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Original article

Robust adaptive course tracking control of ships under actuator faults

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Abstract

This study explores the course tracking control problem of unmanned surface vessels (USVs) under the influence of actuator faults and internal and external uncertainties. In the control strategy design, we first model the unknown dynamics and use adaptive technology to construct an online approximator to compensate for the unknown dynamics of the system. Under the framework of adaptive backstepping, a robust adaptive course tracking control scheme is constructed. This control strategy does not require any prior knowledge of the model in advance. The stability analysis of the theoretical mathematical derivation of the control strategy was conducted based on Lyapunov stability theory. Finally, the effectiveness of the control strategy proposed in this paper was verified through simulation.

Keywords: Course tracking, Unmanned surface vessels, Fault-tolerance control, Adaptive control

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1. Introduction

With the in-depth academic research on unmanned surface vessels (USVs), the market's performance requirements for its systems are also increasing [1][2]. USVs are susceptible to actuator failures, external disturbances, and dynamic uncertainties when performing tasks. Internal and external uncertain dynamics will increase the difficulty of heading control [3][4]. Actuator failure may also cause unpredictable deviations in the actual course of the ship, interfering with normal course control. These problems may lead to a decrease in ship heading control performance, which may lead to accidents. Therefore, studying ship heading fault-tolerant control has become an important means to improve the robustness of ship systems and navigation safety.

Among the current course tracking control methods, PID is the most commonly used algorithm. The PID controller continuously adjusts the ship's rudder angle by setting proportional, integral, differential terms to make the actual heading consistent with the desired heading. However, PID is a linear controller and its adaptability to nonlinear systems is relatively poor. PID may not provide good performance when faced with nonlinear system dynamics that take into account internal and external uncertain dynamics. To solve this problem, reference [5] developed an adaptive PID control strategy. The dynamic uncertainty and external interference of the system are transformed into a single parameter form. However, under the influence of noise or high-frequency disturbances in the system, real-time adjustment of adaptive parameters may introduce additional oscillations. To further improve the robust performance of the system, references [6][7] developed fuzzy PID and neural network PID control strategies respectively. Compared with adaptive PID control strategies, they have stronger adaptability to nonlinear systems and can better handle the nonlinear characteristics of the system. In addition, compared with traditional PID control strategies, they do not require precise system mathematical models and are more flexible for practical applications. However, the calculations of fuzzy PID control and neural network PID control are relatively complex and consume huge computing resources when dealing with multi-input and multi-output systems. Reference [16] uses a T-S fuzzy system to approximate the nonlinear uncertainty of the control system and designs a control scheme combining dynamic surface (DSC) and minimum learning parameter (MLP). Reference [17] uses neural networks to approximate the uncertain dynamics within the system. The introduction of the first-order commander solves the problem of repeated differential operations in the traditional back-stepping design method. They provide new ideas for the design of concise control schemes.

In practice, heading tracking is a control task with high real-time requirements. This makes it necessary for the system to make appropriate adjustments within the required time to cope with external disturbances and changes. In the study of improving the rapid response of the system, limited time is an effective solution. References [8][9][10] developed a heading-tracking control scheme with limited time convergence, which effectively improved the transient response of the system. It is worth mentioning that this document also introduces a finite-time disturbance observer, which further improves the steady state of the system. Although the limited time control strategy enables the system to achieve rapid response, it also results in a high computational burden on the system. To address the problem of high computational burden, references [11][12] developed simple nonlinear feedback and nonlinear modified heading tracking control algorithms. The control strategy developed based on the two can better adapt to complex nonlinear systems and provide a more flexible control strategy for the nonlinear dynamic characteristics existing in heading tracking. In addition to the above two control strategies for establishing nonlinear error-driven links, event triggering also has certain advantages in saving computing resources. It triggers updates to the controller based on changes in the system state, rather than at fixed intervals. This approach can effectively reduce computational requirements, especially when system changes are small or slow. References [13][14] applied the ETC strategy to design the heading maintenance control law.

When a ship performs control tasks, the mechanical components in the actuator may wear out over time. In addition, seawater erosion aggravates the corrosion of actuator parts. However, most of the methods in the above literature do not have the limitation of designing actuator failure. After an in-depth study of the above literature, this paper introduces the limitation of actuator fault to design a robust adaptive fault-tolerant control strategy for USVs. The main contributions of this article are as follows:

(1) This article fully considers the failure and offset fault problems faced by USVs in actual navigation, and designs a corresponding compensation mechanism. Compared with references [7][10][13], the control strategy designed in this paper can still ensure the tracking performance of the system in the case of actuator failure or sensor failure.

