Depth Control of ROVs Using Time Delay Estimation with Nonsingular Terminal Sliding Mode

Yaoyao Wang, Linyi Gu, Gaosheng Luo, Xiaodong Li,
Feng Zhou, Xiaoxu Cao
State Key Laboratory of Fluid Power Transmission and Control, Zhejiang University
Hangzhou, China
yaoyaowang@zju.edu.cn, lygu@zju.edu.cn

Jiawang Chen
Ocean College
Zhejiang University
Hangzhou, China
arwang@zju.edu.cn

***Abstract*—In this paper, a nonsingular terminal sliding mode (NTSM) control method based on time delay estimation (TDE) is proposed and investigated for the depth control of remotely operated vehicles (ROVs). The complex dynamics is approximately compensated by TDE leading to an attractive model-free nature, which is more suitable for practical applications than other model-based methods. Furthermore, the NTSM manifold based on nonlinear error dynamics can ensure better control performance than the traditional sliding mode (SM) manifold with linear error dynamics. Stability of the closed-loop system is analyzed using Lyapunov theory. Finally, the faster convergence and higher tracking accuracy compared with traditional TDE method with linear error dynamics are verified through simulation.**

***Keywords*—depth control; ROVs; nonsingular terminal sliding mode (NTSM); time delay estimation(TDE).**

I. INTRODUCTION

In the past few decades, underwater remotely operated vehicles (ROVs) have become an important tool for underwater commercial and scientific investigations due to their capabilities in the deep sea. High-precision tracking control and fast dynamic response are required during many missions, however, these characteristics remain very challenging to achieve. The major difficulties in designing proper controllers for ROVs include the strongly nonlinear behavior and uncertainties in the hydrodynamic coefficients, the time-varying dynamic behavior, and the external disturbances caused by the manipulator motion [1].

Sliding mode (SM) control method is an efficient and effective tool to handle control problems that suffer from the above-mentioned difficulties [1]. Therefore, it is now widely implemented in practical systems, especially for nonlinear systems with all kinds of uncertainties and external disturbances, such as ROVs [2, 3], autonomous underwater vehicles (AUVs) [4] and hydrostatic transmission [5]. Usually, traditional SMC method is based on linear error dynamics and can only obtain asymptotic stability. Thus, a variant scheme of SM control, named terminal sliding mode (TSM) control, was proposed [6]. By replacing the linear manifold with a nonlinear one, the TSM control can ensure higher control precision and faster convergence. Afterwards, improved versions of TSM were gradually proposed and investigated, such as nonsingular TSM (NTSM) [7], fast TSM (FTSM) [8], continuous nonsingular TSM (CNTSM) [9] and nonsingular fast TSM (NFTSM) [10].

However, the abovementioned TSM-based methods are typically model-based ones, which means lots of parameters are required. But the hydrodynamic parameters of a ROV are significantly laborious to obtain even for their approximate ranges. Furthermore, when hydrodynamic parameters with large uncertainties are adopted in the controller, high control gains are required which in turn may lead to actuator saturation and worse control performance.

To solve this problem, the time delay estimation (TDE) is adopted here. The core thought of TDE is to evaluate the unknown lumped dynamics directly using the intentionally time-delayed information of the closed-loop systems [11], which is model-free and easy to implement. Thus, TDE has been widely used in many practical systems since it was proposed [12, 13], such as tilt rotor unmanned aerial vehicle [14], air supply systems [15] and underwater vehicles [16].

Inspired by the achievements of the aforementioned studies, we proposed a NTSM control approach based on TDE for the depth control of ROVs. The proposed method enjoys an attractive model-free feature due to TDE and can also ensure fast convergence and high tracking precision due to NTSM. The efficiency and validity of the new proposed method is verified through numerical simulations.

The rest of this paper is organized as follows. In Section II, the dynamic model of ROV along z-axis is briefly given. Afterwards, the TDE-based NTSM control method is proposed and investigated for the depth control of a ROV. In Section IV, corresponding simulation studies are given to demonstrate the effectiveness of the new proposed control method. Finally, Section V briefly concludes this paper.

II. DYNAMIC MODELLING

The following assumptions are necessary for dynamic modelling.

Assumption 1. The angles of roll and pitch are zero.

Assumption 2. The lumped uncertainty d(t) is unknown, time-varying and bounded as $\left|d(t)\right| \le \Delta, \Delta \ge 0$.

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The disturbance between buoyancy and gravity centers for a ROV is usually large enough to stabilize the ROV [3], thus Assumption 1 is reasonable.

