

Research on Dual-Loop Sliding Mode Heading Control for ROVs Based on a Nonlinear Disturbance Observer

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Abstract: In order to solve the issues of strong nonlinearity, underactuation, strong coupling, complex external disturbances, and difficulties in accurate modeling in ROVs, This paper addresses these challenges by designing a cascaded heading controller in which two sliding mode loops cooperate with a nonlinear disturbance observer (NDO). Heading angle regulation is assigned to the outer loop, whereas yaw-rate regulation is handled by the inner loop. Acting in real time, the NDO reconstructs the lumped disturbance and feeds a compensation signal into the control channel, thereby strengthening the robustness of the closed loop. The inner-loop uses a modified double power reaching law to dynamically adjust the reaching speed and achieve fast convergence and chattering suppression. Both loops adopt integral sliding mode surfaces, which improve tracking accuracy, dynamic response, and control smoothness. The joint stability of the observer–controller combination is established within the Lyapunov framework; the analysis guarantees a faster convergence rate for the inner loop than for the outer loop, so that overall stability and heading tracking accuracy are preserved. Theoretical results indicate satisfactory disturbance rejection performance, and the scheme is suitable for engineering implementation.

Keywords: Heading Control; Disturbance Observer; Sliding Mode Control; Reaching Law; Robustness

1. Introduction

The 21st century is the century of ocean exploration. As one type of underwater vehicle, ROVs play a very important and crucial role in various marine production activities. However, the heading dynamics of an ROV involve pronounced nonlinearity, underactuation and

inter-channel coupling; moreover, the vehicle is constantly exposed to time-varying environmental loads, so an accurate dynamic model is rarely available in practice. The design of a controller with good stability and with strong robustness for this controlled system has become a hot topic in control engineering.

In the last 10 years, great advances have been made in control of robotic systems with model errors, external disturbances and other uncertainties. For example, Wang et al. [1] improved the TD and ESO modules in ADRC and applied them to the forward flight mode of a quadrotor, achieving good control performance; Wei et al.[2] proposed an NDO-based adaptive terminal sliding mode control method for ROVs and used a Lyapunov function to assess stability; Tan and Jin [3] combined a traditional high-order extended disturbance observer with a sliding mode controller and provided stability analysis and parameter design principles. Luo et al. [4] combined ESO with dual-loop integral sliding mode control and compared it with ISMC and OESO-DSMC, and showed that the transient performance of the ESO with dual-loop integral sliding mode control is improved; Wei et al. [5] presented an NDO-based adaptive single integral backstepping controller for ROVs, which showed good tracking performance, while Ali et al. [6] employed a third-order finite-time extended state observer together with a nonsingular fast terminal sliding mode law, establishing finite-time stability of AUV position and attitude trajectories through Lyapunov arguments. A dual-loop sliding mode control strategy with a high-gain disturbance observer for load tracking of a pressurized water reactor in the presence of external disturbances was proposed in Hui and Yuan[7]. Qin et al.[8] improved the CFal function, verified the feasibility of the CFalFilter and the nonlinear extended state observer CFal_NESO, designed a novel observer CFalFilter_CFal_NESO, and conducted

comparative experiments, showing that it is applicable to both nonlinear and high-order systems. In Yan et al.[9] the properties of a quadratic function were used to create a nonlinear piecewise function cfal to replace the fal function in an ESO, and a time-varying ESO was designed, with its stability being proven by applying a Lyapunov function. Lu et al.[10] dealt with the vertical plane motion of a submarine, proposed a sliding mode controller designed with an improved double power reaching law and a full-dimensional state observer, compared its control performance with that of a PID controller through simulation and demonstrated the superiority of the sliding mode controller.

