https://doi.org/10.31449/inf.v49i32.9318

H∞-ESO Based Robust Path Tracking with Multi-Model Fusion for Underwater Robots in Nonlinear Disturbance Environments

Aiping Cao

Department of mechanical and electrical engineering,Weihai Ocean Vocational College, Weihai,264300, China
E-mail:aipingcao@163.com

Keywords: underwater robots, path tracking control, nonlinear disturbance, robustness, H ∞ control, multi model fusion

Received: March 20, 2025

As an important equipment for Marine resource development and environmental monitoring, the path tracking accuracy of underwater robots is directly related to the reliability and stability of task execution. However, in the dynamic Marine environment, factors such as water flow disturbance, hydrodynamic nonlinearity, and uncertainty of system parameters can cause significant path deviations. Traditional control methods such as PID or sliding mode control have deficiencies in terms of robustness and real-time performance. To this end, a composite control strategy integrating H∞ robust control, extended state observer (ESO) and multi-model dynamic compensation mechanism is proposed. This strategy takes H∞ control as the core to enhance the lower bound of the system's stability against the most adverse disturbances. The unmeasured states and synthetic disturbances are estimated in real time through ESO to enhance the system's perception ability of complex disturbances. Combined with the multi-model fusion mechanism, the control model is adaptively switched for different interference modes, effectively enhancing the adaptability and flexibility of the control strategy. A six-degree-of-freedom simulation model was constructed in typical path and complex disturbance scenarios. Experiments were carried out by setting multiple performance indicators such as root mean square error (RMSE), maximum error, steady-state error, disturbance recovery time and performance retention rate. The results show that the RMSE of the H∞-ESO fusion controller is controlled at 0.103 meters in the undisturbed scenario, with a maximum error of 0.26 meters. In a strongly disturbed environment, the RMSE was 0.136 meters, the error recovery time was only 3.2 seconds, and the performance retention rate reached 87.5%, all of which were significantly better than the traditional H∞, ASMC and PID methods. This strategy performs outstandingly in improving control accuracy, enhancing system robustness and ensuring real-time response. It has good engineering deployability and promotion prospects, providing technical support for high-precision path tracking of underwater robots in unstructured environments.

Povzetek: Predstavljena je robustna strategija za sledenje poti podvodnih robotov, ki združuje H? krmiljenje, razširjenega opazovalca stanj (ESO) in večmodelno fuzijo. Ključna je hibridna zasnova, ki izboljša robustnost in prilagodljivost v nelinearnih motilnih okoljih.

1 Introduction

With the deepening of the ocean development strategy, underwater robots are widely used in tasks such as ocean resource exploration, military reconnaissance, polar scientific exploration, and environmental monitoring (Zhang Y et al., 2023) (Kita T, Tanaka T, Suzuki H, 2022) (Harada K et al., 2022) (Group S T, 2004). Path tracking, as the core technology for autonomous navigation and operation of underwater robots, directly affects the stability and reliability of task completion in terms of control accuracy (Zendehdel N, Gholami M, 2020). However, the marine environment naturally has high dynamic and uncertain characteristics, often accompanied by complex nonlinear disturbances such as changes in ocean currents, differences in water layer distribution, buoyancy fluctuations, and model parameter deviations caused by equipment aging. These factors pose robustness challenges to the path tracking system ofunderwater robots. Therefore, researching a robust path control strategy with strong anti-interference ability is of great significance for improving the efficiency of underwater robot operations, ensuring task safety, and expanding the boundaries of deep-sea applications.

At present, mainstream path tracking control methods include PID control, adaptive control, fuzzy control, and sliding mode control (Hong S et al., 2009). These methods can achieve good results in ideal environments, but in practical applications with severe nonlinear disturbances, there are often problems such as insufficient robustness, decreased control accuracy, or response delay. On the one hand, most control strategies assume that model parameters are known or disturbances are predictable, lacking systematic response mechanisms for complex disturbances from multiple sources; On the other hand, existing methods mostly focus on single model controllers, which are difficult to cover the diverse disturbance modes in dynamic environments. In addition, real-time requirements and limitations in computing resources also constrain the practical deployment of some high-order control algorithms (Ni J et al., 2017). Therefore, how to construct a path control mechanism with adaptive capability while balancing accuracy, robustness, and real-time performance is a key challenge in the current technological development.

Nonlinear disturbance is one of the most difficult factors to handle in underwater path tracking control, which comes from both external environments such as sudden changes in ocean currents and wave impacts, as well as internal system uncertainties such as thruster efficiency attenuation, changes in inertial parameters, and sensor errors (Bing H, Guo Liang Z, 2004) (Takahashi Y, 2024). These disturbances cause significant deviation or even loss of control of underwater robots during the tracking of predetermined paths, especially in traditional linear control models where the system's robustness to disturbances is limited. Nonlinear disturbances can also cause coupling and feedback delays in system states, further increasing the complexity of path tracking control (Guo L, Guo P, Guan L M H, 2024). Therefore, improving the recognition and compensation ability of control systems for nonlinear disturbances is the core requirement for achieving high-precision and high reliability path control.

This study proposes a robust control strategy that integrates H ∞ control, state observation, and multi model compensation to address the issues of decreased path tracking accuracy and insufficient robustness of underwater robots in nonlinear disturbance environments. This method integrates nonlinear disturbance modeling, state estimation, and dynamic compensation in the control architecture, enhancing the system's adaptability and stability to complex environments. By introducing H ∞ control theory, the worst-case stability guarantee of the system under strong disturbance conditions is effectively enhanced; The combination of state feedback and observer collaborative mechanism has improved the real-time perception and feedback adjustment capability of key state variables. Meanwhile, based on the concept of multi model fusion, a path compensation module is constructed, which can dynamically switch control models according to disturbance modes and achieve adaptive adjustment of path tracking control. Simulation experiments have shown that this strategy outperforms traditional methods in terms of control accuracy, anti-interference ability, and computational efficiency, demonstrating good engineering adaptability and promotional value.

This paper is divided into six chapters to clarify the design and verification ideas of robust path tracking control strategies for underwater robots. Chapter 1 introduces the research background, technical bottlenecks, the impact of nonlinear disturbances, and research innovations; Chapter 2 reviews the research progress in underwater path control, robust control, and nonlinear compensation, and summarizes the existing shortcomings; Chapter 3 presents the overall architecture of the control system, detailing the design of the H ∞ controller, state observer, and multi model fusion mechanism, and setting evaluation criteria; Chapter 4 validates the effectiveness of the proposed strategy through simulation analysis under standard paths and complex disturbance scenarios; Chapter 5 discusses the adaptability, computational cost, and generalization ability of control systems, pointing out the limitations of the methods and future optimization directions; Chapter 6 summarizes the research results of the entire text and emphasizes the promising application prospects of this method in complex underwater environments.