Finally, for a low-speed (less than 4knots) ROV, following equation can be used to describe the motion along z-axis [3]

$$m_0\ddot{z}+c_1\dot{z}+c_2\dot{z}\left|\dot{z}\right|+d=u \tag{1}$$

where m_0 is the nominal mass of a ROV including added mass, c_1 and c_2 stand for the nominal coefficients of hydrodynamic damping, d is the unknown but bounded lumped uncertainties. And u is the control input provided by propellers.

Remark 1. It should be noted that the dynamic model (1) will not be used in our proposed controller. It is given here just for the understanding of the ROV dynamics on the basis of which our proposed controller is to be designed [13].

III. TDE-BASED NTSM CONTROLLER DESIGN

Inspired by [3, 16], a TDE-based NTSM controller is proposed for the depth control of a ROV. Following assumption is necessary for the controller designing.

Assumption 3. The desired trajectory z_d is smooth, i.e., $\dot{z}_d$ and $\ddot{z}_d$ are exist and bounded.

A. Controller Design

Equation (1) can be rewritten as

$$\bar{m}\ddot{z}+H\left(z,\dot{z},\ddot{z}\right)=u \tag{2}$$

where $H\left(z,\dot{z},\ddot{z}\right)=\left(m_0-\bar{m}\right)\ddot{z}+c_1\dot{z}+c_2\dot{z}\left|\dot{z}\right|+d$ stands for the unknown lumped dynamics of the ROV, which is usually very laborious to obtain using traditional technology. And $\bar{m}$ is a constant to be designed.

Define the tracking error as $e=z_d-z$. Then the NTSM manifold is designed as

$$s=e+a\,sig\left(\dot{e}\right)^b \tag{3}$$

where a>0, 1< b <2 and $\mathrm{sig}(x)^b=|x|^b\mathrm{sign}(x)$.

Equation (3) is differentiable and continuous, and its first derivative can be expressed as [9]

$$\dot{s}=\dot{e}+ab\left|\dot{e}\right|^{b-1}\ddot{e} \tag{4}$$

Thus, the controller can be designed as

$$\begin{aligned}&u=\bar{m}u_1\left(t\right)+\hat{H}\left(t\right),\\&u_1\left(t\right)=\ddot{z}_d+a^{-1}b^{-1}sig\left(\dot{e}\right)^{2-b}+k\,\mathrm{sgn}\left(s\right).\end{aligned} \tag{5}$$

where $\hat{H}\left(t\right)$ represents the estimation of $H\left(z,\dot{z},\ddot{z}\right)$ in (2), which is usually very difficult to obtain using traditional method. Therefore, the TDE technique is adopted here to obtain $\hat{H}\left(t\right)$ as

$$\hat{H}\left(t\right)=H_{t-L}=u_{t-L}-\bar{m}\ddot{z}_{t-L} \tag{6}$$

where t-L stands for the time-delayed value with a delayed time L.

Substituting (6) into(5), we can obtain the final control scheme as

$$u=\bar{m}\left(\ddot{z}_d+a^{-1}b^{-1}sig\left(\dot{e}\right)^{2-b}+k\,\mathrm{sgn}\left(s\right)\right)+u_{t-L}-\bar{m}\ddot{z}_{t-L} \tag{7}$$

As shown in controller(7), the dynamic model (1) is not used which means the proposed controller is model-free.

B. Analysis of the System Stability

The stability of the closed-loop system will be analyzed in this subsection. Substituting the controller (7) into the rearranged model (2) yields

$$\ddot{e}+a^{-1}b^{-1}sig\left(\dot{e}\right)^{2-b}+k\,\mathrm{sgn}\left(s\right)=\varepsilon \tag{8}$$

with the TDE error ε defined as

$$\varepsilon\left(t\right)=-\bar{m}^{-1}\left(\hat{H}\left(t\right)-H\left(t\right)\right)=u_1-\ddot{z} \tag{9}$$

Consider the Lyapunov function $V=s^2/2$. Differentiating $V(t)$ with respect to time, and substituting the controller (7) into it yields

$$\begin{aligned}\dot{V}&=s\dot{s}=s\left[\dot{e}+ab\left|\dot{e}\right|^{b-1}\ddot{e}\right]\\&=s\left[\dot{e}+ab\left|\dot{e}\right|^{b-1}\left(\varepsilon-a^{-1}b^{-1}sig\left(\dot{e}\right)^{2-b}-k\,\mathrm{sgn}\left(s\right)\right)\right]\\&=-ab\left|\dot{e}\right|^{b-1}\left[k\left|s\right|-\varepsilon s\right]\\&\le-ab\left|\dot{e}\right|^{b-1}\left|s\right|\left[k-\left|\varepsilon\right|\right]\end{aligned} \tag{10}$$

In(10), since 1< b <2, we have $\left|\dot{e}\right|^{b-1}>0$ for $\dot{e}\neq0$. Thus $\dot{V}<0$ will be always fulfilled under the following condition

$$k>\left|\varepsilon\right| \tag{11}$$

Thus, if ε is bounded, the condition (11) will ensure $\dot{V}<0$ and the tracking error is then bounded.