(2) This reconstruction considers the limitations of uncertainty inside and outside the system and designs corresponding control strategies based on advanced control theory. Compared with the traditional PID control strategy, the control strategy designed in this paper has stronger adaptability and is easier to adapt to changes in system status.

This peper is closely related to e-navigation. In practice, e-navigation accuracy relies on precise control of the system. The adaptive fault-tolerant heading tracking control strategy developed in this study can enable USVs to complete the tracking task when facing various uncertainties. This control strategy directly improves the reliability of the electronic navigation system through a robust adaptive method. Therefore, this study is of great significance to the field of e-navigation.

2. Problem Formulation and Preliminaries

The nonlinear ship course tracking mathematical model can be expressed as the following form [12]:

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

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

Let $x_1 = \psi$, $x_2 = \dot{\psi} = r$, $u^{f} = \delta^{f}$, we can get

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

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

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

where $y \in R$ is the system output and R is the set of real numbers. $\omega = \dfrac{K}{T}$, $f(x_2) = [-x_2, -x_2^{3}]^{T}$, $\theta = \left[\dfrac{a}{T}, \dfrac{b}{T}\right]^{T}$, ξ are external unmeasured interference. u is the control input that receives the actuator failure. The specific forms of actuator failure are as follows:

$$u^{f} = \pi u + \varpi \tag{5}$$

where $0 < \pi < 1$ represents Loss-of-effectiveness (LOE) faults, $\varpi \neq 0$ represents bias fault.

Assumption 1: [15]The external environmental disturbance ξ is unknown and bounded, that is, there is a constant ξ_d greater than 0, satisfying

$|\xi| \le \xi_d$.

Assumption 2: [18]The reference heading y_d is smooth and differentiable, and $\dot{y}_d$ and $\ddot{y}_d$ are available.

Assumption 3: [19]Both model parameters θ and ω are unknown.

3. Control Design and Stability Analysis

Define the error variable:

$$e_\psi = \psi - \psi_d \tag{6}$$

$$e_r = r - r_d \tag{7}$$

where ψ_d is the reference heading and r_d is the virtual control variable.

Define the following virtual control variables

$$\alpha = -\gamma_{11} e_\psi + \dot{\psi}_d \tag{8}$$

where a is γ_r positive definite design parameter.

By deriving Eq. (7), we can get

$$\dot{e}_r = F(x_2) + \omega\pi u + \xi_\varpi - \dot{r}_d \tag{9}$$

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

The design control law is as follows

$$\begin{cases} u = \left(\omega^{-1}\kappa\right)\hat{\lambda} \\ \kappa = -\gamma_{21} e_r - \hat{\xi}_\varpi + \dot{r}_d - e_\psi - \hat{F}(x_2) \end{cases} \tag{10}$$

and adaptive law

$$\begin{cases} \dot{\hat{F}}(x_2) = \varepsilon_{11}\left[e_r - \varepsilon_{12}\hat{F}(x_2)\right] \\ \dot{\hat{\xi}}_\varpi = \varepsilon_{21}\left[e_r - \varepsilon_{22}\hat{\xi}_\varpi\right] \\ \dot{\hat{\lambda}} = \varepsilon_{31}\left[e_r\kappa - \varepsilon_{32}\hat{\lambda}\right] \end{cases} \tag{12}$$

where γ_{21}, ε_{11}, ε_{12}, ε_{21}, ε_{22}, ε_{31}, ε_{32} are both design parameters and $\lambda = \pi^{-1}$.

The Lyapunov function is constructed as follows

$$V = \frac{1}{2}{e_\psi}^2 + \frac{1}{2}{e_r}^2 + \frac{1}{2\varepsilon_{11}}\tilde{F}^2(x_2) + \frac{1}{2\varepsilon_{21}}{\tilde{\xi}_\varpi}^2 + \frac{1}{2\varepsilon_{31}}\pi\tilde{\lambda}^2 \tag{13}$$

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

By deriving Eq. (13), we can get

$$\begin{aligned} \dot{V} &= e_\psi \dot{e}_\psi + e_r \dot{e}_r - \frac{1}{\varepsilon_{11}}\tilde{F}(x_2)\dot{\hat{F}}(x_2) \\ &\quad - \frac{1}{\varepsilon_{21}}\tilde{\xi}_\varpi \dot{\hat{\xi}}_\varpi - \frac{1}{\varepsilon_{31}}\pi\tilde{\lambda}\dot{\hat{\lambda}} \end{aligned} \tag{14}$$