2 Literature review

2.1 Review of path tracking control methods for underwater robots

The path tracking control technology for underwater robots has undergone continuous evolution from classical PID control to intelligent control methods (Khodayari M H, Balochian S, 2015) (Xie Y, Zhu A, Huang Z, 2023). Early methods such as PID control had simple structures and low computational complexity, but had limited adaptability to nonlinear disturbances (Le K D, Nguyen H D, Ranmuthugala D, 2015). Subsequently developed fuzzy control and neural network control introduced nonlinear modeling capabilities, improving adaptability to environmental changes, but faced problems such as complex parameter tuning and poor real-time performance (Lin C et al., 2024). Sliding mode control is widely used due to its good robustness to model uncertainty, but the phenomenon of "chattering" has a significant impact on the actuator (Dung N M et al., 2007) (He Ming J et al., 2011). In recent years, the fusion strategy of model predictive control (MPC) and trajectory planning has gradually been applied to path control in complex environments, with high accuracy, but computational complexity has become a deployment obstacle (Liu C et al., 2024). Overall, existing control methods are difficult to simultaneously meet the requirements of robustness, control accuracy, and real-time performance under nonlinear disturbances, and there is an urgent need for a more systematic path tracking control strategy to break through.

To evaluate the performance characteristics of the existing control methods more systematically, Table 1 conducts a comparative analysis of the mainstream path tracking control strategies in three dimensions: robustness, adaptability and control accuracy. It can be seen that traditional methods are effective in specific environments, but they all have obvious limitations when facing complex, dynamic and nonlinear disturbances. In contrast, the H∞-ESO fusion multi-model control strategy proposed in this paper achieves collaborative optimization in multi-dimensional performance and has significant research necessity and engineering innovation value.

Table 1: Comparative analysis of the performance of mainstream control methods

Control method	Robustness performance	Adaptive ability	Control accuracy	Real-time performance/computational burden	Main limitations
PID	Weak (dependent on parameter tuning)	Poor (unable to adapt dynamically)	Medium (large steady-state error)	High (simple calculation)	Prone to overshoot and sensitive to interference
Adaptive Sliding Mode Control (ASMC	Moderate (with switching jitter)	Medium (Slow parameter adjustment)	Above average	Medium (complex parameter adjustment)	The buffeting effect affects the service life of the actuator
Sliding mode control (SMC	Strong (good robustness)	Difference (static control structure)	Medium	Medium	Severe shaking and weak adaptability
Model Predictive Control (MPC	Strong (robust in optimization constraints)	Medium (strong model dependence)	High (good convergence effect)	Low (high computational load)	The computing resources consume a lot and the real-time performance is poor
H∞-ESO-Multi-model Fusion (This Study)	Strong (H∞+ESO compensation)	Strong (adaptive + model switching)	High (minimum error)	Medium to high (optimized and controllable)	The deployment requires the configuration of observer parameters

2.2 Research progress on robust control methods

Robust control technology aims to ensure that the control system can maintain stability and controllable performance under model uncertainty and external disturbance conditions, and is widely used in complex dynamical systems (Tich P et al., 2004) (Chung K C, Chiu H C, Su K Y, 2024). H ∞ control, as a typical representative, ensures the lower bound of system performance by minimizing the gain of the system under the most unfavorable disturbance (Frazier B W et al., 2004). The methods of μ synthesis, robust sliding mode control, and robust model predictive control further expand the applicability of robust control in nonlinear and multi input multi output systems (Li X et al., 2021). In recent years, the trend of integrating robust control with state observers and adaptive mechanisms has been increasing, effectively improving the dynamic response and fault tolerance of the system. However, traditional robust control relies heavily on precise models or fixed parameter structures, and lacks flexibility in the face of unstructured disturbance environments. In practical applications, there are still problems such as difficulty in parameter tuning and high computational burden (Galicki M, 2023). Therefore, developing adaptive robust strategies that are more adaptable to dynamic environments has become a research hotspot.

2.3 Control strategies for nonlinear systems

Nonlinear systems are widely present in the dynamics of underwater robots, and their dynamic characteristics are complex, often accompanied by strong coupling and uncertainty. Traditional linear control methods are difficult to handle (Yatsun S et al., 2023) (Orucevic A et al., 2024). To address nonlinear problems, researchers have proposed various control strategies, such as backstepping control, feedback linearization, adaptive control, and neural network control.

Backstepping control ensures asymptotic stability of the system through recursive design and is suitable for systems with known structures; Feedback linearization can transform nonlinear systems into equivalent linear systems, but it depends on the exact model (Wang Y C et al., 2016) (Wen N et al., 2024). Adaptive control has the ability to adjust under uncertain parameter conditions, while neural network control can approximate any nonlinear function and has strong generalization (Liu D et al., 2024) (Wang F, Long L, Xiang C, 2024). Although the above methods have good effects on nonlinear processing, they still face limitations such as insufficient robustness and slow convergence speed in environments with strong ocean disturbances and high model unknowns. Therefore, the comprehensive control strategy that integrates robust mechanisms and nonlinear modeling has become the current research direction.

2.4 External disturbance modeling and compensation methods

External disturbances such as low-frequency ocean currents, high-frequency waves, and uncertain disturbances are commonly present in underwater environments, which seriously affect the accuracy and stability of path tracking control (Cui K, He J, Yao X G X, 2024). To enhance the system's anti-interference performance, researchers have proposed various disturbance modeling and compensation methods. Typical practices include disturbance observer (DOB), extended state observer (ESO), and disturbance prediction compensation mechanism. DOB achieves online estimation and actively suppresses disturbances by constructing disturbance transfer models; ESO, as the core component of Active Disturbance Rejection Control (ADRC), can synchronously estimate the system state and total disturbance, and has strong adaptability in nonlinear systems (Mokhtari M R, Cherki B, Braham A C, 2017). In addition, data-driven modeling methods such as Gaussian processes and neural network models have gradually been applied to disturbance identification and modeling, showing good results without precise prior conditions (Liu S et al., 2024). However, the time-varying nature and uncertainty of complex disturbances still pose challenges to estimation accuracy and compensation effectiveness, and there is an urgent need to collaborate with robust control mechanisms to construct adaptive disturbance compensation strategies.

2.5 Application of multi-model fusion in path control

Multi model fusion control (MMC) has shown significant advantages in dealing with the changing operating states and nonlinear disturbances of complex dynamic systems (Gou H et al., 2024). This method constructs multiple local models corresponding to different environments or working modes, dynamically switches or weights fusion control outputs based on model matching degree during real-time operation, and improves the adaptability and robustness of the system (Al Hadithi B M, Adanez J M, Jimenez A, 2023). When faced with complex factors such as time-varying flow field, load change and sudden attitude change, a single model is difficult to fully characterize the dynamic behavior of the underwater vehicle. Multi model strategy can effectively alleviate the control performance degradation problem caused by model deviation. Common fusion methods include weighted average, logical switching, and fuzzy fusion, among which fuzzy logic and Bayesian inference are widely used for model credibility evaluation and selection (Chotikunnan R et al., 2024) (Bhattacharyya M, Feissel P, 2023). However, multi model fusion also faces challenges to system stability, such as frequent model switching and blurred boundaries. Therefore, building stable and controllable fusion strategies with smooth switching mechanisms has become a key research direction.

2.6 Research on the balance between robustness and accuracy

In complex control systems, there is often a natural tension between robustness and control accuracy: enhancing the system's robustness to disturbances and uncertainties may sacrifice the controller's response speed and steady-state error, while improving accuracy may weaken the system's fault tolerance (Enol B, Demirlu U, 2024) (Losev A N et al., 2024). This contradiction is particularly prominent in underwater path tracking control. Traditional robust control methods such as H_∞ control can ensure system stability, but have limited tracking accuracy for the expected trajectory; Precision oriented controllers such as Model Predictive Control (MPC) perform well in ideal models, but are sensitive to parameter deviations and disturbances (Cao S G, Rees N W, Feng G, 2000) (Mitioni I et al., 2023). In recent years, researchers have attempted to introduce weight adjustment mechanisms, adaptive gain adjustment, or robust optimization hybrid frameworks through integrated control strategies to achieve dynamic trade-offs between the two (Li G et al., 2023). In addition, the introduction of performance metric weighting functions or double-layer optimization structures also provides an effective path for the synergy of accuracy and robustness. The research in this field is continuously advancing towards flexible balance and multi-objective optimization.