And the boundedness of ε can be ensured under the following condition [12, 13]:

$$\left|m_0^{-1}\bar{m}-1\right|<1\Rightarrow0<\bar{m}<2m_0 \tag{12}$$

which can be easily fulfilled by suitable choice of $\bar{m}$.

Finally, the stability of the closed-loop system is proved.

C. Simplicity of the Proposed Controller

The model-based NFTSM controller proposed in [3] can be expressed as

$$\begin{aligned}&u=u_1+u_2,\\&u_1=m_0\ddot{z}_d+c_1\dot{z}+c_2\dot{z}\left|\dot{z}\right|\\&u_2=-m_0qb^{-1}p^{-1}[k_1s+k_2sig(s)^{m/n}+\\&\qquad(1+agh^{-1}\left|e\right|^{g/h-1})sig(\dot{e})^{2-p/q}].\end{aligned} \tag{13}$$

with a NFTSM manifold and a new reaching law defined as

$$s = e + a\,sig(e)^{g/h} + b\,sig(\dot{e})^{p/q},$$
$$\dot{s} = -\left[k_1 s + k_2 sig(s)^{m/n}\right]|\dot{e}|^{p/q-1}. \tag{14}$$

where a, b, k_1, k_2 are positive gains to be designed, and g, h, p, q, m, n are odd numbers fulfilling the following inequality:

$$1 < p/q < 2, 0 < m/n < 1, g/h > p/q. \tag{15}$$

It is obvious that controller (13) is highly complex: all the nominal model parameters are required, which may greatly limit its practical applications because the aforementioned parameters are usually very difficult to obtain. Meanwhile, our proposed controller (7) is quite simple and model-free thanks to TDE. Most nonlinear complex dynamics of the system are canceled by TDE with the recent past control input and acceleration as $u_{t-L} - \bar{m}\ddot{z}_{t-L}$. And since we usually cannot directly measure the past acceleration signal $\ddot{z}_{t-L}$, following numerical differentiation is often used

$$\ddot{z}_{t-L} = \left(z_t - 2z_{t-L} + z_{t-2L}\right)/L^2 \tag{16}$$

Remark 2. In practical applications, the numerical differentiation (16) will be greatly bothered by noise, which, however, can be effectively suppressed by lowering $\bar{m}$ or introducing a filter after (16) [17].

D. Anti-windup Scheme

The anti-windup scheme proposed by Chang [18] is also applied to our proposed controller, as shown in Fig. 1. The windup phenomenon is usually caused by the saturation of the propellers, which is nearly unavoidable in practical applications and may lead to serious degradation in the control performance.

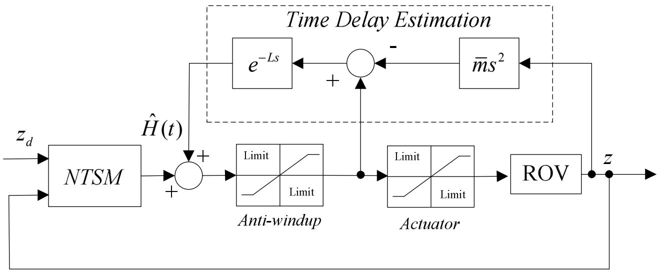

Fig. 1. TDE-based NTSM controller with an anti-windup scheme

IV. Numerical Simulation

To illustrate the effectiveness of the proposed control method, we performed several comparative numerical simulations using our new proposed one denoting as NTSM-TDE, and the one proposed in [16] denoting as Linear-TDE. The ROV used in the simulations is a small one named POLARIS, which was developed in Zhejiang University. Corresponding nominal parameters for POLARIS are m_0=11.5 kg, c_1=16.5kg/s, c_2=3.5kg/m, $u_{f\max}$=1.6N, $u_{b\max}$=-3.2N. $u_{f\max}$ and $u_{b\max}$ are the maximum thrust that propeller can produce in forward and reverse directions. The control parameters for NTSM-TDE is chosen as a=0.8, b=1.2, k=1, L=10ms. For $\bar{m}$, it was turned through a small one, until comprehensive satisfactory control performance was obtained. Finally, we choose $\bar{m} = 0.4$. Furthermore, to ease the chatters caused by the sign term in the controller, the boundary layer of 0.002 is adopted. For Linear-TDE, we change the parameter b from 1.2 to 1, the others remained unchanged. The simulation was performed using a fixed-step fourth-order Runge-Kutta solver with a step of 1ms. To illustrate the robustness of the two controllers against the unknown disturbing forces typically caused by ocean currents, a time-varying external disturbance is added to the propeller as $d = 0.2\sin(\pi t)$. The initial position is chosen as z_0=0.1m and the initial velocity is chosen as zero.

