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Research Article

Adaptive Terminal Sliding Mode NDO-Based Control of Underactuated AUV in Vertical Plane

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The depth tracking issue of underactuated autonomous underwater vehicle (AUV) in vertical plane is addressed in this paper. Considering the complicated dynamics and kinematics model for underactuated AUV, a more simplified model is obtained based on assumptions. Then a nonlinear disturbance observer (NDO) is presented to estimate the external disturbance acting on AUV, and an adaptive terminal sliding mode control (ATSMC) based on NDO is applied to enhance the depth tracking performance of underactuated AUV considering both internal and external disturbance. Compared with the traditional sliding mode controller, the static error and chattering problem of the depth tracking process have been clearly improved by adopting NDO-based ATSMC. The stability of control system is proven to be guaranteed according to Lyapunov theory. In the end, simulation results imply that the proposed controller owns strong robustness and satisfied control effectiveness in comparison with the traditional controller.

1. Introduction

Autonomous underwater vehicle (AUV) is a kind of underwater vehicles with onboard power supply and intelligence. Due to its autonomous ability, AUV has become a very hot research topic in the past few decades for its wide applications in ocean scientific survey, emergency rescue, and military mission, such as gas and mine sources detection, marine environment research, and observation and manipulation task of military [1–3]. Traditionally, fully actuated AUVs are applied to underwater missions in the ocean. The trait of fully actuated AUVs is that the number of actuators equals degrees of freedom (DOF). However, with the development of ocean equipment, underactuated AUVs play more and more important role in marine tasks, whose degrees of freedom (DOF) are more than actual control inputs. In practical occasions, many AUVs are actually underactuated as they lack thrusters or other actuators in the heave or sway directions, and when the actuator failures of fully actuated AUVs occur, they will also transform into underactuated states. A significant advantage for underactuated AUV is that its own weight can be decreased due to less actuators and sensors. However, these underactuated AUVs bring a challenging control issue considering their lack of actuators. Furthermore, they own highly coupled and strongly nonlinear kinematic and dynamic models [4]. Therefore, various controllers for underactuated AUV need to estimate and deal with uncertainties, hydrodynamic effects, inherent nonlinearity, and so on.

Trajectory tracking in the vertical plane is one of the essential research problems for underactuated AUVs; many researchers have concentrated upon this control problem. Subudhi et al. [2] proposed an output feedback controller to complete AUV's path tracking task in its vertical plane according to a linearized motion model. Cristi et al. [5] applied sliding mode approach to overcome dynamical uncertainties of AUV in a diving maneuver; Lapierre [6] presented a robust diving control technique based on adaptive backstepping technique and switching schemes, which could meet the robustness requirement; Naik and Singh [7] treated the suboptimal control issue of underactuated AUV by using SDRE technique, and AUV showed satisfactory performance in spite of system's uncertainties and other constraints. Loc et al. [8] used an analytical method based on sliding mode control technique to obtain the optimal trajectory for unmanned underwater vehicle, which made the vehicle follow the desired trajectory as well. Adhami-Mirhosseini et al. [9] put forward a controller combining Fourier series and pseudo-spectral thoughts to solve the bottom tracking problems for AUV. Lakhekar et al. constructed an enhanced dynamic fuzzy SMC to improve the control performance of AUV's depth following mission [10].

Sliding mode control (SMC) is noticed for its strong robustness against various disturbances and uncertainties in the application of controllers [11]. Due to this, SMC has been widely used by many researchers in different systems [12–14], such as the inverted-pendulum control systems, and motion control systems for underwater vehicles. Jia et al. [15] built an iterative nonlinear sliding mode (INSM) controller to achieve bottom-following of underactuated AUV; Lakhekar and Saundarmal [16] introduced a novel fuzzy sliding mode controller for AUV's depth control task. SMC can handle system's uncertainties in a robust way. However, SMC is limited for its dependence on the plant model. To overcome this disadvantage, lots of controllers based on adaptive thoughts are introduced. Adaptive control algorithm is an efficient way to enhance the performance of AUV's tracking controllers [17]. Antonelli et al. [18] proposed an adaptive controller for ODIN AUV; Yu et al. [19] used adaptive technique on the basis of neural networks to control AUV; Zhang et al. [20] constructed an adaptive output feedback controller combined with DRFNN method to realize the tracking control target of AUV. Disturbance is another key factor which affects AUV, and it is always unpredictable, nonperiodic, and even highly nonlinear. Nonlinear disturbance observer (NDO) [21] is an effective method to reduce the bad influence of unknown external disturbance on the plant. Accounting for this, NDO has been widely applied into estimating and compensating disturbances in many areas, such as manipulators and motors [22, 23]. The application of NDO in underactuated AUV is crucial to handle with the unexpected condition in presence of disturbance.

In this paper, an adaptive sliding mode controller based on NDO is introduced to solve the depth tracking problems of AUV. Firstly, the mathematical model of underactuated AUV in the vertical plane is described and simplified. Secondly, a NDO is built with reference to the above AUV's model, and an adaptive terminal sliding mode control (ATSMC) method considering NDO is presented as well. The system's stability is proven by choosing appropriate Lyapunov functions in the controller's construction process. Finally, the simulation experiments verify the effectiveness of the proposed controller, and the robustness of underactuated AUV's depth tracking in the vertical plane is shown in the case of external disturbance.