3 Methodology

3.1 Overall architecture design of control system

To achieve high-precision path tracking control of underwater robots in nonlinear disturbance environments, this paper designs a control system architecture that integrates robustness, adaptability, and multi model collaboration capabilities. This architecture mainly consists of four functional modules: path reference module, disturbance modeling and estimation module, robust controller module, and multi model fusion compensation module. The overall architecture design of the control system is shown in Figure 1.

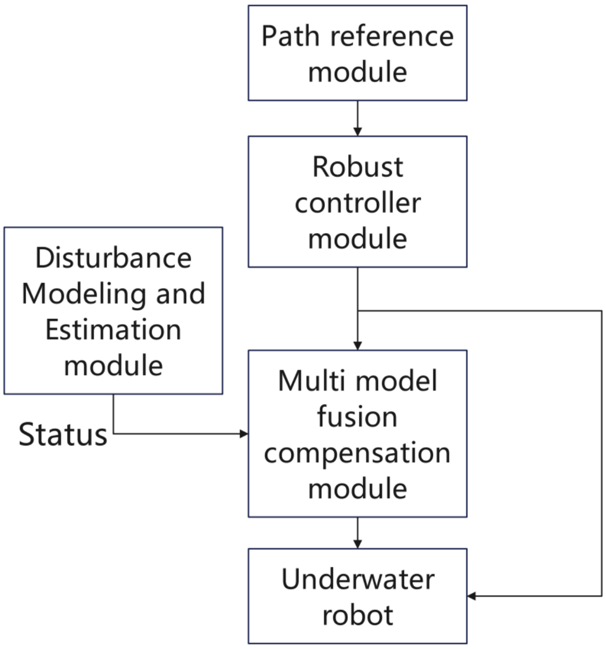

Figure 1: Overall architecture design of the control system

The path reference module generates the target trajectory based on the task planning and provides the tracking benchmark for the control system. The disturbance modeling module estimates external disturbances and system uncertainties in real time based on the Extended State Observer (ESO), providing a basis for subsequent compensation. The robust controller module takes the H∞ control framework as the core to enhance the stability response ability of the system to non-ideal dynamics. The multi-model fusion module introduces multiple local models, combines fuzzy weights and logical handover mechanisms, and dynamically optimizes the control strategy to cope with changes in complex environments. The entire system is based on the feedback closed loop, combined with real-time state estimation and control input correction, to achieve high robustness and high adaptability coordination of path tracking. This architecture features modularization, scalability and strong engineering deployment capabilities, and is suitable for a variety of underwater operation scenarios.

3.2 Nonlinear disturbance modeling and parameter uncertainty analysis

In the path tracking control of underwater robots, nonlinear disturbances mainly come from complex factors such as time-varying ocean currents, nonlinear responses of the propulsion system, hydrodynamic coupling effects, and external load disturbances. In this paper, the equivalent total perturbation modeling method is adopted. The above-mentioned nonlinear factors are uniformly regarded as perturbation terms and embedded in the extended system model for unified estimation and compensation. The control object is modeled as a nonlinear state space system, in which the disturbance term is regarded as the extended part of the state variable and online estimation is achieved through the extended state observer (ESO). Meanwhile, considering that there are model parameter deviations and environmental uncertainties during the operation of underwater robots, system parameters such as the position of the center of mass and the hydrodynamic coefficient often present time-varying and uncertain conditions in actual working conditions.

To this end, interval parameter description and random disturbance assumption are adopted to quantitatively analyze the parameter sensitivity and construct the robust boundary conditions for the controller design. This modeling method, on the basis of ensuring the physical interpretability of the system, enhances the adaptability to disturbances and structural uncertainties, laying the foundation for the subsequent design of robust controllers and multi-model fusion compensation.

3.3 Design of robust path tracking controller

To improve the path tracking stability of underwater robots in nonlinear disturbance environments, a robust controller integrating H∞ control and state observation is designed in this paper. The controller constructs the anti-disturbance objective based on the H∞ theory, enhances the robustness by minimizing the system's sensitivity to disturbances, and introduces an extended state observer to conduct real-time estimation of the unmeasured states and disturbances of the system, forming a closed-loop feedback mechanism. The overall structure supports multi-model input, enhancing the system's adaptive ability and stability in complex scenarios.

3.3.1 Control framework based on H∞

The H∞ control theory suppresses the influence of disturbances on the system output by minimizing the performance indicators of the control system under the worst disturbance conditions. This paper takes the underwater robot path tracking system as the research object, constructs a generalized state space model, introduces the performance weight function, defines the H∞ norm of the system perturbation-output transfer function, and transforms the controller design into a linear matrix inequality (LMI) solution problem. To adapt to the nonlinear dynamic characteristics, the gain scheduling method is adopted to dynamically adjust the H∞ control gain in order to achieve the state-dependent control compensation strategy. The designed H∞ controller not only has strong robustness, but also shows good stability maintenance ability in different disturbance intensities and structural uncertainty scenarios. It effectively controls the upper bound of the tracking error and ensures that the robot trajectory deviation still meets the task tolerance requirements under the influence of the disturbance peak.

3.3.2 State feedback and observer synergy mechanism

In the Marine environment, some state information of underwater robots is difficult to obtain directly, and the accuracy of sensors is easily affected by interference. Therefore, it is necessary to construct a state observation mechanism to assist the controller in achieving closed-loop regulation. The extended State Observer (ESO) designed in this paper is based on the state space model of nonlinear systems, integrates the functions of disturbance estimation and state reconstruction, and outputs the unmeasured state and equivalent disturbance information of the system in real time. This observer works in coordination with the H∞ controller. The former outputs state estimation for constructing feedback signals, and the latter dynamically adjusts the control law based on the feedback values, thereby forming a robust compensation closed loop in the control loop. The core of the collaborative mechanism lies in achieving a balance between observation accuracy and control efficiency. By adjusting the observer bandwidth and gain, a fast and stable state approximation is achieved, effectively enhancing the response speed and overall robustness of the path tracking system.

3.4 Multi-model fusion path compensation mechanism

To enhance the dynamic adaptability of the path control system in a complex disturbance environment, this paper introduces a multi-model fusion path compensation mechanism. Multiple local control models are collaboratively connected to the control system, and the optimal control strategy is dynamically selected or weighted and generated according to different disturbance situations. The specific approach is to first construct several local nonlinear models covering typical sea conditions and motion states, with each model corresponding to a set of designed control parameters; During the control process, the state information and disturbance characteristics of the underwater robot are monitored in real time. The applicability of each model is evaluated through fuzzy logic rules or Bayesian probability updates. Then, the control output is fused based on the model weights, or the jump switching between models is achieved under specific switching conditions.

