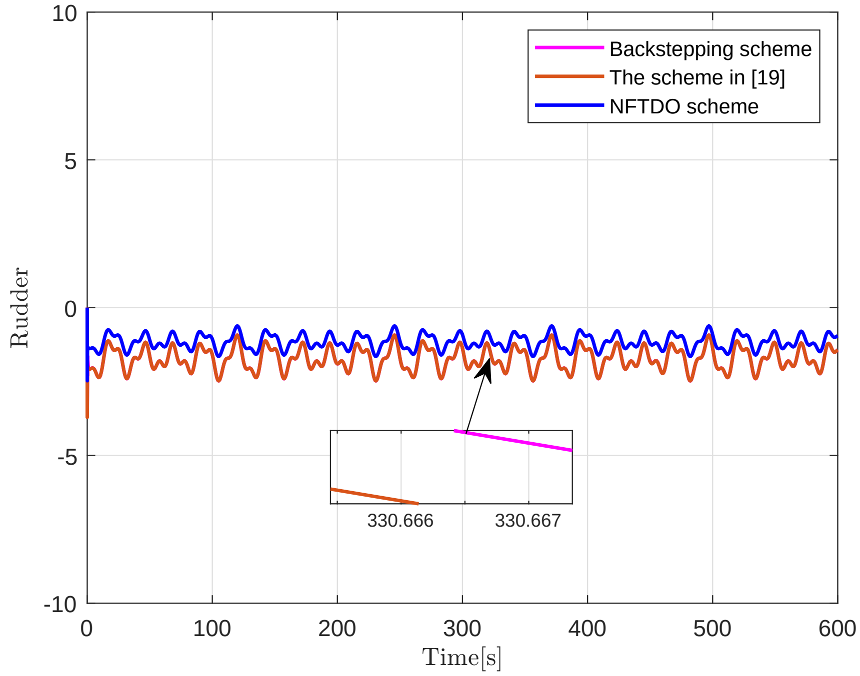

Figure 5. Rudder angle.

Ref.[19] and the traditional Backstepping control scheme is not as good as that of the NFTDO scheme. It can be seen from the tracking error duration curve shown in Figure 4 that the tracking accuracy under the NFTDO

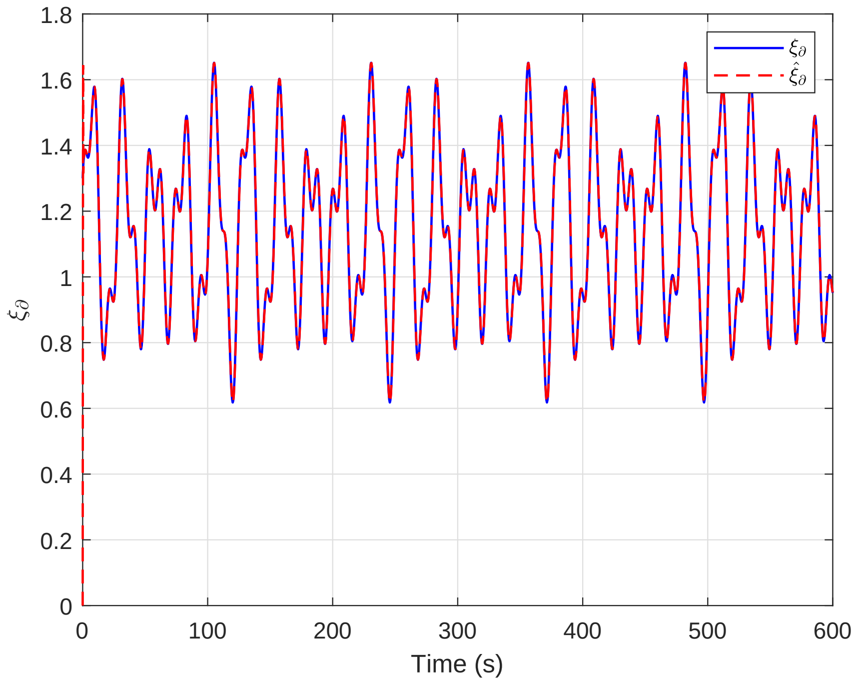

Figure 6. The reconstruction of ξ_∂.