Motivated by the works reviewed above, this paper makes the following contributions:

- 1) A dual closed-loop control structure combining a nonlinear disturbance observer with dual-loop sliding mode control is proposed for the heading mathematical model of an ROV. The outer-loop sliding mode controller is used for heading angle tracking whereas the inner-loop sliding mode controller is used for angular velocity tracking. In real time, the NDO estimates and compensates for external disturbances and model uncertainties, which significantly improves the robustness and disturbance rejection capability of the system.
- 2) A modified double power reaching law is formulated for the velocity loop. It automatically adjusts the reaching speed dynamically, achieving both fast response and chattering suppression, thereby solving the trade-off between convergence speed and smoothness in traditional reaching laws.
- 3) Integral sliding mode surfaces in both the outer and inner loops are used. With the dual-loop structure, the outer-loop enhances tracking accuracy, and the yaw-rate regulation enhances dynamic response. The introduction of the integral term further suppresses the chattering effects in SMC and improves the smoothness of the control input. Furthermore, the cooperative stability of the dual-loop sliding mode controller and the nonlinear disturbance observer is strictly proved by a Lyapunov function, ensuring that the yaw-rate regulation converges faster than the outer one, thus theoretically guaranteeing the stability and tracking performance of the global system.

2. Mathematical Model of ROV Heading Motion

Following the notation recommended by the

International Towing Tank Conference (ITTC) and the Society of Naval Architects and Marine Engineers (SNAME), the yaw dynamics of the ROV can be described as:

$$\begin{cases} \dot{\psi} = r \\ \dot{r} = \frac{\tau_{\psi}}{I_z - N_r} + \frac{N_{r|\dot{\psi}|}}{I_z - N_r} r |r| + d \end{cases} \quad (2)$$

Where, ψ and r denote the heading angle and the yaw rate; I_z is the moment of inertia of the vehicle about the vertical axis of the motion coordinate frame; N_r and $N_{r|\dot{\psi}|}$ are the first-order and second-order hydrodynamic parameters, respectively, d represents model errors, external disturbances, and other uncertainties, and τ_{ψ} is the thrust input.

To streamline the subsequent observer and controller synthesis, model (1) is recast into the standard second-order state-space form widely adopted in modern control theory:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = f(x_1, x_2) + g u_t + d \end{cases} \quad (3)$$

Where, $x_1 = \psi, x_2 = r, f(x_1, x_2) = \frac{N_{r|\dot{\psi}|}}{I_z - N_r} r |r|, g = \frac{1}{I_z - N_r}, u_t = \tau_{\psi}$.

3. Design of Heading Motion Controller

Figure 1 depicts the overall structure of the proposed cascaded scheme, which comprises three functional units: an NDO and two sliding mode controllers arranged in series. The specific process is as follows: the desired signal ψ_c enters the outer-loop controller, whose output serves as the virtual yaw-rate command r_c . The inner-loop controller then computes a preliminary control action u_{st} from the mismatch e_r between this virtual command and the measured yaw rate. The nonlinear disturbance observer generates the disturbance control output u_f . Considering the difference between the initial control output and the disturbance control output as the actual control input u_t , which acts on the ROV, the ROV feeds back x_1, x_2 to both loops to realize dual closed-loop control.

3.1 Nonlinear Disturbance Observer

When an ROV performs underwater operations, it usually suffers from complex and diverse external disturbance forces and model uncertainties, such as external ocean currents and the reaction force of the umbilical cable. While disturbance observation offers an effective means of counteracting such effects. Accordingly, the following basic NDO structure is introduced:

$$\begin{cases} \dot{z} = -Lz + L(-p(x_2) - f(x_1, x_2) - gu_t) \\ \hat{d} = z + p(x_2) \end{cases} \quad (3)$$

Here, z denotes the internal state of the observer, $p(x_2)$ is an auxiliary nonlinear function of x_2 to be determined, and $\hat{d}$ is the estimate of the lumped disturbance d . L is the observer gain matrix, expressed as:

$$\frac{dp(x_2)}{dx_2} = L\dot{x}_2 \quad (4)$$

The estimation error of the observer is defined as:

$$\begin{cases} z_d = d - \hat{d} \\ \dot{z}_d = \dot{d} - \dot{\hat{d}} = -\dot{\hat{d}} \\ \dot{\hat{d}} = 0 \end{cases} \quad (5)$$

Where, z_d is the observer error, $\dot{z}_d$ is the derivative of the observer error. Since in general it is impossible to obtain the first derivative of the external disturbance d , and the external disturbance d usually changes very slowly, it can be set to 0.