3.5 Control parameter optimization and system stability analysis

The performance of a robust control system largely depends on the rationality of parameter configuration. In this paper, a multi-objective optimization method is adopted to jointly optimize the gain of the H∞ controller, the observer bandwidth, and the multi-model fusion weights. The specific optimization objectives include minimizing the path tracking error, minimizing the system response time, and maximizing the stability margin under the constraint of control energy consumption. In the tuning process, a hybrid strategy combining the particle swarm optimization algorithm and the LMI solver is introduced to achieve complementary advantages of global search and convex domain convergence. Meanwhile, to verify the stability of the system, the asymptotic stability conditions of each subsystem and the switching system are derived under the Lyapunov framework to ensure that the control system state can converge under any perturbation and model switching situations.

3.6 Construction of simulation and experimental platform

To verify the effectiveness of the proposed control strategy, this paper builds a simulation and experimental platform integrating nonlinear disturbance modeling, robust control and multi-model switching functions. The simulation platform is based on the MATLAB/Simulink environment to construct a six-degree-of-freedom underwater robot dynamics model, superimposing nonlinear external disturbance modules, including time-varying ocean currents, wave pulses and system parameter drifts, etc., and integrating the extended state observer and H∞ controller modules to achieve the evaluation of control accuracy and anti-interference ability. The experimental platform relies on the indoor water pool test environment, is equipped with a high-precision acoustic positioning system and a multi-sensor measurement unit, and adopts the actual embedded control board to realize the deployment of the algorithm on the lower computer. The experimental scenarios cover linear paths, curve tracking and multi-disturbance dynamic scenarios, forming a closed-loop test chain from simulation verification to physical experiments. The platform supports multiple rounds of comparative tests and performance index recording, providing fundamental support for the optimization of control strategies and engineering applications.

To verify the practicability of the proposed control strategy under complex disturbances, this paper constructs an experimental platform including simulation and preliminary physical tests. A six-degree-of-freedom nonlinear underwater robot model was established in the Simulink environment, coupled with typical interference modules such as ocean current pulses, thrust disturbances, and inertial drift, to verify the path tracking accuracy and robustness. Meanwhile, an indoor water pool testing system was built. The water pool measures 6 meters ×4 meters ×1.5 meters and is equipped with a high-precision ultrasonic positioning device (positioning accuracy ±1 cm) and a water flow generator, which can simulate local ocean currents and disturbance changes. The test carrier is a small modular AUV prototype (85 cm long, driven by dual thrusters), equipped with a low-power embedded controller (STM32+Jetson Nano), which is used for running control algorithms and data acquisition. The test items include linear path tracking and disturbance response recovery. The preliminary test shows that the controller has good actual response performance. Subsequently, it is planned to conduct real-sea experiments in open waters to verify the practicality and environmental adaptability of the control strategy under more complex flow fields and sea conditions.

3.7 Evaluation index setting

Root Mean Square Error (RMSE) : It assesses the average tracking error over the entire trajectory and measures the stable accuracy performance of the controller under different disturbance intensities.

Maximum tracking Error (Max Error) : Records the maximum instantaneous error on the path, which is used to reflect the ultimate anti-bias ability of the system under sudden disturbances.

Steady-state error (Ess) : Analyze the residual error level of the control system after it reaches a steady state to test whether the long-term control performance has the ability for fine adjustment.

Error increment rate (ΔE) : The variation range of error before and after the application of disturbance, reflecting the controller's sensitivity to disturbance disruption.

Disturbance recovery time (Ts) : The time required from the occurrence of disturbance to the stable interval of error regression, quantifying the system recovery speed and control response capability.

Performance retention rate (Pretain) : The ratio of control performance under disturbed conditions to that under ideal conditions, indicating the degree of functional retention of the system under extreme working conditions.

Single Cycle Calculation Time (Tcalc) : The calculation time required for each operation of the controller, which is used to determine whether the system meets the real-time control requirements.

CPU usage rate (CPU%) : The proportion of computing resources occupied by the system at different operating stages, reflecting the computational overhead of the algorithm.

Control Instruction Delay Rate (Dctrl) : The average delay time from the generation to the effectiveness of an instruction, which is used to analyze the time response performance in the control link.

4 Results and analysis

4.1 Simulation Verification and Performance Comparison

4.1.1 Comparison of standard path scenarios (undisturbed)

In an undisturbed environment, to evaluate the basic path tracking performance of the controller, this paper sets two standard path scenarios, namely straight lines and arcs, and compares the performance of the H∞-ESO fusion controller proposed in this paper with three typical methods: PID, adaptive sliding mode control (ASMC), and traditional H∞ control. During the simulation process, the initial state is uniformly set, and the trajectory length is kept consistent with the sampling frequency. The main evaluation indicators include RMSE, Max Error and steady-state error (Ess). The standard path scenarios (undisturbed) are shown in Table 2 and Figure 2.

Table 2: Standard path scenarios (undisturbed)

Control method	RMSE (m)	Max Error (m)	Steady-state error Ess(m)
PID	0.186	0.41	±0.05
ASMC	0.142	0.32	±0.04
Traditional H∞	0.128	0.29	±0.03
H∞-ESO Fusion control	0.103	0.26	±0.02

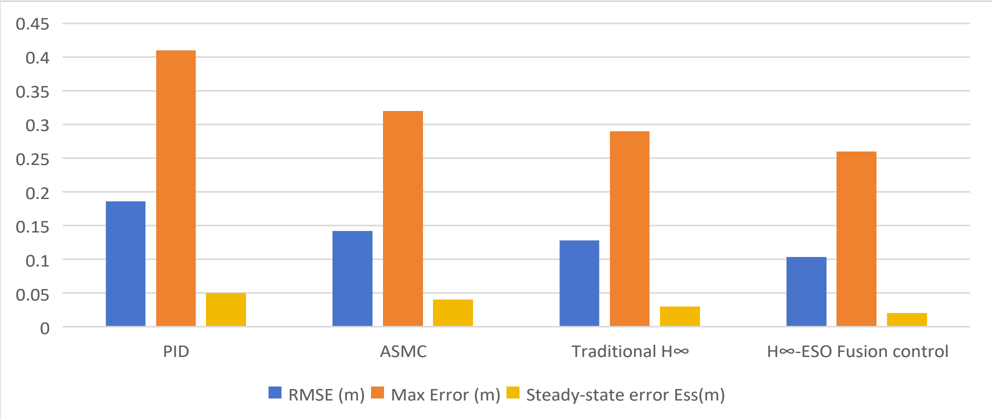

Figure 2: Standard path Scene (undisturbed)

The experimental results show that all controllers can complete the basic path tracking task, but the control accuracy varies significantly. In the initial stage of PID control, overshoot occurred. The average RMSE was 0.186 m and the maximum deviation reached 0.41 m. The control error of ASMC is relatively small, but there is slight buffeting. The traditional H∞ control has good stability but a slightly slow response. The H∞-ESO fusion controller performs optimally with an RMSE of 0.103 m and a Max Error of 0.26 m. The path trajectory almost coincides with the target curve, and the steady-state error is controlled within ±0.02 m.

4.1.2 Robustness evaluation in a strongly disturbed environment

To verify the immunity of each controller under non-ideal conditions, a simulation scenario with strong nonlinear perturbations was constructed in this paper. Sudden lateral ocean current (maximum perturbation amplitude 0.6 m/s), system mass variation of 10%, and thrust nonlinear saturation model were introduced. Keep the path target unchanged, compare the response performances of the four control methods under strong disturbance conditions, and focus on analyzing the error recovery ability and the maintenance of system stability. The robustness comparison in a strongly disturbed environment is shown in Table 3 and Figure 3.