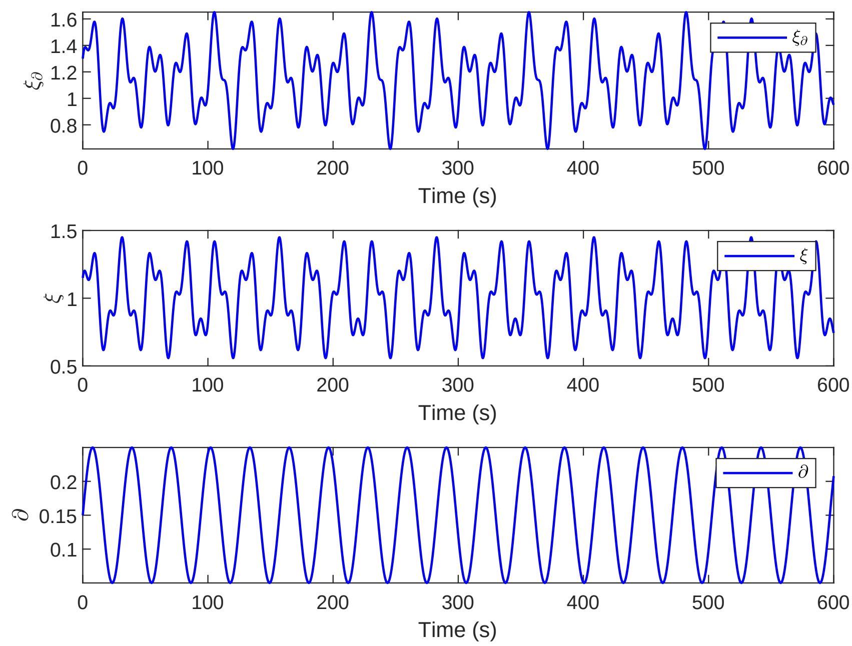

Figure 7. Time evolution of ξ_∂, ξ, ∂.

control scheme is higher than that of the comparison scheme. Figure 5 shows the control input response for the three control schemes. The control inputs of the three control schemes tend to be stable over time.

Figure 6 shows the reconstruction effect of the NFTDO scheme on the composite uncertain term composed of time-varying interference and actuator attack signals. Figure 7 is the change curve of uncertain items over time. In summary, compared with the control scheme designed in this paper, the tracking effect has been greatly improved.

5. CONCLUSIONS

In this paper, by combining FTC and disturbance compensation technology, the problems of actuator attacks, external unknown disturbances, and dynamic uncertainty in USV course tracking control are effectively solved. Without any prior knowledge, a finite-time course tracking control scheme is designed. Finally, the effectiveness is verified by simulation. The simulation results show that the steady-state performance and transient response of the USV are improved under the control scheme designed in this paper. In addition, since ships have unstable situations caused by uncertainties, such as mooring forces during offshore operations, it is necessary to systematically deal with such uncertainties and ensure stability. We will explore this area further in future research.

DECLARATIONS

Acknowledgments
The authors would like to acknowledge the National Natural Science Foundation of China (NSFC51779136), Science and Technology Commission of Shanghai Municipality (NO.20dz1206002), and the Natural Science Foundation of Fujian Province of China (2022J011128).

Authors' contributions
Methodology, software, validation, writing- original draft: Meng X
Writing-reviewing and editing, investigation: Zhang G
Conceptualization, data curation, visualization: Han B

Availability of data and materials
Not applicable.

Financial support and sponsorship
None.

Conflicts of interest
All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

REFERENCES

1. Liu H, Li Y, Tian X, Mai Q. Event-triggered predefined-time $H\infty$ formation control for multiple underactuated surface vessels with error constraints and input quantization. *Ocean Eng* 2023;277:114294. DOI