Substituting (3) into the second sub-equation of (5) yields

$$\dot{z}_d = -\dot{\hat{d}} = -\dot{z} - \dot{p}(x_2) = -\dot{z} - L\dot{x}_2 = -Lz_d \quad (6)$$

Taking L as a constant and $L > 0$, solving (6)

gives

$$z_d(t) = z_d(0)e^{-Lt} \quad (7)$$

Where, z_d converges exponentially to 0 with time, i.e., $\lim_{t \rightarrow +\infty} z_d(0)e^{-Lt} = 0$. Performing a gain transformation on the second sub-equation of (2) yields

$$\begin{cases} \dot{x}_2 = f(x_1, x_2) + g(u'_t + \frac{\hat{d}}{g}) \\ u'_t = u_t + \frac{z_d}{g} \\ u_f = \frac{\hat{d}}{g} \end{cases} \quad (8)$$

Where, u'_t is an intermediate variable of the control output. Substituting the third sub-equation of (8) into the second sub-equation of (2) yields

$$\dot{x}_2 = f(x_1, x_2) + g(u_{st} - u_f) + d = f(x_1, x_2) + gu_{st} + z_d \quad (9)$$

After rearrangement and substitution into (2), we obtain

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = f(x_1, x_2) + gu_{st} + z_d \end{cases} \quad (10)$$

By introducing the nonlinear disturbance observer, the effects of model errors, external disturbances, and other uncertainties can be reduced.

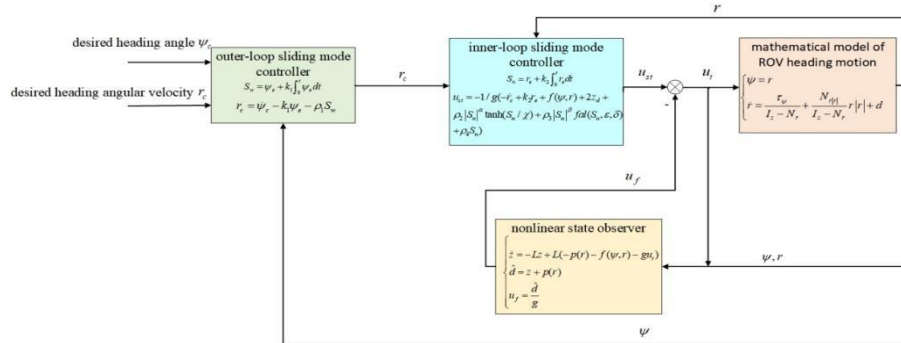


Figure 1. Structure of the Proposed NDO-based Dual-loop Sliding Mode Heading Control System

3.2 Outer-Loop Position Controller

For the outer loop, an integral-type sliding surface is selected. This loop is responsible for regulating the heading angle ψ toward its reference and outputs the desired yaw rate r_c ; it is therefore referred to as the position loop.

The outer-loop sliding mode surface and the heading angle error are defined as:

$$\begin{cases} S_w = \psi_e + k_1 \int_0^t \psi_e dt \\ \psi_e = \psi - \psi_c \end{cases} \quad (4)$$

Where, S_w is the outer-loop sliding mode surface, k_1 is the integral gain and $k_1 > 0$, and ψ_e measures the deviation of the actual heading

ψ from its command ψ_c .

Differentiating (11) yields

$$\dot{S}_w = \dot{\psi}_e + k_1 \psi_e = \dot{\psi} - \dot{\psi}_c + k_1 \psi_e \quad (5)$$

The disadvantage of the outer-loop surface alone does not provide $\ddot{\psi}$, resulting in the inability to obtain the actual initial control variable τ_{st} . This problem is resolved by the inner-loop sliding mode surface. Taking the desired heading angular velocity r_c as the virtual control term, we have:

$$\begin{cases} r_e = r - r_c \\ \dot{\psi} = r_c + (r - r_c) = r_c + r_e \end{cases} \quad (6)$$

Substituting the second sub-equation of (13) into (12) yields

$$\dot{S}_w = r_c + r_e - \dot{\psi}_c + k_1 \psi_e \quad (7)$$

The virtual outer-loop control term is designed as:

$$r_c = \dot{\psi}_c - k_1 \psi_e - \rho_1 S_w \quad (8)$$

Where, $\rho_1 > 0$.