Three cases were simulated. The first case is to illustrate the control performance of NTSM-TDE compared with Linear-TDE with time-vary disturbance under a sinusoidal desired trajectory. The second case is to illustrate the control performance of both controllers with time-vary disturbance under square desired trajectory. And in the third case, measurement noise is introduced into the system while the control parameters remain unchanged under the same sinusoidal desired trajectory with case one.

A. Case one

The desired trajectory is chosen as $z_d = 0.1\sin(0.2\pi t)$ + 0.15m. It should be noted that the frequency of the disturbance is five times faster than the one of the desired trajectory. Corresponding simulation results are given in Fig. 2~Fig. 5.

It is obvious that both controllers can ensure good trajectory tracking control performance under a time-varying external disturbance. And our proposed controller can provide with a better control performance compared with the one obtained by Linear-TDE as shown in Fig. 2 and Fig. 3.

As shown in Fig, 4, Linear-TDE can provide with a little faster convergence of the sliding manifold than our proposed controller in the reaching phase. Afterwards, our proposed controller obtained a much faster convergence of tracking error in the sliding phase which clearly shows the advantages of NTSM over linear SM.

On the other hand, the control input of our proposed controller is a little larger than that of Linear-TDE, which is reasonable.

B. Case two

In this case, the square desired trajectory was simulated. Corresponding results are given in Fig. 6~ Fig. 9.

As shown in the simulation results, both controllers can ensure satisfactory dynamic control performance, and our proposed method can still obtain a better one compared with the Linear-TDE method.

As shown in Fig. 9, the control input of our proposed controller is a little larger than that of Linear-TDE method at the start-up phases which leads to a relative faster convergence rate. Moreover, it is also obvious that in the middle stage the control inputs is still time-varying, which is mainly used to compensate the time-varying disturbances.

C. *Case three*

In this case, measurement noise is taken into consideration which is usually unavoidable in the practical applications. To simulate the noise, a band-limited white noise model with noise power of 4×10^{-5} and sample time of 1×10^{-3}s is introduced in the depth measurement. The noise is pre-filtered using a first order inertial filter with a time constant of 1s. Furthermore, another first order inertial filter with a time constant of 0.1s is introduced after the numerical differentiation (16) to ease the greatly enlarged effect from noise for both controllers. Corresponding simulation results are given in Fig. 10~Fig. 13.

It can be clearly observed from the simulation results that the trajectory tracking control performance for both controllers have been degraded after introducing the measurement noise. However, the control performance is still satisfactory. Furthermore, our proposed controller can still provide with a better control performance than that of the Linear-TDE method.

As shown in Fig. 13, the control input of our proposed controller is a little noisier than that of the Linear-TDE method, which can be effectively suppressed by lowering the parameter $\bar{m}$.