2. Liu H, Huang X, Mai Q, Tian X. Fixed-time self-structuring neural network fault-tolerant tracking control of underactuated surface vessels with state constraints. *Ocean Eng* 2023;279:114599. DOI
3. González-Prieto JA. Adaptive finite time smooth nonlinear sliding mode tracking control for surface vessels with uncertainties and disturbances. *Ocean Eng* 2023;279:114474. DOI
4. Zhu H, Yu H, Guo C. Finite time PAILOS based path following control of underactuated marine surface vessel with input saturation. *ISA Trans* 2023;135:66-77. DOI
5. Meng XF, Zhang GC, Zhang Q. Robust adaptive neural integrated fault-tolerant control for underactuated surface vessels with finite-time convergence and event-triggered inputs. *Math Biosci Eng* 2023;20:2131-56. DOI
6. Xu SW, Wang XF, Yang JM, Wang L. A fuzzy rule-based PID controller for dynamic positioning of vessels in variable environmental disturbances. *J Mar Sci Technol* 2020;25:914-24. DOI
7. Witkowska A, Tomera M, Smierzchalski R. A backstepping approach to ship course control. *Int J Appl Math Comput Sci* 2007;17:73-85. DOI
8. Le MD, Nguyen TH, Nguyen TT, et al. A new and effective fuzzy PID autopilot for ships. In: IEEE International Symposium on Computational Intelligence in Robotics and Automation; 2003 Jul 16-20; Kobe, Japan. IEEE; 2003. p. 1411-5. DOI
9. Annamalai ASK, Sutton R, Yang C, Culverhouse P, Sharma S. Robust adaptive control of an uninhabited surface vehicle. *J Intell Robot Syst* 2015;78:319-38. DOI
10. Yang YS. Output feedback robust control algorithm applied to ship steering autopilot with uncertain nonlinear system. *J Traffic Transp Eng* 2002;2:118-121. Available from: https://transport.chd.edu.cn/en/article/id/200201026. [Last accessed on 24 Jul 2023]
11. Li YH, Qiang S, Zhuang XY, Kaynak O. Robust and adaptive backstepping control for nonlinear systems using RBF neural networks. *IEEE Trans Neural Netw* 2004;15:693-701. DOI
12. Zhang GQ, Zhang XK. Concise robust adaptive path-following control of underactuated ships using DSC and MLP. *IEEE J Ocean Eng* 2014;39:685-94. DOI
13. Lv MG, Peng ZH, Wang D, Han QL. Event-triggered cooperative path following of autonomous surface vehicles over wireless network with experiment results. *IEEE Trans Ind Electron* 2022;69:11479-89. DOI
14. Song S, Zhang EH, Wang WK, Liu T. Distributed dynamic edge-based event-triggered formation control for multiple underactuated unmanned surface vessels. *Ocean Eng* 2022;264:112319. DOI
15. Liu L, Zhang WD, Wang D, Peng ZH. Event-triggered extended state observers design for dynamic positioning vessels subject to unknown sea loads. *Ocean Eng* 2020;209;107242. DOI
16. Zhang GQ, Gao S, Li JQ, Zhang WD. Adaptive neural fault-tolerant control for course tracking of unmanned surface vehicle with event-triggered input. *Proc Inst Mech Eng Part I J Syst Control Eng* 2021;235:1594-604. DOI
17. Zhang XK, Zhang Q, Ren HX, Yang GP. Linear reduction of backstepping algorithm based on nonlinear decoration for ship course-keeping control system. *Ocean Eng* 2018;147:1-8. DOI
18. Zhang XK, Han X, Guan W, Zhang GG. Zhang GQ. Improvement of integrator backstepping control for ships with concise robust control and nonlinear decoration. *Ocean Eng* 2019;189;106349. DOI
19. Zhang Q, Zhang M, Hu Y, Zhu G. Error-driven-based adaptive nonlinear feedback control of course-keeping for ships. *J Mar Sci Technol* 2021;26:357-67. DOI
20. Zhang X, Yang G, Zhang Q, Zhang G. Improved concise backstepping control of course keeping for ships using nonlinear feedback technique. *J Navig* 2017;70:1401-14. DOI
21. Zhang HG, Zhang XK, Bu RX. Active disturbance rejection control of ship course keeping based on nonlinear feedback and ZOH component. *Ocean Eng* 2021;233:109136. DOI
22. Gao SH, Zhang XK. Course keeping control strategy for large oil tankers based on nonlinear feedback of swish function. *Ocean Eng* 2022;244:110385. DOI
23. Ye J, Roy S, Godjevac M, Reppa V, Baldi S. Robustifying dynamic positioning of crane vessels for heavy lifting operation. *IEEE/CAA J Autom* 2021;8:753-765. DOI
24. Fossen TI. Handbook of marine craft hydrodynamics and motion control. Hoboken: Wiley; 2011. DOI
25. Xia G, Sun C, Zhao B, Xue J. Cooperative control of multiple dynamic positioning vessels with input saturation based on finite-time disturbance observer. *Int J Control Autom Syst* 2019;17:370-9. DOI
26. Yu S, Yu X, Shirinzadeh B, Man Z. Continuous finite time control for robotic manipulators with terminal sliding mode. *Automatica* 2005;41:1957-64. DOI
27. Zhang Q, Zhang MJ, Yang RM, Im N. Adaptive neural finite-time trajectory tracking control of MSVs subject to uncertainties. *Int J Control Autom Syst* 2019;19:2238-2250. DOI
28. Wang Y, Zhang J, Zhang H, Xie X. Finite-time adaptive neural control for nonstrict-feedback stochastic nonlinear systems with input delay and output constraints. *Appl Math Comput* 2021;393:125756. DOI