2. Mathematical Model of Underactuated AUV

The frame coordinate systems' schematic drawing for the mathematical model of underactuated AUV is shown in Figure 1; the reference frame o_E-$x_E y_E z_E$ is fixed on the earth, wherein ϕ, θ, and φ are the roll angle, pitch angle, and yaw angle, respectively, in this reference frame; the body-fixesd reference frame o_B-$x_B y_B z_B$ is fixed on the underactuated AUV; its origin o_B is located at AUV's center of buoyancy,

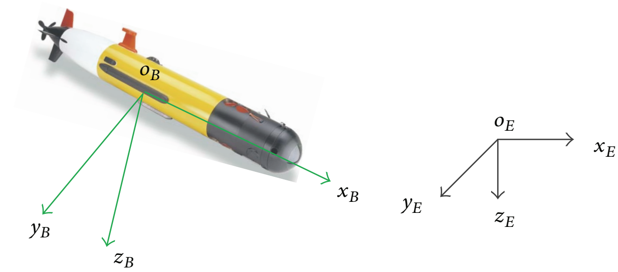

Figure 1: Coordinate systems of underactuated AUV.

wherein u, v, w, p, q, and r are the surge velocity, sway velocity, heave velocity, roll angular velocity, pitch angular velocity, and yaw angular velocity, respectively, in the body-fixed reference frame.

As underactuated AUV is a highly nonlinear and coupled system, its kinematics and dynamics equations in the vertical plane are constituted of a few nonlinear equations, which can be expressed in the following forms [7]:

$$
\begin{aligned}
\dot{z} &= w\cos\theta - u\sin\theta, \\
\left(m - Z_{\dot{w}}\right)\dot{w} &= Z_{\dot{q}}\dot{q} + m\left(uq + x_G\dot{q} + z_G q^2\right) + Z_{uq}uq \\
&\quad + Z_{uw}uw + Z_{w|w|}w\left|w\right| + Z_{q|q|}q\left|q\right| \\
&\quad + \left(W_{\text{eig}} - B_{\text{uo}}\right)\cos\theta + Z_{uu}u^2\delta_s, \\
\dot{\theta} &= q, \\
\left(I_{yy} - M_{\dot{q}}\right)\dot{q} &= m\left[x_W\left(\dot{w} - uq\right) - z_G wq\right] + M_{\dot{w}}\dot{w} \\
&\quad + M_{uq}uq + M_{uw}uw + M_{w|w|}w\left|w\right| \\
&\quad + M_{q|q|}q\left|q\right| \\
&\quad - \left(x_W W_{\text{eig}} - x_B B_{\text{uo}}\right)\cos\theta \\
&\quad - \left(z_W W_{\text{eig}} - z_B B_{\text{uo}}\right)\sin\theta \\
&\quad + M_{uu}u^2\delta_s + D_{\text{out}},
\end{aligned}
\tag{1}
$$

where I_{yy} is the inertial movement of AUV about the pitch axis y_B, m is the mass of AUV, (x_W, y_W, z_W), (x_B, y_B, z_B) are the coordinates of AUV's mass center and buoyancy center, respectively, in the body-fixed frame o_B-$x_B y_B z_B$, z is the diving depth of AUV in the frame o_E-$x_E y_E z_E$, W_{eig} is the weight of AUV, B_{uo} is the buoyancy of AUV in the water, D_{out} is the disturbance from the outside environment, δ_s is the rudder input, M_{uu}, Z_{uu} are the coefficients of rudder, and $Z_{\dot{w}}, Z_{\dot{q}}, Z_{uq}, Z_{uw}, Z_{w|w|}, Z_{q|q|}, M_{\dot{q}}, M_{\dot{w}}, M_{uq}, M_{uw}, M_{w|w|}$, $M_{q|q|}$ are the hydrodynamics coefficients of AUV.

Aiming at simplifying the controller design for underactuated AUV, the effect of heave velocity w is neglected by assuming $w \approx 0, \dot{w} \approx 0$; according to the definition of body-fixed frame o_B-$x_B y_B z_B$, it is obvious that $x_B = y_B = z_B = 0$. It is assumed that the surge velocity u keeps a constant value as $u = U_c$, $U_c > 0$ with the help of main thruster mechanism.

Define $x_1 = z$, $x_2 = \theta$, and $x_3 = q$; the previous equations would be replaced by a new one:

$$\begin{aligned} \dot{x}_1 &= -U_c x_2 + D_1, \\ \dot{x}_2 &= x_3, \\ \dot{x}_3 &= M_1 x_3 + M_2 \sin x_2 + M_3 \delta_s + M_4 \left| x_3 \right| x_3 \\ &\quad + M_5 \cos x_2 + D_2, \end{aligned} \tag{2}$$

where $M_1 = M_{uq}U_c/(I_{yy} - M_{\dot{q}})$, $M_2 = -z_W W_{\text{eig}}/(I_{yy} - M_{\dot{q}})$, $M_3 = M_{uu}U_c^2/(I_{yy} - M_{\dot{q}})$,$M_4 = M_{q|q|}/(I_{yy} - M_{\dot{q}})$, $M_5 = -x_W W_{\text{eig}}/(I_{yy} - M_{\dot{q}})$, $D_1 = U_c(x_2 - \sin x_2)$, and D_1 is regarded as internal disturbance of state equations, $D_2 = D_{\text{out}}/(I_{yy} - M_{\dot{q}})$, and D_2 is regarded as external disturbance of state equations, which is also the main disturbance for the system.