Substituting Eqs. (6)(7)(10)-(12) into (14), we can get

$$\begin{aligned} \dot{V} &= e_r\left[F(x_2) + \omega\pi\left(\omega^{-1}\kappa\right)\hat{\lambda} + \xi_\varpi - \dot{r}_d + e_\psi\right] \\ &\quad - \tilde{F}(x_2)\left[e_r - \varepsilon_{12}\hat{F}(x_2)\right] - \tilde{\xi}_\varpi\left[e_r - \varepsilon_{22}\hat{\xi}_\varpi\right] \\ &\quad - \gamma_{11}{e_\psi}^2 - \pi\tilde{\lambda}\left[e_r\kappa - \varepsilon_{32}\hat{\lambda}\right] \end{aligned} \tag{15}$$

Simplifying Eq. (15) we can get

$$\begin{aligned} \dot{V} &= -\gamma_{11}{e_\psi}^2 - \gamma_{21}{e_r}^2 + \varepsilon_{12}\tilde{F}(x_2)\hat{F}(x_2) \\ &\quad + \varepsilon_{22}\tilde{\xi}_\varpi\hat{\xi}_\varpi + \pi\tilde{\lambda}\varepsilon_{32}\hat{\lambda} \end{aligned} \tag{16}$$

According to Young's inequality and combined with Eq. (16), we can get

$$\begin{aligned} \dot{V} &\le -\gamma_{11}{e_\psi}^2 - \gamma_{21}{e_r}^2 + \varepsilon_{12}\tilde{F}(x_2)\left[F(x_2) - \tilde{F}(x_2)\right] \\ &\quad + \varepsilon_{22}\tilde{\xi}_\varpi\left(\xi_\varpi - \tilde{\xi}_\varpi\right) + \varepsilon_{32}\pi\tilde{\lambda}\left(\lambda - \tilde{\lambda}\right) \\ &\le -\gamma_{11}{e_\psi}^2 - \gamma_{21}{e_r}^2 + \frac{\varepsilon_{12}}{2}F^2(x_2) - \frac{\varepsilon_{12}}{2}\tilde{F}(x_2)^2 \\ &\quad + \frac{\varepsilon_{22}}{2}{\xi_\varpi}^2 - \frac{\varepsilon_{22}}{2}{\tilde{\xi}_\varpi}^2 + \frac{\varepsilon_{32}}{2}\pi\lambda^2 - \frac{\varepsilon_{32}}{2}\pi\tilde{\lambda}^2 \\ &\le \Theta V + C \end{aligned} \tag{17}$$

where $\Theta = \min\left\{2\gamma_{11}, 2\gamma_{21}, \varepsilon_{12}, \varepsilon_{22}, \varepsilon_{32}\right\}$, $C = \frac{\varepsilon_{12}}{2}F^2(x_2) + \frac{\varepsilon_{22}}{2}{\xi_\varpi}^2 + \frac{\varepsilon_{32}}{2}\pi\lambda^2$.

4. Simulation

This paper uses the Dalian Maritime University internship ship "Yulong" as the test object to conduct simulation research [12]. The relevant parameters used for simulation are set to $K=0.48$, $T=216$, $a=1$, $b=30$, $\gamma_{11}=0.1$, $\gamma_{21}=0.2$, $\gamma_r=0.02$, $\varepsilon_1=0.1$, $\varepsilon_2=0.015$, $\varepsilon_{11}=8$, $\varepsilon_{12}=0.1$, $\varepsilon_{21}=10$, $\varepsilon_{22}=0.03$, $\varepsilon_{31}=0.5$, $\varepsilon_{32}=0.06$. Time-varying disturbances, LOE faults and bias faults are set as:

$$\begin{cases}\xi=\left[0.5+0.2\sin(0.15t)+0.2\cos(0.5t)\right]\\ \pi=0.2+0.1\sin(0.1t)\\ \varpi=0.2+0.1\sin(0.1t)\end{cases} \tag{18}$$