The following Lyapunov function is defined as:

$$V_1 = \frac{1}{2} S_w^2 \quad (9)$$

Differentiating (16) yields

$$\dot{V}_1 = S_w \dot{S}_w = S_w (-\rho_1 S_w + r_e) = -\rho_1 S_w^2 + r_e S_w \leq 0 \quad (10)$$

For (17), to ensure $V_1 \leq 0$, the heading angular velocity error r_e needs to be sufficiently small.

This requires designing the inner-loop sliding mode controller to converge faster than the outer-loop sliding mode controller.

3.3 Inner-Loop Velocity Controller

Within the cascaded structure, how faithfully the measured yaw rate r follows its command r_c directly governs the achievable heading accuracy. Considering the error of the nonlinear disturbance observer, an inner-loop sliding mode controller is designed to ensure that when $t \rightarrow +\infty$, $r_e \rightarrow 0$. Similarly, the integral sliding mode control is adopted to design the inner-loop sliding mode surface as:

$$S_n = r_e + k_2 \int_0^t r_e dt \quad (11)$$

Where, S_n is the inner-loop sliding mode surface, and k_2 is the integral gain and $k_2 > 0$.

Differentiating (18) yields

$$\dot{S}_n = \dot{r}_e + k_2 r_e = \dot{r} - \dot{r}_c + k_2 r_e \quad (12)$$

Substituting the second sub-equation of (10) into (19) yields

$$\dot{S}_n = f(x_1, x_2) + g u_{st} + z_d - \dot{r}_c + k_2 r_e \quad (13)$$

The inner-loop control input is structured as:

$$u_{st} = u_{eq} + u_{sn} \quad (14)$$

Where, u_{eq}, u_{sn} represent the equivalent and switching components, respectively. In this paper, the improved double power reaching law is adopted for the switching component:

$$\begin{cases} u_{sn} = -\frac{1}{g}(\rho_2 |S_n|^{\alpha} \tanh(S_n / \chi) + \rho_3 |S_n|^{\beta} \text{fal}(S_n, \varepsilon, \delta) / \chi + \rho_4 S_n) \\ \text{fal}(S_n, \varepsilon, \delta) = \begin{cases} \frac{S_n}{\delta^{1-\varepsilon}}, & |S_n| \leq \delta \\ |S_n|^{\varepsilon} \text{sgn}(S_n), & |S_n| > \delta \end{cases} \end{cases} \quad (15)$$

Where, $\rho_2 > 0$, $\rho_3 > 0$, $\rho_4 > 0$, $\alpha > 1$, $0 < \beta < 1$, $\varepsilon > 0$, $\delta > 0$, χ is the boundary layer thickness,

and $\tanh(\Delta) = \frac{e^{\Delta} - e^{-\Delta}}{e^{\Delta} + e^{-\Delta}}$ is the hyperbolic tangent

function. When the heading angular velocity r is far from the inner-loop sliding mode surface

S_n , i.e., $|S_n| > 1$, the term $\rho_2 |S_n|^{\alpha} \tanh(S_n / \chi)$ plays the main switching role, and $\rho_4 S_n$ accelerates the convergence speed of the switching term. Obviously, when the heading angular velocity r is close to the inner-loop sliding mode surface S_n , i.e., $|S_n| \leq 1$, $\rho_3 |S_n|^{\beta} \text{fal}(S_n, \varepsilon, \delta)$ plays the main switching role. Borrowed from active disturbance rejection control, the $\text{fal}(\cdot)$ saturation function embodies the idea of “large gain for small errors and small gain for large errors”, which the plain signum function $\text{sgn}(\cdot)$ lacks. The parameter ε determines the degree of nonlinearity of the function; generally, the smaller ε is, the higher the degree of nonlinearity. The parameter δ determines the width of the linear interval of the $\text{fal}(\cdot)$ function; generally, the larger δ is, the higher the degree of linearization.