3. Terminal Sliding Mode Control Based on NDO

3.1. Nonlinear Disturbance Observer Design. The main disturbance for the underactuated AUV is external disturbance D_{out}; for the purpose of eliminating its effect on the motion of AUV, it is necessary to predict the D_{out} changing tend. This thought is transformed into estimating D_2 in the progress of constructing controller. Assume $\widehat{D}_2$ is the estimation value of D_2, $\widehat{D}_{\text{out}}$ is the estimation value of D_{out}, and, obviously, $\widehat{D}_{\text{out}} = (I_{yy} - M_{\dot{q}})\widehat{D}_2$. Define state variable vector $x = [x_1, x_2, x_3]^T$; according to (2), a vector-form state equation is obtained [24, 25]:

$$\dot{\mathbf{x}} = \mathbf{G}(\mathbf{x}) + \mathbf{E}(\mathbf{x})\delta_s + \mathbf{J}(\mathbf{x}) D_2, \tag{3}$$

where

$$\begin{aligned} &\mathbf{G}(\mathbf{x}) \\ &= \begin{bmatrix} -U_c x_2 + D_1 \\ x_3 \\ M_1 x_1 + M_2 \sin x_2 + M_4 \left| x_3 \right| x_3 + M_5 \cos x_2 \end{bmatrix}; \\ &\mathbf{E}(\mathbf{x}) = \begin{bmatrix} 0 \\ 0 \\ M_3 \end{bmatrix}; \\ &\mathbf{J}(\mathbf{x}) = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}. \end{aligned} \tag{4}$$

Define f is the internal state variable of NDO; then a nonlinear disturbance observer can be constructed as below:

$$\begin{aligned} f &= \widehat{D}_2 - h(x), \\ \dot{f} &= -\mathbf{T}\left(\mathbf{G}(\mathbf{x}) + \mathbf{E}(\mathbf{x})\delta_s + \mathbf{J}(\mathbf{x})\left(f + h(x)\right)\right), \end{aligned} \tag{5}$$

where $h(x)$ can be designed as $h(x) = h_1 x_1 + h_2 x_2 + h_3 x_3$ under the condition that $h_1 > 0$, $h_2 > 0$, $h_3 > 0$, $\mathbf{T} = [h_1, h_2, h_3]$.

Define $\widetilde{D}_2 = D_2 - \widehat{D}_2$. In fact, there is seldom or even no prior knowledge about the changing law of D_2. Only when the changing speed of D_2 is slower compared with whole system's dynamic traits, it is preferable to assume the derivative of D_2 satisfies $\dot{D}_2 = 0$.

From (5), we can obtain

$$\begin{aligned} \dot{\widetilde{D}}_2 &= \dot{D}_2 - \dot{\widehat{D}}_2 = -\dot{\widehat{D}}_2, \\ \dot{\widehat{D}}_2 &= \dot{f} + \dot{h}(x) = \mathbf{TJ}(\mathbf{x})\widetilde{D}_2. \end{aligned} \tag{6}$$

Then $\dot{\widetilde{D}}_2$ can be gotten as

$$\dot{\widetilde{D}}_2 = -\mathbf{TJ}(\mathbf{x})\widetilde{D}_2 = -h_3\widetilde{D}_2. \tag{7}$$

From (7), the value of $\widetilde{D}_2$ converges to zero due to the fact that $h_3 > 0$.

3.2. Adaptive Terminal Sliding Mode Control. The overall schematic drawing for the NDO-based terminal sliding mode control method is presented in Figure 2. Considering $\widehat{D}_2$ is available, (2) can be rewritten as

$$\begin{aligned} \dot{x}_1 &= -U_c x_2 + D_1, \\ \dot{x}_2 &= x_3, \\ \dot{x}_3 &= M_1 x_3 + M_2 \sin x_2 + M_3 \delta_s + M_4 \left| x_3 \right| x_3 \\ &\quad + M_5 \cos x_2 + \widehat{D}_2 + \Psi, \end{aligned} \tag{8}$$

where $\Psi = \widetilde{D}_2$.

Let us define the estimation of Ψ is $\widehat{\Psi}$, and $\widetilde{\Psi} = \Psi - \widehat{\Psi}$. According to the same principle of getting the derivate law of $\widetilde{D}_2$, assuming Ψ varies more slowly compared to the system dynamics, then we have $\dot{\Psi} = 0$, and $\dot{\widetilde{\Psi}} = \dot{\Psi} - \dot{\widehat{\Psi}} = -\dot{\widehat{\Psi}}$ in further step.

The following task is to design sliding surfaces for this controller construction based on the basic idea of backstepping strategy. In order to follow the desired depth trajectory, the first sliding surface is defined as

$$S_1 = z - z_d = x_1 - z_d. \tag{9}$$

Considering that D_1 is another equivalent internal disturbance in the state equations, it is necessary to estimate its value as well. Define $\widehat{D}_1$ as the estimation of D_1, and $\widetilde{D}_1 = D_1 - \widehat{D}_1$. $\widehat{D}_1$ can be obtained by introducing the following adaptive control law, as shown in (10). Consider

$$\dot{\widehat{D}}_1 = \varepsilon_1 S_1, \quad \varepsilon_1 > 0. \tag{10}$$

Aiming at eliminating the static error of depth tracking, an integral part relative to S_1 is necessarily included:

$$\Omega_1 = \int_0^t S_1 dt. \tag{11}$$

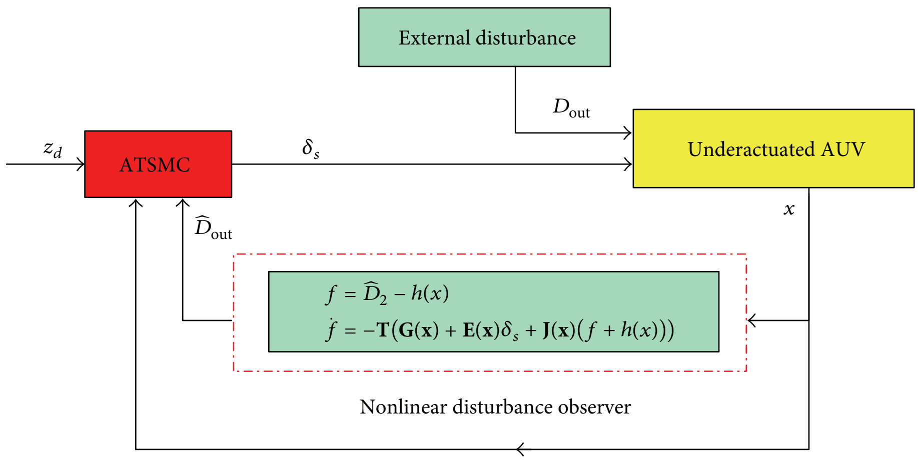

FIGURE 2: The structure of NDO-based terminal sliding mode control for AUV.

Choose a Lyapunov function as

$$V_1 = \frac{1}{2}S_1^2 + \frac{1}{2\varepsilon_1}\widetilde{D}_1^2 + \frac{1}{2}K_{\Omega_1}\Omega_1^2, \quad K_{\Omega_1} > 0. \tag{12}$$

Define a virtual input as

$$\alpha_1 = \frac{1}{U_c}\left(k_1 S_1 + \widehat{D}_1 + K_{\Omega_1}\Omega_1 - \dot{z}_d\right), \quad k_1 > 0. \tag{13}$$

Define the second sliding surface and choose a Lyapunov function separately as

$$\begin{aligned} S_2 &= \theta - \alpha_1 = x_2 - \alpha_1, \\ V_2 &= V_1 + \frac{1}{2}S_2^2. \end{aligned} \tag{14}$$

Define a virtual input and the tracking error of pitch angular velocity separately as

$$\alpha_2 = -k_2 S_2 + \dot{\alpha}_1 + U_c e_1, \quad k_2 > 0, \tag{15}$$

$$S_3 = q - \alpha_2 = x_3 - \alpha_2. \tag{16}$$

Then a novel terminal sliding mode surface is constructed as

$$\sigma = S_3 + \int_0^t \left[m_1 \mathrm{sig}^{r_1}(S_3) + m_2 \mathrm{sig}^{r_2}(S_3)\right] d\tau, \tag{17}$$

where $\mathrm{sig}^{r_1}(S_3) = |S_3|^{r_1}\,\mathrm{sign}(S_3)$, $\mathrm{sig}^{r_2}(S_3) = |S_3|^{r_2}\,\mathrm{sign}(S_3)$, $m_1, m_2, r_1 \geq 1$, $0 < r_2 < 1$, all of them are positive constant, and the definition of $\mathrm{sign}(S_3)$ is $\mathrm{sign}(S_3) = 1, S_3 > 0; 0, S_3 = 0; -1, S_3 < 0$.

In order to obtain the change rule of $\widehat{\Psi}$, the adaptive law of $\widehat{\Psi}$ is built as

$$\dot{\widehat{\Psi}} = \varepsilon_2\sigma, \quad \varepsilon_2 > 0. \tag{18}$$

According to above adaptive laws and sliding mode surfaces design process, the control input of rudder is finally established as below:

$$\begin{aligned} \delta_s = &-\frac{1}{M_3}\Big(M_1 x_3 + M_2 \sin x_2 + M_4 \left|x_3\right| x_3 \\ &+ M_5 \cos x_2 + \widehat{\Psi} + \widehat{D}_2 - \dot{\alpha}_2 + m_1 \mathrm{sig}^{r_1}(S_3) \\ &+ m_2 \mathrm{sig}^{r_2}(S_3) + L_{\mathrm{weight}}\left|W_\sigma\right| \mathrm{sign}(\sigma)\Big), \\ &\qquad L_{\mathrm{weight}} > 0, \end{aligned} \tag{19}$$

where $W_\sigma = \int_0^t (L_W W_\sigma + K_\sigma \sigma)dt$, $L_W < 0$, $K_\sigma > 0$, and this weighted integral section W_σ is designed to reduce the chattering phenomenon of traditional sliding mode control.

Define a Lyapunov function which includes the NDO part and terminal sliding surface as

$$V_3 = \frac{1}{2}\sigma^2 + \frac{1}{2}\widetilde{D}_2^2 + \frac{1}{2\varepsilon_2}\widetilde{\Psi}^2. \tag{20}$$