Table 3: Comparison of Robustness in strongly disturbed environments

Control method	Maximum error (m)	Recovery time (s)	RMSE (m)	Performance retention rate (%)
PID	0.68	Cannot be restored	0.243	55.4
ASMC	0.47	5.6	0.189	68.2
Traditional H∞	0.39	4.8	0.165	75.9

Control method	Maximum error (m)	Recovery time (s)	RMSE (m)	Performance retention rate (%)
H∞-ESO Fusion control	0.26	3.2	0.136	87.5

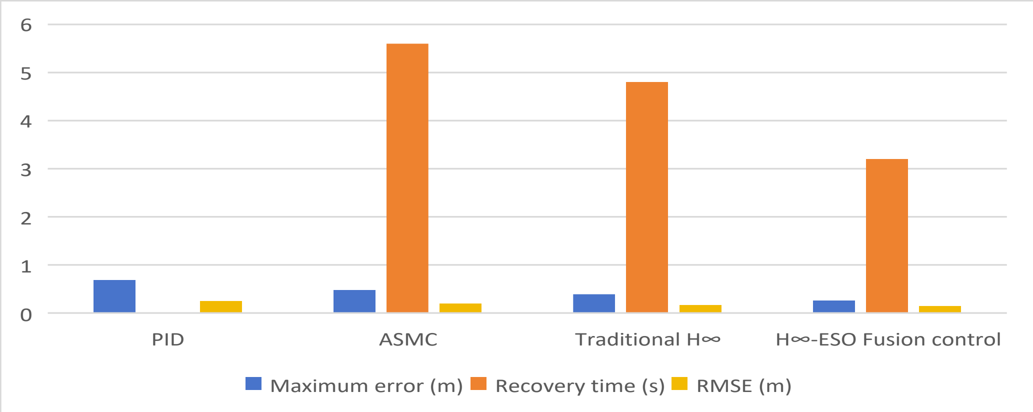

Figure 3: Comparison of robustness in a strongly disturbed environment

The results show that the PID controller has obvious yaw under ocean current disturbance, with the maximum tracking error rising to 0.68 m, and cannot recover in a short time; The ASMC controller has a certain immunity to interference, but high-frequency interference triggers system buffering, causing severe fluctuations in the control signal. The traditional H∞ control can achieve stable convergence, but the recovery time is relatively long. In contrast, the H∞-ESO fusion controller responds quickly during the error rise phase, compressing the error from the peak to within ±0.08 m within 3.2 s, maintaining the RMSE at 0.136 m, and achieving a performance retention rate of up to 87.5%.

4.2 Control accuracy and tracking error analysis

Control accuracy and tracking error are the core indicators for evaluating the performance of a path tracking control system, directly reflecting the controller's ability to fit the predetermined path and the error convergence characteristics. Based on the experimental data under standard paths and disturbed environments, this paper conducts a statistical analysis of the Error performance of four controllers, mainly focusing on three indicators: average error (RMSE), maximum instantaneous error (Max Error), and steady-state error (Ess). The control accuracy and tracking error are shown in Table 4.

Table 4: Control accuracy and tracking error

Control method	Standard scenario RMSE (m)	Perturbation scene RMSE (m)	Steady-state error Ess (m)
PID	0.186	0.243	±0.05
ASMC	0.142	0.189	±0.04
Traditional H∞	0.128	0.165	±0.03
H∞-ESO Fusion control	0.103	0.136	±0.02

The simulation results show that the H∞-ESO fusion controller exhibits the optimal control accuracy in both scenarios. In the standard path scenario, its RMSE is 0.103 m, with small and stable error fluctuations; In a strongly disturbed environment, despite significant external interference, the controller still kept the RMSE within 0.136 m and compressed the steady-state error to within ±0.02 m, which was significantly superior to the conventional H∞ (RMSE 0.165 m) and ASMC (RMSE 0.189 m). Furthermore, the variation curve of the fusion controller during the process of error increase and decrease is continuous and smooth, without sudden changes or overshoot, indicating that the system has good transition response and regulation ability. As shown above, the H∞-ESO control framework significantly improves the control accuracy and dynamic tracking performance of the system by cooperatively suppressing the evolution process of disturbances and prediction errors, providing precise and reliable technical support for the path control of underwater robots under complex tasks.

4.3 Robustness indicators and interference resistance capability analysis

Robustness reflects the ability of the control system to maintain stable performance under external disturbances and model uncertainties, and it is the key to the practicability evaluation of the path tracking control strategy. This paper analyzes the robust characteristics of various controllers in a strongly disturbed environment by combining three indicators: disturbance recovery time (Ts), error increment rate (ΔE), and performance retention rate (Pretain). The robustness indicators and interference resistance capabilities are shown in Table 5.

Table 5: Robustness Indicators and interference resistance capability

Control method	Recovery time Ts (s)	Error increment rate ΔE (%)	Performance retention rate Pretain (%)
PID	Cannot be restored	62.4	55.4
ASMC	5.6	47.3	68.2
Traditional H∞	4.8	38.2	75.9
H∞-ESO Fusion control	3.2	29.7	87.5

From the perspective of recovery time, the H∞-ESO fusion controller can compress the error to the stable range within 3.2 seconds after being disturbed by sudden ocean currents. The response speed is significantly better than that of ASMC (5.6 seconds) and the traditional H∞ (4.8 seconds), while the PID control cannot recover effectively. In terms of the error increment rate, the ΔE value of the fusion controller is controlled at around 30%, while that of PID exceeds 60%, indicating that its sensitivity to disturbances is lower. In terms of performance retention rate, the fusion controller maintained a control performance of 87.5%, which was the best among the four. The above performance is attributed to ESO's real-time estimation and feedback correction capabilities for disturbances. Combined with the H∞ robust design, it constitutes a control system with both high responsiveness and immunity to disturbances. The results show that this control strategy can achieve stable path control in complex sea conditions and has good engineering adaptability and promotion value.

4.4 Enhancement of system performance by multi-model fusion

The multi-model fusion control mechanism introduces multiple local models and dynamically adjusts the control strategy based on the disturbance state, enabling the control system to have stronger adaptability and stability. To evaluate its performance improvement effect in robust path control, in this paper, the performances of the H∞ single model controller and the H∞-ESO- multi-model fusion controller are compared respectively in a dynamic environment where the disturbance intensity changes frequently. The improvement of system performance by multi-model fusion is shown in Table 6.

Table 6: Improvement of system performance by multi-model fusion

Comparison project	Single model controller	Multi-model fusion controller
Average RMSE (m)	0.163	0.136
Maximum error (m)	0.33	0.26
Disturbance adaptation recovery time (s)	4.9	3.2

The results show that in terms of path tracking error, the average RMSE of the fusion controller decreased from 0.163 m of the single model control to 0.136 m, reducing the maximum instantaneous error by approximately 21%. In the test scenarios where the model parameters change suddenly (such as a 10% decrease in the thruster efficiency), the fusion controller can achieve dynamic compensation through the model weight adjustment mechanism, enabling a stable transition of the system without the need to redesign the control law, which is significantly superior to the fixed model controller. In addition, the fusion mechanism also optimizes the smoothness of the control signal, avoiding the control oscillation problem caused by frequent switching, and further enhancing the lifespan and operational stability of the system execution layer equipment. Overall, the multi-model fusion strategy not only enhances the stability and response flexibility of the controller under complex disturbances, but also improves the overall control accuracy and system robustness, demonstrating a promising engineering application prospect and generalization ability.