To highlight its advantages, the proposed reaching law is first benchmarked against four classical ones, namely the constant-rate, exponential, power and conventional double power reaching laws. The respective sliding mode variables are:

$$\begin{cases} \dot{S} = -k' \text{sgn}(S) \\ \dot{S} = -k' \text{sgn}(S) - \lambda S \\ \dot{S} = -k' |S|^{\alpha_1} \text{sgn}(S) \\ \dot{S} = -k' |S|^{\alpha_1} \text{sgn}(S) - k'' |S|^{\alpha_2} \text{sgn}(S) \end{cases} \quad (16)$$

Where, $k' > 0, k'' > 0, \lambda > 0, \alpha_2 > 1 > \alpha_1 > 0$. The constant reaching law always approaches the sliding mode surface at a constant speed, yielding linear convergence. The exponential reaching law combines linear and exponential terms, so that the curve converges rapidly in the initial stage and stabilizes smoothly in the later stage. The power reaching law (with exponent α_1) and the double power reaching law (with exponents α_1, α_2) adjust the reaching speed, making the reaching speed fast when the system state is far from the sliding mode surface and smooth when it is close to it. With the parameters selected as $k' = 2, k'' = 2, \lambda = 1, \alpha_1 = 0.5, \alpha_2 = 1.1$, the comparison of the five reaching laws is shown in Figure 2.

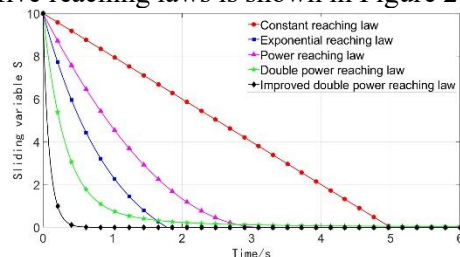


Figure 2. Comparison of Reaching Laws
The inner-loop control law incorporating the

improved reaching law is:

$$u_{st} = -\frac{1}{g}(-\dot{r}_c + k_2 r_e + f(x_1, x_2) + 2z_d + \rho_2 |S_n|^\alpha \tanh(S_n / \chi) + \rho_3 |S_n|^\beta \text{fal}(S_n, \varepsilon, \delta) + \rho_4 S_n) \quad (17)$$

The following Lyapunov function is considered:

$$V_2 = \frac{1}{2} S_n^2 \quad (18)$$

Differentiating (25) yields

$$\dot{V}_2 = S_n \dot{S}_n = -z_d S_n - \rho_2 |S_n|^{\alpha+1} \tanh(S_n / \chi) - \rho_3 |S_n|^{\beta+1} \text{fal}(S_n, \varepsilon, \delta) - \rho_4 S_n^2 \leq -\rho_2 |S_n|^{\alpha+1} \tanh(S_n / \chi) - \rho_3 |S_n|^{\beta+1} \text{fal}(S_n, \varepsilon, \delta) - \rho_4 S_n^2 \leq -\rho_4 S_n^2 \quad (19)$$

Further simplification yields

$$\begin{cases} \dot{V}_2 \leq -2\rho_4 V_2 \\ V_2(t) \leq V_2(0)e^{-2\rho_4 t} \end{cases} \quad (20)$$

Where, when $t \rightarrow +\infty$, $V_2(t) \rightarrow 0$ converges exponentially and the convergence rate is related to ρ_4 .

Combining Sections 2.2 and 2.3, when $S_n \rightarrow 0$, then $r_e \rightarrow 0$; when $S_w \rightarrow 0$, then $\psi_e \rightarrow 0$. Furthermore, according to (15), $r_c \rightarrow \dot{\psi}_c$, and thus $r \rightarrow \dot{\psi}_c$. According to Lyapunov stability analysis, when the inner-loop parameters $t \rightarrow +\infty$, $k_2 \geq k_1$ and ρ_4 is sufficiently large, the both loops can

$$\begin{cases} d = 50 \sin(0.025\pi t) + 3 \frac{2}{\pi} \arctan(\psi) + 1.5\psi + 0.5rand + \\ \quad 5 \operatorname{sgn}(\sin(0.1\pi t)) + 10y(t) + 8\delta(t)(N \cdot m) \\ \quad y(t) \sim N(0, 0.25) \\ \quad \delta(t) = \begin{cases} +\infty, t = 0 \\ 0, t \neq 0 \end{cases}, \int_{-\infty}^{+\infty} \delta(t)dt = 1 \end{cases} \quad (21)$$