3.3. Stability Analysis of System. To study the convergence of depth trajectory, each sliding mode surface of controller should be analyzed. These positive definite Lyapunov functions constructed as V_i $(i = 1, 2, 3)$ are discussed in detail to study sliding mode surfaces' convergent issues, and their derivatives with respect to time can be obtained as

$$\begin{aligned} \dot{V}_1 &= S_1\dot{S}_1 + \frac{1}{\varepsilon_1}\widetilde{D}_1\dot{\widetilde{D}}_1 + K_{\Omega_1}\Omega_1\dot{\Omega}_1 \\ &= S_1\left(-U_c x_2 + D_1 - \dot{z}_d\right) - \frac{1}{\varepsilon_1}\widetilde{D}_1\dot{\widehat{D}}_1 + K_{\Omega_1}\Omega_1 S_1 \\ &= S_1\left(-U_c S_2 - U_c\alpha_1 + D_1 - \dot{z}_d\right) - \frac{1}{\varepsilon_1}\widetilde{D}_1\dot{\widehat{D}}_1 \\ &\quad + K_{\Omega_1}\Omega_1 S_1 \end{aligned}$$

$$
\begin{aligned}
&= S_1\left(-U_c S_2 - k_1 S_1 + \widetilde{D}_1 - K_{\Omega_1}\Omega_1\right) - \frac{1}{\varepsilon_1}\widetilde{D}_1\dot{\widehat{D}}_1 \\
&\quad + K_{\Omega_1}\Omega_1 S_1 = -k_1 S_1^2 - U_c S_1 S_2.
\end{aligned}
\tag{21}
$$

If $S_2 = 0$, we can conclude that $V_1 = -k_1 S_1^2 \le 0$, which means S_1 gradually converges to zero. Then the next step is to study

$$
\begin{aligned}
\dot{V}_2 &= \dot{V}_1 + S_2\dot{S}_2 = -k_1 S_1^2 - U_c S_1 S_2 + S_2\left(S_3 + \alpha_2 - \dot{\alpha}_1\right) \\
&= -k_1 S_1^2 - U_c S_1 S_2 \\
&\quad + S_2\left(S_3 - k_2 S_2 + \dot{\alpha}_1 + U_c S_1 - \dot{\alpha}_1\right) \\
&= -k_1 S_1^2 - k_2 S_2^2 + S_2 S_3.
\end{aligned}
\tag{22}
$$

In the same way, if $S_3 = 0$, then we can conclude that $V_2 = -k_1 S_1^2 - k_2 S_2^2 \le 0$, which means S_2 gradually converges to zero as well. From (17), it is easy to know that $S_3 = 0$ is equivalent to $\sigma = 0$; the key point is to verify the convergence of terminal sliding mode surface σ.

From (8), (13), (15), (17), and (19), we can obtain

$$
\begin{aligned}
\dot{\sigma} &= \dot{S}_3 + m_1 \operatorname{sig}^{r_1}(S_3) + m_2 \operatorname{sig}^{r_2}(S_3) \\
&= \dot{x}_3 - \dot{\alpha}_2 + m_1 \operatorname{sig}^{r_1}(S_3) + m_2 \operatorname{sig}^{r_2}(S_3) \\
&= M_1 x_3 + M_2 \sin x_2 + M_3 \delta_s + M_4 \left|x_3\right| x_3 \\
&\quad + M_5 \cos x_2 + \widehat{D}_2 + \Psi - \dot{\alpha}_2 + m_1 \operatorname{sig}^{r_1}(S_3) \\
&\quad + m_2 \operatorname{sig}^{r_2}(S_3) = -L_{\text{weight}}\left|W_\sigma\right| \operatorname{sign}(\sigma) + \widetilde{\Psi}.
\end{aligned}
\tag{23}
$$

From (7), (18), and (23), we can obtain

$$
\begin{aligned}
\dot{V}_3 &= \sigma\dot{\sigma} + \widetilde{D}_2\dot{\widetilde{D}}_2 + \frac{1}{\varepsilon_2}\widetilde{\Psi}\dot{\widetilde{\Psi}} \\
&= \sigma\left(-L_{\text{weight}}\left|W_\sigma\right| \operatorname{sign}(\sigma) + \widetilde{\Psi}\right) - h_3\widetilde{D}_2^2 - \frac{1}{\varepsilon_2}\widetilde{\Psi}\dot{\widehat{\Psi}} \\
&= -L_{\text{weight}}\left|W_\sigma\right|\left|\sigma\right| - h_3\widetilde{D}_2^2 \le 0.
\end{aligned}
\tag{24}
$$

Considering the fact that $V_3 \ge 0$, $\dot{V}_3 \le 0$, it is easy to know that terminal sliding mode surface σ is reachable. Once $\sigma = 0$, we can know that S_3 will converge rapidly to zero in a finite period. Due to (22), S_2 converges to zero as well when $S_3 = 0$; and once $S_2 = 0$, it implies that S_1 converges to zero quickly. All above analysis proves that all closed-loop sliding mode surfaces will converge to the equilibrium points in finite time.

4. Simulation Experiment

In this section, simulations are presented to verify the effectiveness of designed controller, which is ATSMC with NDO. The method is applied into the depth control of REMUS AUV. REMUS is a small-size, low-cost moving platform applied into various oceanographic activities; it is developed by both Massachusetts Institute of Technology (MIT) and Woods Hole Oceanographic Institution. The parameters about REMUS can be obtained from [7]; here some parameters which will be used in this paper are shown in Tables 1 and 2.

Table 1: Hydrodynamic parameters of REMUS AUV.

Variables	Values	Units
$M_{\dot{q}}$	−4.88	kg m^2/rad
$M_{w\|w\|}$	3.18	kg
M_{uu}	−6.15	kg/rad
M_{uw}	24	kg
$Z_{\dot{q}}$	−1.93	kg m/rad
$Z_{q\|q\|}$	−0.632	Kg m/rad^2
Z_{uq}	−5.22	kg/rad
$M_{\dot{w}}$	−1.93	kg m
$M_{q\|q\|}$	−188	kg m^2/rad^2
M_{uq}	−2	kg m/rad
$Z_{\dot{w}}$	−35.5	kg
Z_{ww}	−131	kg/m
Z_{uw}	−28.6	kg/m
Z_{uu}	−6.15	kg/(m rad)

Table 2: Physical parameters of REMUS AUV.