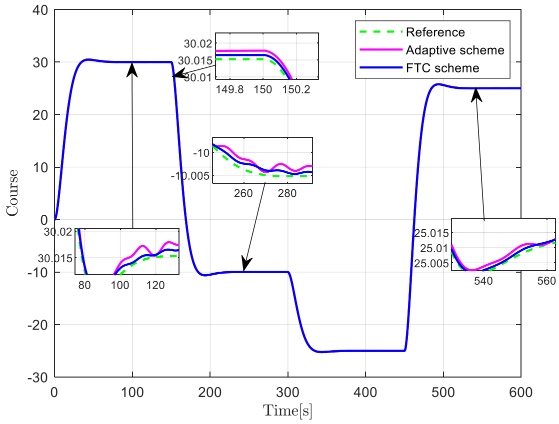

Figure 1. Course-keeping

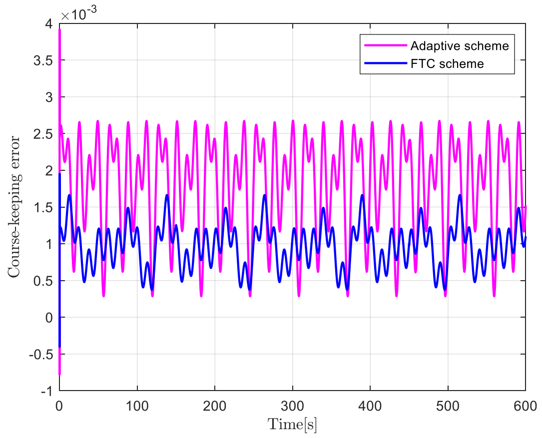

Figure 2. Course-keeping error

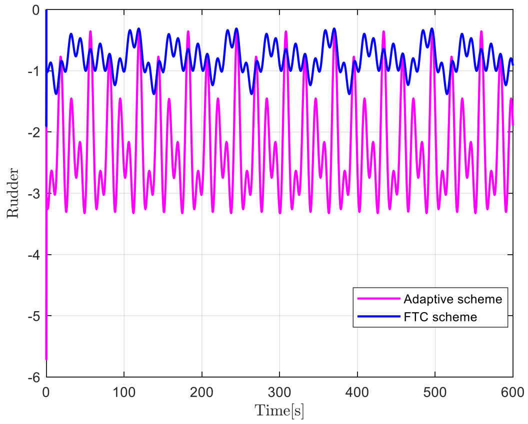

Figure 3. Rudder angle

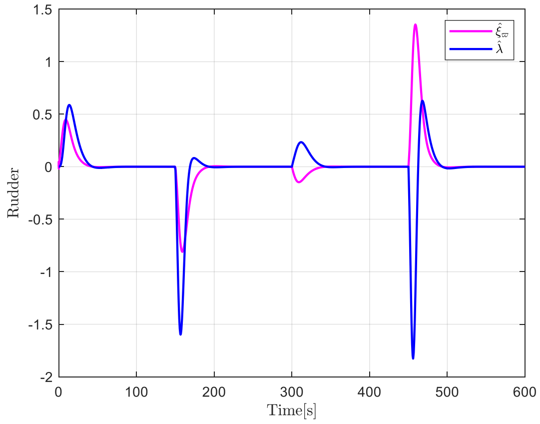

Figure 4. Adaptive duration curve.

Figures 1-3 show the tracking effect of USV under the influence of dynamic uncertainties, time-varying disturbances and actuator faults respectively. Figure 1 clearly shows the comparison between the actual heading and the reference heading of the USV. Both the fault-tolerant control scheme (FTC scheme) and the traditional adaptive control scheme designed in this article have completed the tracking task excellently. However, compared with the comparison scheme, the actual heading of FTC is closer to the reference heading. Figure 2 shows the course tracking error duration curve of USV. We can see that the tracking error of the FTC scheme is smaller than that of the traditional adaptive scheme. Since the traditional adaptive control scheme does not design a compensation mechanism for actuator failure, it is a passive fault-tolerant control scheme. Therefore, the active fault-tolerant control scheme we designed can better meet actual requirements. Figure 3 shows the control input duration curves of the two control schemes. Over time, they all tend to be bounded. Figure 4 shows the system adaptive duration curve. They overshoot when the course changes drastically. However, overall they are within a reasonable range. In summary, the fault-tolerant control scheme designed in this article effectively solves the actuator failure problem faced by the system.

5. Conclusions

This study systematically constructs an active fault-tolerant control strategy suitable for USVs under the theoretical framework of adaptive back-stepping. In addition to the consideration of actuator failure, we also consider the constraints of dynamic uncertainty and unknown external disturbances. Through simulation experiments, the results clearly show that the fault-tolerant control scheme proposed in this article has significantly improved the heading tracking accuracy compared with the traditional passive fault-tolerant control scheme. This research successfully overcame the system's actuator failure problem and provided an effective and feasible solution for the robustness of USVs in the face of various complex working environments.

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References

Melnyk, O., Volianska, Y., Onishchenko, O., Onyshchenko, S., Kononova, O. and Vasalatii, N. (2022), Development of Computer-based Remote Technologies and Course Control Systems for Autonomous Surface Ships. International Journal of Computer Science and Network Security, Vol.22, No.9, pp. 183-188.