Where, *rand* is a random number between the given values, $y(t)$ represents zero-mean Gaussian white noise with a standard deviation of 0.5, and $\delta(t)$ is a continuous pulse function. Considering practical conditions, the controller output is limited to $(-150, 150)(kgf \cdot m)$. The simulation time is set to 150 s with a fixed-step solver whose fundamental step size is 0.001 s. The ROV model parameters are $I_z = 125.0, N_r = -152.4, N_{r|l} = -77.3$; the controller parameters are $L = 3, k_1 = 0.1, k_2 = 10, \rho_1 = 5, \rho_2 = 5, \rho_3 = 100, \rho_4 = 10, \chi = 1960, \alpha = 3, \beta = 0.1, \varepsilon = 0.1, \delta = 0.01$. The control effects are shown in Figure 3 and Figure 4. Comparative simulations are carried out with the nonlinear disturbance observer-based adaptive terminal sliding mode control (NDO-ATSMC) proposed in Wei et al.[2] and the nonlinear disturbance observer-based adaptive integral backstepping control (NDO-AIBC) proposed in Wei et al.[5]. The dual-loop sliding mode control quickly tracks the filtered desired heading angle during the control phase, and the tracking trajectory is stable and smooth without overshoot. Its control performance is superior to that of NDO-AIBC, with a smaller tracking error,

simultaneously satisfy stability, and the inner-loop converges faster than the outer-loop.

4. Simulation Verification

1) In order to verify the effect of the dual-loop sliding mode control based on the nonlinear disturbance observer proposed in this paper in continuous large heading angle motion control, a simulation environment was built in MATLAB/Simulink. Assume that the desired continuous large heading angle of the ROV is:

$$\psi_{cl} = \begin{cases} 30^\circ, 0 < t \leq 30 \\ 60^\circ, 30 < t \leq 60 \\ 120^\circ, 60 < t \leq 90 \\ 50^\circ, 90 < t \leq 120 \\ 0^\circ, 120 < t \leq 150 \end{cases} \quad (21)$$

At this time, the heading angular velocity is 0, so the original desired heading angle needs to be filtered. A low-pass filter $G_2(s) = \frac{1}{8s+1}$ is selected, incorporating the improved reaching law is 0.2 rad with zero yaw rate. The model errors, external disturbances, and other uncertainties d are:

and is slightly better than that of NDO-ATSMC, demonstrating excellent overall performance.

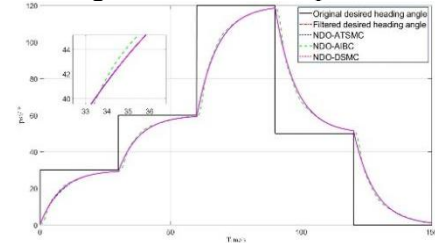


Figure 3. Comparison of Trajectory Tracking for Continuous Large Heading Angle

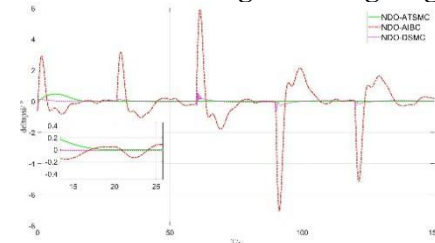


Figure 4. Comparison of Trajectory Tracking Errors for Continuous Large Heading Angle

2) A sinusoidal tracking scenario is further examined to evaluate the proposed scheme in general heading maneuvers, again on a MATLAB/Simulink platform. Assume that the desired heading angle trajectory given for ROV

heading motion is $\psi_{c2} = 8\sin(0.05\pi t)$ (rad). The responses are given in Figure 5 to Figure 7. Comparative simulations are carried out with the nonlinear disturbance observer-based adaptive terminal sliding mode control (NDO-ATSMC) proposed in Wei et al.[2] and the nonlinear disturbance observer-based adaptive integral backstepping control (NDO-AIBC) proposed in Wei et al.[5].

As illustrated, the proposed controller tracks both the heading angle and the yaw rate with high fidelity, and its control moment varies more smoothly than those of the two benchmarks. This benefit stems from the NDO, which reconstructs the lumped disturbance with high accuracy and thus prevents d from deteriorating the control action. In addition, owing to the improved double power reaching law embedded in the inner loop, the velocity channel converges rapidly, while the integral-augmented surfaces of the two loops jointly refine the tracking precision and the transient behavior.