Variables	Values	Units
x_W	0	m
z_W	0.0196	m
y_B	0	m
W_{eig}	299	N
m	30.48	kg
y_W	0	m
x_B	0	m
z_B	0	m
B_{uo}	306	N
I_{yy}	3.45	Kg m^2

Case 1. In order to undergo the simulation, due to Section 3, the parameters of NDO are chosen as $h_1 = h_2 = h_3 = 1$; the parameters of ATSMC are set as $k_1 = 1.2$, $k_2 = 1.8$, $k_3 = 1.1$, $\varepsilon_1 = 0.1$, $\varepsilon_2 = 0.01$, $m_1 = m_2 = 1.1$, $r_1 = 1.2$, $r_2 = 0.5$, $L_W = -1$, $K_\sigma = 1$, $L_{\text{weight}} = 1$, and $K_{\Omega_1} = 0.5$. The initial values of state variables are $[w(0), \theta(0), z(0), p(0)] = [0, 0, 4, 0]$ for the REMUS AUV. The external disturbance exposed on REMUS is assumed to be in the following form $D_{\text{out}} = 20\sin(\pi t/10) + 10\sin(\pi t/15) + 6\cos(\pi t/20 + \pi/2)$ during the time period $20\,\text{s} \le t < 40\,\text{s}$. The surge velocity u holds constant with $U_c = 1.54$ m/s. The desired depth of AUV is defined as a time varying function $z_d = 5 + 1.5\sin(\pi t/10)$. The task of the designed ATSMC based on NDO is to achieve the depth trajectory tracking of REMUS AUV in reference to desired depth z_d.

Figure 3 shows the depth tracking process of underactuated AUV, and the changing trend of rudder control input δ_s. We can obtain that the tracking error of depth

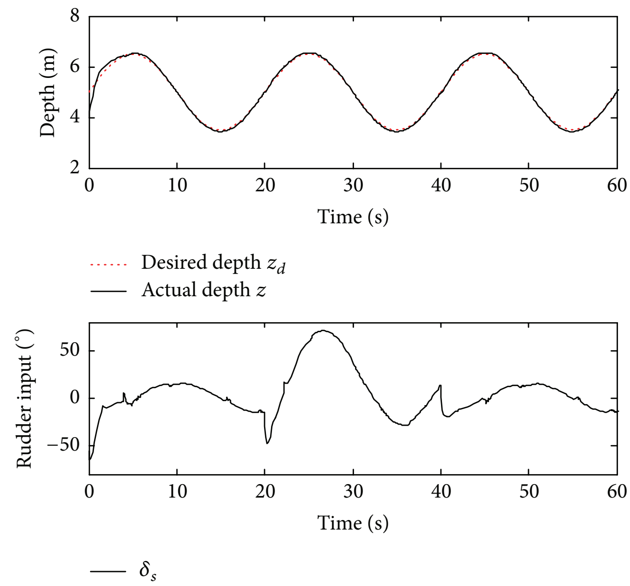

FIGURE 3: Depth trajectory and rudder input δ_s of REMUS AUV.

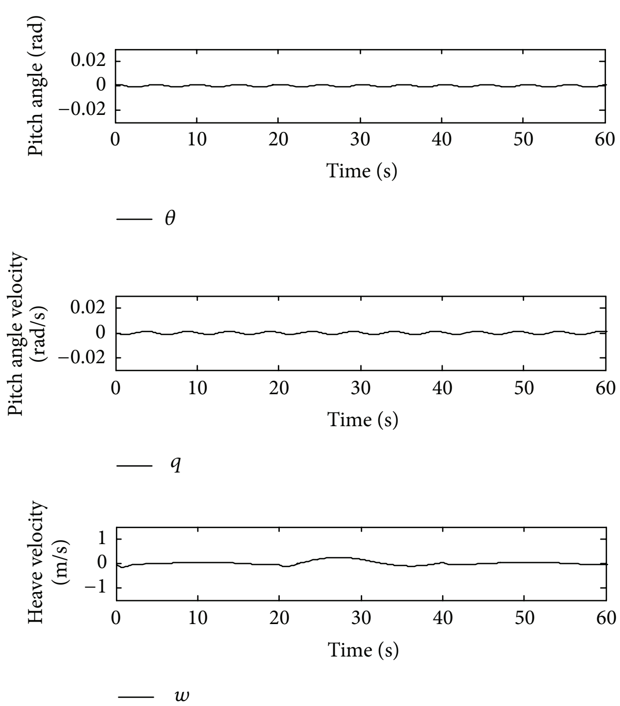

FIGURE 4: State variables changing trend of REMUS AUV.

can be nearly zero in the stable procedure, even when the AUV suffers from unknown external disturbance D_{out} during $20\,s \leq t < 40\,s$. All these verify that the AUV could meet depth tracking requirements. In addition, the control input obtained from the proposed method is smooth, and its chattering phenomenon is seldom vanished.