Wu, Y. B., Gao, P. F., Wu, R. and Du, J. L. (2023), ESPO based course-tracking control of ships with input delay. International Journal of Control Automation and Systems.

Zou, C. J., Yu, J. and Guo, Y. X. (2021), Concise robust control of the nonlinear ship in course-keeping control. Applied System Innovation, Vol. 4, No. 2.

Muhammad, A. H., Paroka, D., Rahman, S. and Firmansyah, M. R. (2021), Twin-rudder-system configurations' impact on ferry ships' course-keeping ability under windy conditions. International Journal of Technology, Vol. 12, No. 2, pp. 432-443.

Zhang, Q., Ding, Z. Y. and Zhang, M. J. (2020), Adaptive self-regulation pid control of course-keeping for ships. Polish Maritime Research, Vol. 27, No. 1, pp. 39-45.

Li, G. Y., Chen, B. J., Chen, H. Y. and Deng, W. (2022), Fractional-Order PIλDμ Controller Using Adaptive Neural Fuzzy Model for Course Control of Underactuated Ships. Applied Sciences-Basel, Vol. 12, No. 11.

Yang, C. M. and Zou, Z. J. (2018), A fuzzy PID autopilot for ship steering based on membership function optimized by an improved genetic algorithm. Journal of Multiple-Valued Logic and Soft Computing, Vol. 30, No. 4-6, pp. 559-572.

Meng, X. F., Zhang, G. C. and Han B. (2023), Robust adaptive finite-time course tracking control of vessel under actuator attacks. Complex Engineering System, Vol. 3, No. 3.

Yang, D., Hu, X., Liu, W. J. and Guo, C. (2022), Finite-time control design for course tracking of disturbed ships subject to input saturation. International Journal of Control, Vol. 95, No. 5, pp. 1409-1418.

Hosseinabadi, P. A., Abadi, A. S. and Mekhilef, S. (2022), Fuzzy adaptive finite-time sliding mode controller for trajectory tracking of ship course systems with mismatched uncertainties. International Journal of Automation and Control, Vol. 16, No. 3-4, pp. 255-271.

Zhang X. K., Yang G. P., Zhang Q., Zhang, G. Q. and Zhang, Y. Q. (2017), Improved concise backstepping control of course keeping for ships using nonlinear feedback technique. Journal of Navigation, Vol. 70, No. 6, pp. 1401-1414.

Zhang X. K., Han X., Guan W. and Zhang G. Q. (20

19), Improvement of integrator backstepping control for ships with concise robust control and nonlinear decoration. Ocean Engineering, Vol. 189.

Zhao, B. G., Zhang, X. K., Liang, C. L. and Han, X. (2021), An improved model predictive control for path-following of usv based on global course constraint and event-triggered mechanism. IEEE Access, Vol. 9, pp. 79725-79734.

Zhang, G. Q., Gao, S., Li, J. Q. and Zhang, W. D. (2021), Adaptive neural fault-tolerant control for course tracking of unmanned surface vehicle with event-triggered input. Proceedings of The Institution of Mechanical Engineers Part I-Journal of Systems and Control Engineering, Vol. 235, No. 9, pp. 1594-1604.

Hu, Y. C., Zhang, Q. Liu, Y. and Meng, X. F. (2023), Event trigger based adaptive neural trajectory tracking finite time control for underactuated unmanned marine surface vessels with asymmetric input saturation. Scientific Reports, Vol. 13, No. 1.

Hu, Y. C., Park, G. K., Wu, H. T. and Zhang Q. (2017), Robust Adaptive Fuzzy Design for Ship Linear-tracking Control with Input Saturation. International Journal of e-Navigation and Maritime Economy, Vol. 6, pp. 9-16.

Zhang, Q., Jiang, N., Hu, Y. C. and Pan, D. W., (2017), Design of Course-Keeping Controller for a Ship Based on Backstepping and Neural Networks. International Journal of e-Navigation and Maritime Economy, Vol. 7, pp. 34-41.

Li, T. S., Zhao, R., Chen, C. L. P., Fang, L. Y. and Liu, C. (2018), Finite-Time Formation Control of Under-Actuated Ships Using Nonlinear Sliding Mode Control. IEEE Transactions on Cybernetics, Vol. 48, No. 11, pp. 3243-3253.

Gao, X. Y., Long, Y., Li, T. S., Hu, X., Chen, C. L. P. and Sun, F. C. (2023), Optimal Fuzzy Output Feedback Control for Dynamic Positioning of Vessels With Finite-Time Disturbance Rejection Under Thruster Saturations. IEEE Transactions on Fuzzy Systems, Vol. 31, No. 10, pp. 3447-3458.

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