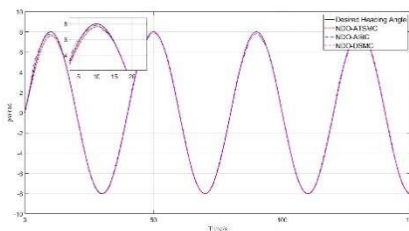


Figure 5. Comparison of Heading Angle Trajectory Tracking

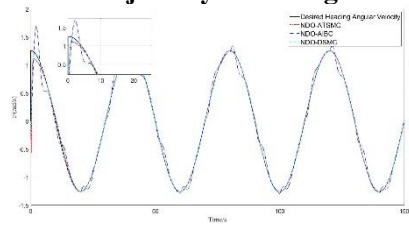


Figure 6. Comparison of Heading Angular Velocity Trajectory Tracking

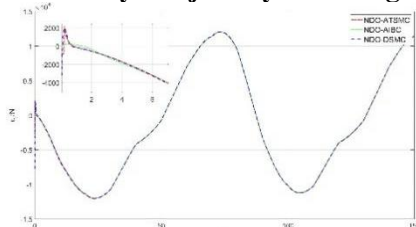


Figure 7. Comparison of Controller Thrust Output

The external disturbance d before and after filtering is shown in Figure 8 and the low-pass filter transfer function adopted is $G_2(s) = \frac{1}{10s+1}$. The observation effects of the nonlinear disturbance observer are shown in Figure 9 and Figure 10.

Comparative simulations are carried out with the nonlinear disturbance observer-based adaptive terminal sliding mode control (NDO-ATSMC) proposed in Wei et al.[2] and the nonlinear disturbance observer-based adaptive integral backstepping control (NDO-AIBC) proposed in Wei et al.[5]. The comparison results are shown in Figure 8 to Figure 10. The nonlinear observer designed in this paper is closer to the actual disturbance value than the other two observers, but its observation error is larger than that of NDO-ATSMC and less smooth than that of NDO-AIBC.

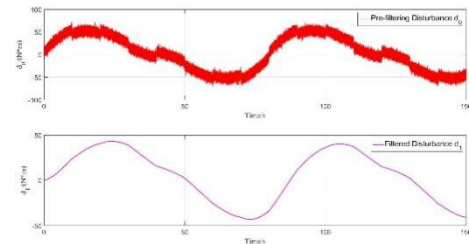


Figure 8. Comparison of External Disturbance d before and after Filtering

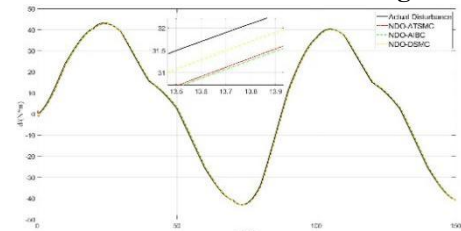


Figure 9. Comparison of Nonlinear Disturbance Observer Outputs

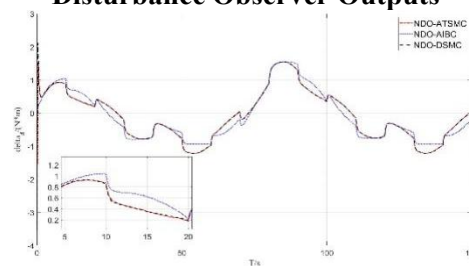


Figure 10. Comparison of Nonlinear Disturbance Observer Observation Errors

5. Conclusion

The problem of external disturbances and model uncertainties in the ROV's heading motion control system during underwater operations is mainly solved by developing a cascaded sliding mode controller augmented with an NDO. Initially, it was inspired by nonlinear observers in modern control theory and by domestic and foreign studies on nonlinear disturbance observers. While the cascaded configuration is inspired by structures commonly adopted in quadrotor flight control. By embedding a hybrid

reaching law—combining the merits of the exponential and double power laws—into the velocity loop, the controller inherits a rapid initial approach, a gentle final settling, and a distance-dependent switching behavior. The integral actions included in both loops further alleviate the chattering that typically accompanies sliding mode schemes. Simulation studies demonstrate that the resulting algorithm outperforms two representative benchmarks, NDO-ATSMC and NDO-AIBC, in terms of tracking accuracy and smoothness of the control signal. Future work will focus on experimental validation on a physical ROV platform and on adaptive tuning of the reaching-law parameters.

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