Figure 4 implies the changing trends of variables w, θ, p during the depth tracking process. It is easy to notice that the pitch angle θ and pitch angle velocity p are both forced to be in the scope of a small value; besides, the heave velocity w keeps

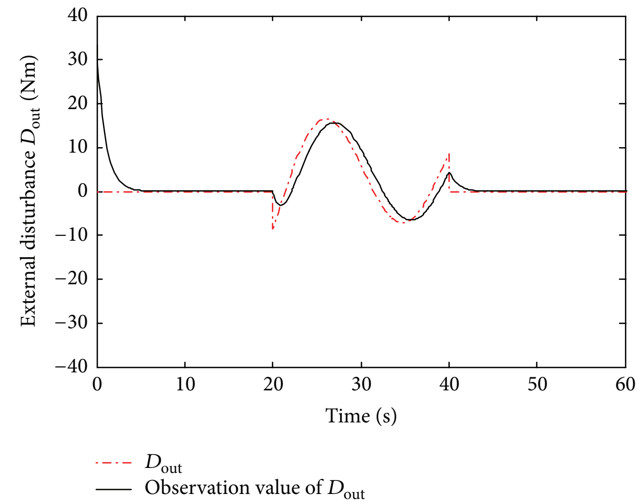

FIGURE 5: External disturbance D_{out} and its observation value $\widehat{D}_{out}$.

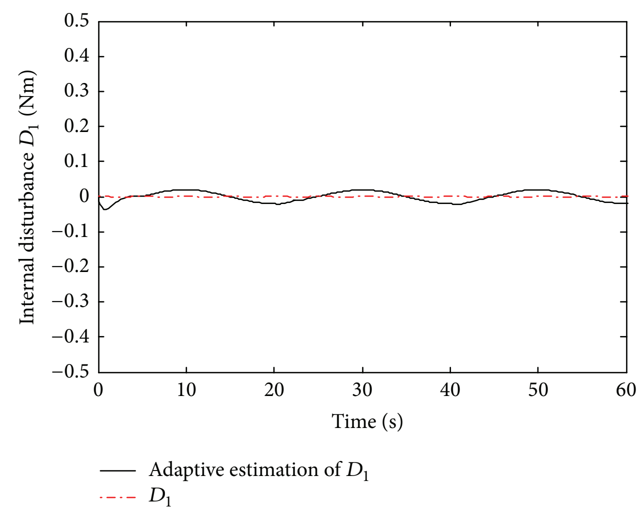

FIGURE 6: Internal disturbance D_1 and its estimation $\widehat{D}_1$.

almost as close to zero in the overall process, which satisfies the assumption that $w \approx 0,\ \dot{w} \approx 0$.

The main disturbance for AUV is external disturbance D_{out}. To reduce external disturbance's effect on AUV, the proposed controller introduces the NDO to observe and predict D_{out}. Another important relationship is $D_{out} = (I_{yy} - M_{\dot{q}})D_2$; it is convenient to estimate D_2 based on NDO in the controller design. We can have the observation value $\widehat{D}_{out}$ due to NDO from Figure 5. Another part of disturbance is the constructed internal disturbance D_1 which is established for convenience of designing proposed controller. An adaptive law for D_1 is also introduced to accelerate the convergent speed of controller; its estimation process is shown in Figure 6.

The traits of sliding mode surfaces in the controller building procedure are vital to the convergence of the whole control system. The internal relationships between each sliding mode surface can be known from Section 3.3. The

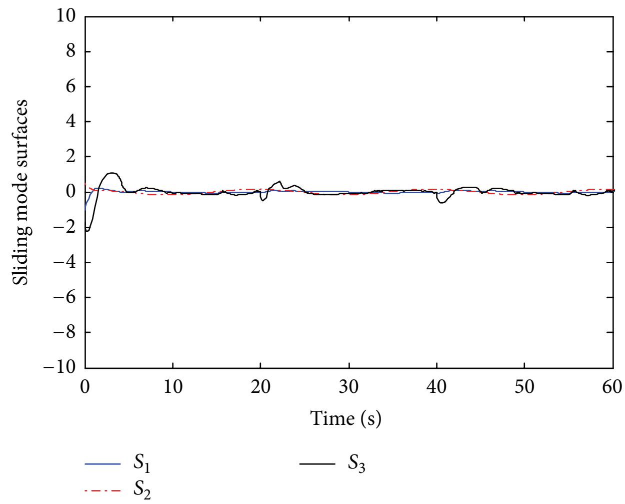

FIGURE 7: Sliding mode surfaces S_1, S_2, S_3.

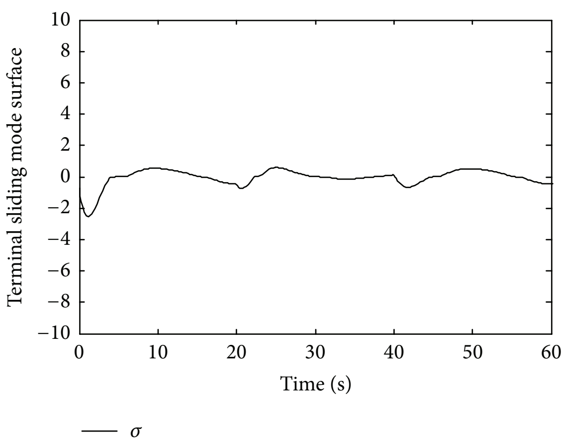

FIGURE 8: Terminal sliding mode surface σ.