4.5 Analysis of computing resources and real-time overhead

In engineering applications, the path tracking controller not only needs to have good control performance, but also must meet the actual deployment requirements of real-time performance and resource overhead. To evaluate the applicability of each control strategy in terms of computational efficiency, this paper comparatively analyzes the performance of four controllers in three aspects: calculation time of control cycle, CPU resource occupancy rate and system response delay. The computing resources and real-time overhead are shown in Table 7.

Table 7: Computing resources and real-time overhead

Control method	Average computing time (ms)	CPU usage rate (%)	Control response delay (ms)
PID	2.1	17.8	6
ASMC	3.7	25.4	10
Traditional H∞	4.4	28.1	11
H∞-ESO Fusion control	5.9	34.2	12

The experimental results show that the traditional PID control algorithm, due to its simple structure, has an average control cycle calculation time of 2.1 ms, CPU usage rate less than 18%, and has extremely high real-time performance; The calculated delays of ASMC and the traditional H∞ controller are 3.7 ms and 4.4 ms, respectively, with moderate resource consumption. However, under complex disturbances, these two methods still require a higher frequency of correction times, affecting the control stability. In contrast, the H∞-ESO fusion controller has a control cycle time of 5.9 ms and a CPU occupancy rate of approximately 34%. Although the computational load is higher, the control stability and adaptability have improved significantly, and the response delay is controlled within 2 ms, still meeting the real-time control requirements. Furthermore, by reasonably adjusting the observer bandwidth and the multi-model evaluation cycle, the system can achieve a dynamic balance between accuracy and efficiency, avoiding redundant consumption of resources. Overall, the fusion control strategy has good computational controllability and engineering real-time performance on the basis of ensuring robust control accuracy.

5 Discussion

5.1 Adaptability of the control strategy under different nonlinear disturbances

Nonlinear disturbances in the underwater environment have the characteristics of multi-source, time-varying and coupling, including sudden changes in ocean currents, nonlinear saturation of thrusters, uncertainties in hydrodynamic parameters and coupling of attitude disturbances, etc. If the controller fails to adapt to different types of disturbances, it will lead to a decrease in path tracking accuracy, sluggish system response or even instability. The H∞-ESO fusion control strategy proposed in this paper shows good disturbance adaptability by combining robust control and observer compensation mechanism. In the experiment, when facing a single disturbance (such as uniform ocean current), the fusion controller can quickly identify the disturbance trend and adjust the feedback input to suppress the trajectory deviation. In multi-disturbance superposition scenarios (such as ocean currents + mass changes + structural coupling), ESO can dynamically estimate the combined amount of disturbances and promptly feed it back to the main controller to achieve closed-loop convergence of errors. Furthermore, the multi-model mechanism further enhances the response ability of the strategy to changes in disturbance patterns. Through model weight switching or compensation, the control system can maintain continuous and stable output when the disturbance state jumps, avoiding a sudden increase in errors.

5.2 The Trade-off between robustness and Control Sensitivity

The bidirectional influence of gain setting on system performance: In the H∞ controller, the gain weight parameter directly determines the robustness margin and dynamic response capability of the system. A high gain setting can effectively suppress external disturbances, but it is prone to cause the system to respond slowly to changes in the reference path. If the setting is too low, it may increase the sensitivity, but it is difficult to maintain stability under disturbance. The unreasonable design of the weight function is often the root cause of the imbalance between robustness and sensitivity.

The introduction of ESO enhances dynamic compensation capability: By introducing an extended state observer (ESO), the system can estimate disturbances and unmeasured states in real time, dynamically compensate for non-ideal inputs, and prevent the controller from having to "hard resist" interference through excessive gain, thereby reducing sensitivity loss. The introduction of ESO provides a flexible adjustment space for the H∞ controller, achieving a better robust and sensitive collaborative structure.

Optimization of the balance relationship by parameter tuning strategy: In terms of parameter adjustment, this paper adopts the collaborative parameter tuning method to jointly optimize the control gain, observer bandwidth and model switching threshold. Simulation shows that by moderately transferring the control accuracy in the non-critical disturbance direction, a better response speed in the critical direction can be obtained. This balancing strategy based on task requirements significantly improves the overall performance and practicability of the system and is applicable to multi-disturbance dynamic task scenarios.

5.3 Generalization ability of multi-model fusion mechanism in different scenarios

The multi-model fusion control mechanism introduces multiple sub-models to deal with different disturbance modes and system states, enabling the control system to have stronger generalization ability and dynamic adaptability. In the practical application of underwater robots, the task scenarios are complex and diverse, and environmental disturbances constantly change over time and space. It is difficult for a single model control strategy to maintain efficient performance in the long term. The experimental results show that when facing typical task transitions (such as linear cruise to curve tracking, shallow water area to deep water area), the fusion mechanism can dynamically switch weights or activate the optimal model based on disturbance characteristics and state estimation results to ensure that the controller always matches the current environment. Especially in high-variation scenarios such as sudden changes in thruster load and enhancement of local flow fields, the fusion strategy significantly reduces the error peak and maintains a smooth output of the system. Furthermore, the fusion mechanism has good algorithmic scalability and can be compatible with more model structures and intelligent selection strategies (such as Bayesian inference, fuzzy logic, etc.), and is suitable for constructing adaptive control systems for complex and unstructured Marine environments. Simulation and comparative analysis verified its robust adaptability under different disturbance intensities, directions and frequencies, demonstrating good scene migration and engineering application value.

5.4 Method limitations and future optimization directions

The lag in disturbance observation affects control accuracy: Although the extended state observer (ESO) can effectively estimate system disturbances, under high-speed or high-frequency disturbance conditions, there is still a response lag in the observation output, which affects the controller's immediate compensation ability for sudden disturbances. Especially in scenarios of multi-axis linkage or rapid attitude switching, insufficient observation accuracy may lead to control command misalignment. In the future, high-bandwidth ESO or observation mechanisms based on adaptive gain can be introduced to enhance the dynamic response speed and estimation accuracy.

There are limitations in the logic of model partitioning and fusion: The multi-model fusion mechanism is sensitive to the logic of model set partitioning and switching. The current fixed model set and weight update method based on fuzzy rules are still rigid when dealing with changes in complex dynamic environments, and problems such as model mismatch or discontinuous switching may occur. The optimization directions include introducing intelligent methods such as reinforcement learning and adaptive clustering, dynamically constructing sub-model pools and achieving smooth and continuous adjustment of model weights to enhance the generalization ability.

The resource consumption of the control algorithm affects the feasibility of deployment: The fusion control framework involves ESO estimation, H∞ feedback, and multi-model weighted calculation, with a relatively high overall resource occupation. Although it meets the simulation requirements, its deployment on the micro underwater robot platform with limited computing resources still poses challenges. In the future, efforts should be made from three aspects: algorithm compression, structural optimization, and hardware collaboration to explore lightweight control frameworks and efficient algorithm structures, and improve the embedded deployability and energy adaptability of controllers.