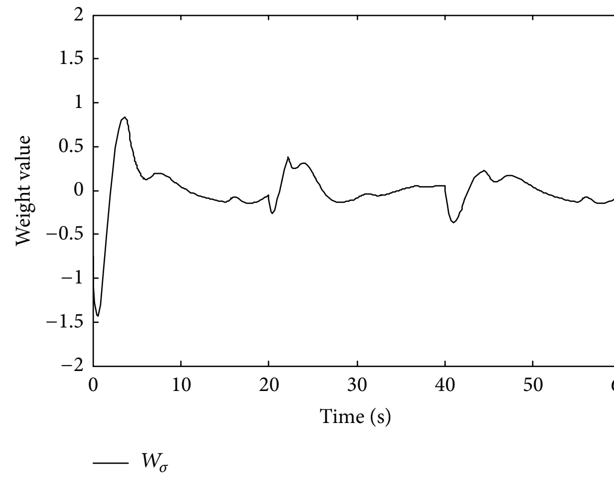

FIGURE 9: Weighted value of W_σ.

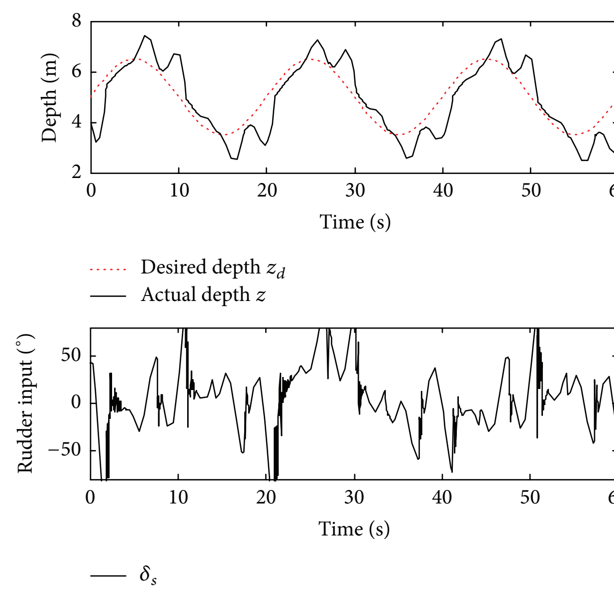

FIGURE 10: Traditional sliding mode control method.

change laws of sliding mode surfaces are shown in Figure 7; we can know that sliding mode surfaces S_1, S_2, S_3 converge to equilibrium points. Another important aspect is the terminal sliding mode surface σ, which can be reachable from Figure 8. σ guarantees the convergence of S_i $(i = 1, 2, 3)$. From (19) and Figure 9, we can understand that weighted value W_σ is used to weaken the chattering issue which occurs frequently in the traditional sliding mode control, and its value changes with σ, and apparently no strong oscillation happens to the rudder in the tracking procedure from Figure 3.

Case 2. In order to compare with the proposed method, a traditional sliding mode controller and a proposed controller which lacks integer part Ω_1 in (11) are separately applied into accomplishing the depth tracking task. Their control performances are shown, respectively, in Figures 10 and 11. Among them, the traditional sliding mode control law [26] can be expressed with the expression of (19) when $m_1 = m_2 = 0$, $W_\sigma = 1$. Through comparing the performance shown in Figure 3 with Figure 10, it is obvious that $m_1 \mathrm{sig}^{r_1}(S_3)$, $m_2 \mathrm{sig}^{r_2}(S_3)$ and the change rule of W_σ play an important role in reducing chattering issue of rudder input; when $K_{\Omega_1} = 0$, the rudder input of the ATSMC based on NDO can make AUV track the desired depth, but a small tracking error always exists by contrasting the control effect of Figure 3 with Figure 11; this illustrates that integer part Ω_1 is necessary to achieve the expected tracking effect.

5. Conclusion

A methodology combined with ATSMC and NDO was presented in this paper. For the convenience of design, both the kinematics and dynamics equations of underactuated AUV in the vertical plane were simplified firstly based on some assumptions. Then, a nonlinear disturbance observer (NDO) was built, and another form of AUV's state variables equation was reconstructed on the basis of NDO. Furthermore, an ATSMC with NDO was designed, and the

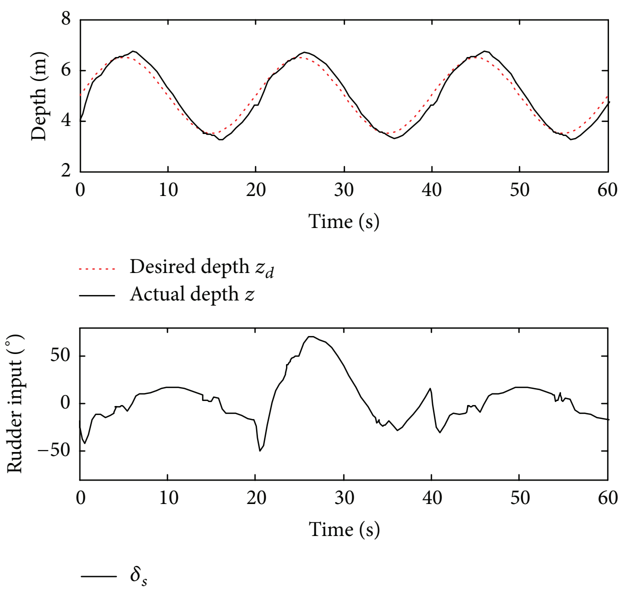

FIGURE 11: ATSMC based on NDO without integer part Ω_1.

controller's stability was verified according to Lyapunov's theory and backstepping technique. Through the simulation experiments of AUV, the designed controller was proved to make the underactuated AUV track the expected time-varying depth trajectory, and it showed strong robustness to external disturbance.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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