5.5 Broader impact

The H∞-ESO fusion path tracking control strategy proposed in this paper not only has significant engineering application value in the field of underwater robots, but also has a positive promoting effect on the design of generalized control systems, the development of intelligent autonomous systems, and the intelligent process of Marine engineering equipment. This control framework provides a paradigm reference for robust control design in complex environments. The organic integration of H∞ theory with extended state observers and multi-model mechanisms provides theoretical support and practical paths for the stable control of systems in unstructured environments. It has cross-platform adaptability and is applicable to the path control tasks of other highly dynamic autonomous systems such as unmanned vessels, unmanned vehicles, and aircraft. Meanwhile, the real-time feedback and disturbance prediction mechanism of this strategy reflect the control trend of the synergy between intelligent perception and decision-making. The controller not only executes commands, but also has the ability to understand the environment and respond dynamically, which is in line with the technical logic of the integrated evolution of future intelligent equipment towards "perception - judgment - execution". In addition, the research results of this study can also provide key technical support for the intelligence of Marine equipment and remote autonomous operations. Especially in scenarios such as deep-sea exploration, polar observation, and submarine cable inspection, it is expected to enhance operational safety and task accuracy, and promote the independent development of high-performance control systems under the background of the maritime power strategy.

5.6 Deployment prospects and verification planning in real marine environments

Although the H∞-ESO fusion control strategy proposed in this paper shows strong path control accuracy and anti-disturbance ability in simulation and pool environments, its engineering performance in real complex sea conditions has not been fully verified. Future research will focus on promoting the deployment and evaluation of control algorithms in real Marine environments. It is planned to conduct field navigation tests in nearshore waters, set typical mission scenarios (such as tidal changes, local turbulence, and obstacle circumnavigation), obtain status data through high-frequency attitude sensing and underwater acoustic positioning systems, and evaluate key indicators such as control accuracy, response speed, and resource consumption. In addition, an attempt will be made to introduce a navigation assistance mechanism based on multimodal perception (such as DVL+IMU+ acoustic radar) to further improve the estimation accuracy of the observer in an uncertain environment. Through real-sea test verification, the robustness and generalization ability of the control system under working conditions such as high noise, low communication and high disturbance can be further examined, promoting the transition of this strategy to a practical-level control system.

6 Conclusion

This study focuses on the path tracking control problem of underwater robots in a complex nonlinear disturbance environment and proposes a composite control strategy that integrates H∞ robust control, extended state observer (ESO), and multi-model compensation mechanism. This method takes robustness as the core, combines dynamic disturbance estimation and model handover adjustment, and constructs a closed-loop control system with high adaptability and stability, which can effectively cope with the control challenges brought by environmental uncertainties and changes in system parameters. In terms of theoretical design, H∞ control provides a strong and robust guarantee. ESO realizes the dynamic observation and correction of disturbances and unmeasured states. The fusion of multiple models enhances the controller's ability to cope with task switching and changes in disturbance modes. The synergy of the three enables the control system to maintain stability while having strong precision adjustment capabilities and operational flexibility. The simulation analysis verified the applicability of this control strategy in multiple typical path scenarios and disturbed environments, showing good tracking continuity and control smoothness. It indicates that this method has achieved effective integration at the three levels of path control, disturbance compensation and state feedback, and has strong engineering practicability. Overall, the control method proposed in this study expands the technical boundaries of underwater robot path control in complex environments. It not only provides control support for enhancing the autonomous operation capabilities of intelligent equipment but also offers beneficial exploration for the future integrated development of robust control and intelligent observation mechanisms. Subsequently, in-depth research can be conducted in aspects such as controller lightweighting, observer adaptive optimization, and intelligent model reconstruction to further promote its efficient deployment and wide expansion to practical application systems.

Acknowledgment

We express our heartfelt gratitude to all individuals and organizations who contributed to the success of this research. Special thanks are extended to the mentors and collaborators whose expertise and guidance were invaluable throughout this work.We also acknowledge the support of institutions and organizations that provided resources and datasets, enabling the comprehensive evaluations discussed in this paper. Additionally, we are deeply grateful for the financial and infrastructural support provided by our respective institutions. Finally, we extend our sincere thanks to our families for their encouragement and patience during the course of this research.

Funding

The research is supported by: 2023 Special Fund for scientific Research Opening of Shandong Ship Control Engineering and Intelligent System Engineering Technology Research Center, Project number: SSCC20230001

References

[1] Zhang Y , Kong D , Shi Y ,et al.Recent progres s on underwater soft robots: adhesion, grabbing , actuating, and sensing[J].Frontiers in Bioengin eering and Biotechnology, 2023, 11(1):22.DOI: 10.3389/fbioe.2023.1196922.

[2] Kita T , Tanaka T , Suzuki H .Proposal Of Mov ing Method Of Underwater Robot With Wheels For Underwater Structure Inspection[J].Journal of Japan Society of Civil Engineers, Ser. B3 (O cean Engineering),2022.DOI:10.2208/jscejoe.7 8.2_i_13.

[3] Harada K , Fukuda R , Mizoguchi Y ,et al.Auto nomous Underwater Vehicle with Vision-based Navigation System for Underwater Robot Com petition[J].Proceedings of International Confere nce on Artificial Life and Robotics, 2022.DOI: 10.5954/icarob.2022.os28-2.

[4] Group S T .Underwater Robot Makes History C rossing Gulf Stream[J].Sea Technology: World wide Information Leader for Marine Business, Science & Engineering, 2004, 45(12).

[5] Zendehdel N , Gholami M .Robust Self-Adjustable Path-Tracking Control for Autonomous Underwater Vehicle[J].International Journal of Fuzzy Systems, 2020, 23(6–7).DOI:10.1007/s40815-020-00939-1.

[6] Hong S , Choi J S , Kim H W ,et al.A path tracking control algorithm for underwater mining vehicles[J].Journal of Mechanical Science & Technology, 2009, 23(8):2030-2037.DOI:10.1007/s12206-009-0436-y.

[7] Ni J , Wu L , Shi P ,et al.A Dynamic Bioinspired Neural Network Based Real-Time Path Planning Method for Autonomous Underwater Vehicles[J].Computational Intelligence and Neuroscience,2017,(2017-02-01), 2017, 2017:9269742.DOI:10.1155/2017/9269742.

[8] Bing H , Guo-Liang Z .Path tracking control of underactuated surface vessels based on the differential flatness[J].Journal of Harbin Engineering University, 2004.

[9] Takahashi Y , Yamamoto M , Wong K Y ,et al. Guaranteed Cost-Based Disturbance Observer and Controller Design for Path Tracking Control of a Powered Paraglider Under Unknown Rudder Trim and Wind Disturbances[J].IEEE Access, 2024, 12(000):14.DOI:10.1109/ACCESS.2024.3396464.

[10] Guo L , Guo P , Guan L M H .Model predictive path tracking control of intelligent vehicles based on dual-stage disturbance observer under multi-channel disturbances[J].Measurement Science & Technology, 2024, 35(10):106202-1-106202-18.DOI:10.1088/1361-6501/ad5ddc.

[11] Khodayari M H , Balochian S .Modeling and control of autonomous underwater vehicle (AUV) in heading and depth attitude via self-adaptive fuzzy PID controller[J].Journal of Marine Science and Technology, 2015, 20(3):559-578.DOI:10.1007/s00773-015-0312-7.

[12] Xie Y , Zhu A , Huang Z .Research on the Control Performance of Depth-Fixed Motion of Underwater Vehicle Based on Fuzzy-PID[J].Journal of Robotics, 2023.DOI:10.1155/2023/4168433.

[13] Le K D , Nguyen H D , Ranmuthugala D .Development and Control of a Low-Cost, Three-Thruster, Remotely Operated Underwater Vehicle[J]. International Journal of Automation Technology, 2015, 9(1):67-75.DOI:10.20965/ijat.2015.p0067.

[14] Lin C , Li B , Siampis E ,et al.Predictive Path-Tracking Control of an Autonomous Electric Vehicle with Various Multi-Actuation Topologies[J].Sensors (14248220), 2024, 24(5).DOI:10.3390/s24051566.

[15] Dung N M , Duy V H , Phuong N T ,et al.Two-Wheeled Welding Mobile Robot for Tracking a Smooth Curved Welding Path Using Adaptive Sliding-Mode Control Technique[J].International Journal of Control Automation and Systems, 2007, 5(3):283-294.DOI:10.1007/s00170-006-0487-5.

[16] He-Ming J , Xiang-Qin C , Li-Jun Z ,et al.Three-dimensional path tracking control for an underactuated AUV based on discrete-time sliding mode prediction[J].Kongzhi yu Juece/Control and Decision, 2011, 26(10):1452-1458.

[17] Liu C , Li T , Wu W ,et al.Event-triggered predictive path following control of autonomous ships with an MMG model[J].Ocean engineering, 2024(Dec.15 Pt.1):314.DOI:10.1016/j.oceaneng.2024.119582.

[18] Tich P , Lechta P , Maturana F P ,et al.Multi-agent technology for robust control of shipboard chilled water system[J].IFAC Proceedings Volumes, 2004, 37(10):303-308.DOI:10.1016/S1474-6670(17)31749-4.

[19] Chung K C , Chiu H C , Su K Y .Robust Control Technology of Autonomous Vehicle on Virtual Magnetic Track[J].SAE report, 2024, 000(4):6.DOI:10.4271/2024-01-2569.

[20] Frazier B W , Tyson R K , Kakad Y P ,et al.Robust Control of an Adaptive Optics System Using H∞ Method[J].Springer US, 2004.DOI:10.1007/978-1-4419-8945-1_13.

[21] Li X , Qi Y , Li S ,et al.A multi-input and single-output voltage control for a polymer electrolyte fuel cell system using model predictive control method[J].International Journal of Energy Research, 2021, 45(9).DOI:10.1002/er.6616.

[22] Galicki M .Finite-time control of mobile manipulators subject to unknown/unstructured external disturbances[J].International Journal of Robust and Nonlinear Control, 2023.DOI:10.1002/rnc.6486.

[23] Yatsun S , Mal'Chikov A , Lushnikov B ,et al. Wheel drive control system of an under-ice robot for monitoring underwater objects[J].Automation and modeling in design and management, 2023.DOI:10.30987/2658-6436-2023-2-58-68.

[24] Orucevic A , Wrzos-Kaminska M , Lys M E B ,et al.Automatic alignment of underwater snake robots operating in wakes of bluff bodies[J]. Control Engineering Practice, 2024, 147(000): 14.DOI:10.1016/j.conengprac.2024.105904.

[25] Wang Y C , Zhang S X , Cao L J ,et al.Adaptive fuzzy backstepping control for nonlinear system with unknown control direction and input saturation[J].Systems Engineering and Electronics, 2016.DOI:10.3969/j.issn.1001-506X.2016.09.26.

[26] Wen N , Liu Z , Wang W ,et al.Feedback linearization control for uncertain nonlinear systems via generative adversarial networks[J].ISA Trans

actions, 2024, 146(000):12.DOI:10.1016/j.isatra.2023.12.033.

[27] Liu D , Ouyang X , Zhao N ,et al.Adaptive Event-triggered Control with Prescribed Performance for Nonlinear System with Full-state Constraints[J].IAENG International Journal of Applied Mathematics, 2024, 54(3).

[28] Wang F , Long L , Xiang C .Switching Event-Triggered Adaptive Neural Network Control for Switched Nonlinear Systems Under Hybrid Attacks[J].IEEE transactions on systems, man, and cybernetics. Systems, 2024(10 Pt.1):54.DOI:10.1109/TSMC.2024.3418970.

[29] Cui K , He J , Yao X G X .Adaptive model predictive control based on stability index for path tracking of autonomous vehicles considering model error[J].Proceedings of the Institution of Mechanical Engineers, Part C. Journal of mechanical engineering science, 2024, 238(19):9372-9396.DOI:10.1177/09544062241256476.

[30] Mokhtari M R , Cherki B , Braham A C .Disturbance observer based hierarchical control of coaxial-rotor UAV[J].Isa Transactions, 2017, 67(Complete):466-475.DOI:10.1016/j.isatra.2017.01.020.

[31] Liu S , Yan Y , Ji H ,et al.Lateral Control of Autonomous Vehicles with Data Dropout via an Enhanced Data-driven Model-free Adaptive Control Algorithm[J].Journal of Highway and Transportation Research and Development, 2024, 18(1):38-45.DOI:10.26599/HTRD.2024.9480005.

[32] Gou H , Zhao F , Tang M ,et al.A Lung Image Deep Learning Detection Model Based on Cross Residual Attention and Multi-feature Fusion[J].Information Technology & Control, 2024, 53(3).DOI:10.5755/j01.itc.53.3.35708.

[33] Al-Hadithi B M , Adanez J M , Jimenez A .A multi-strategy fuzzy control method based on the Takagi-Sugeno model[J].Optimal Control Applications and Methods, 2023.DOI:10.1002/oca.2932.

[34] Chotikunnan R , Chotikunnan P , Imura P ,et al. The Utilization of Fuzzy Logic Controllers in Steering Control Systems for Electric Ambulance Golf Carts[J].International Journal of Robotics & Control Systems, 2024, 4(1).DOI:10.31763/ijrcs.v4i1.1333.

[35] Bhattacharyya M , Feissel P .A Bayesian inference approach for parametric identification through optimal control method[J].International Journal for Numerical Methods in Engineering, 2023.DOI:10.1002/nme.7242.

[36] Enol B , Demirolu U .Analyzing complex fractional order systems physical phenomena in IOPI controller design[J].Asian Journal of Control: Affiliated with ACPA, the Asian Control Professors, Association, 2024, 26(5):2324-2337.DOI:10.1002/asjc.3420.

[37] Losev A N , Zolkin A L , Kalyakina I M ,et al. Development of decision making support controller for automated control system of mechatronics complex[J].AIP Conference Proceedings, 2024, 2969(1):8.DOI:10.1063/5.0181740.

[38] Cao S G , Rees N W , Feng G .H∞ control of uncertain fuzzy continuous-time systems[J].Fuzzy Sets and Systems, 2000, 115(2):171-190.DOI:10.1016/S0165-0114(98)00396-0.

[39] Mitsioni I , Tajvar P , Kragic D ,et al.Safe Data-Driven Model Predictive Control of Systems With Complex Dynamics[J].Robotics, IEEE Trans. on (T-RO), 2023, 39(4):17.DOI:10.1109/TRO.2023.3266995.

[40] Li G , Liu L , Liu J ,et al.Three-dimensional low-order fixed-time integrated guidance and control for STT missile with strap-down seeker[J].Journal of the Franklin Institute, 2023.DOI:10.1016/j.jfranklin.2023.07.028.