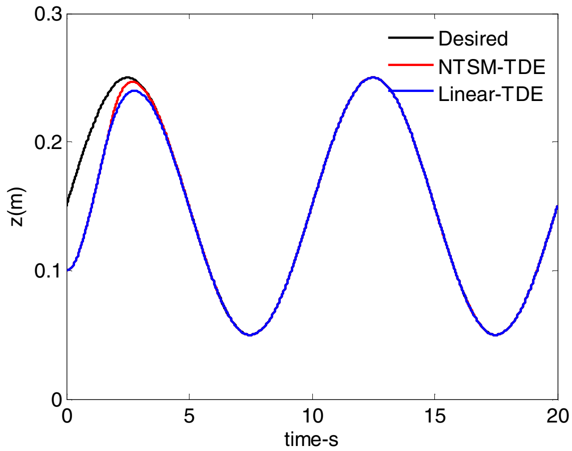

Fig. 2. Tracking performance of our proposed controller and Linear-TDE

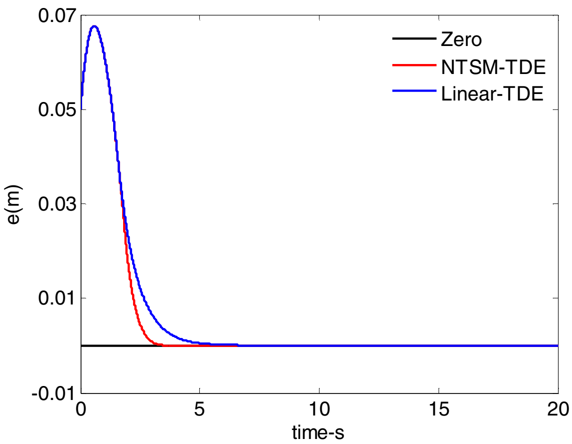

Fig. 3. Tracking error of our proposed controller and Linear-TDE

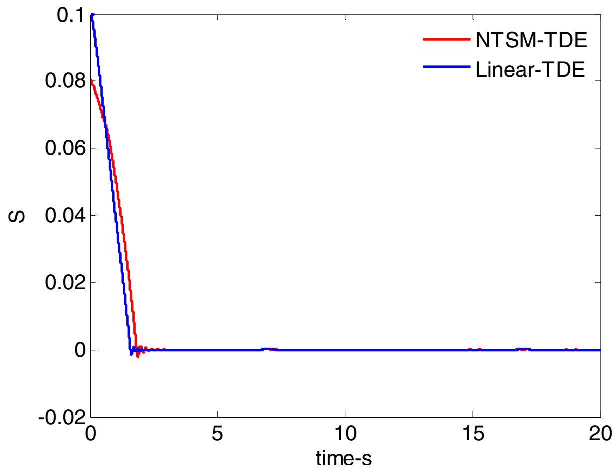

Fig. 4. Sliding manifold of our proposed controller and Linear-TDE

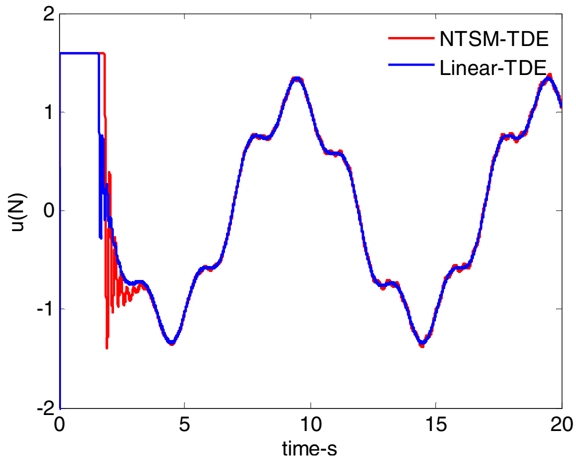

Fig. 5. Control input of our proposed controller and Linear-TDE

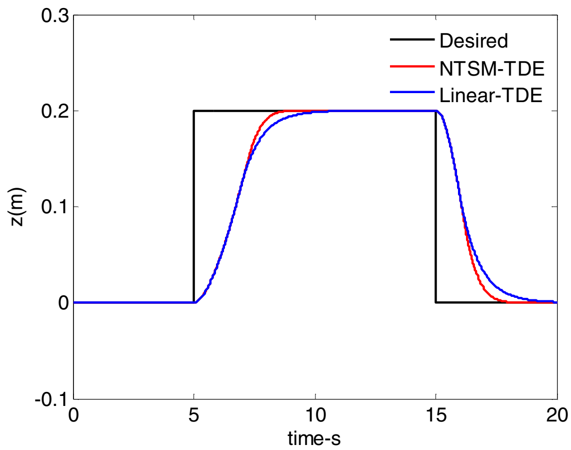

Fig. 6. Tracking performance of our proposed controller and Linear-TDE under square desired trajectory

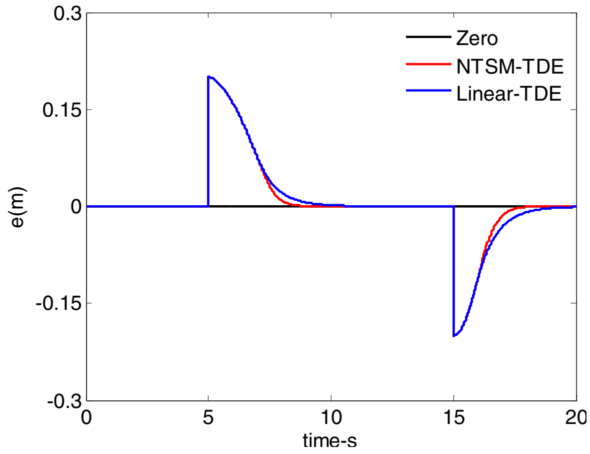

Fig. 7. Tracking error of our proposed controller and Linear-TDE under square desired trajectory

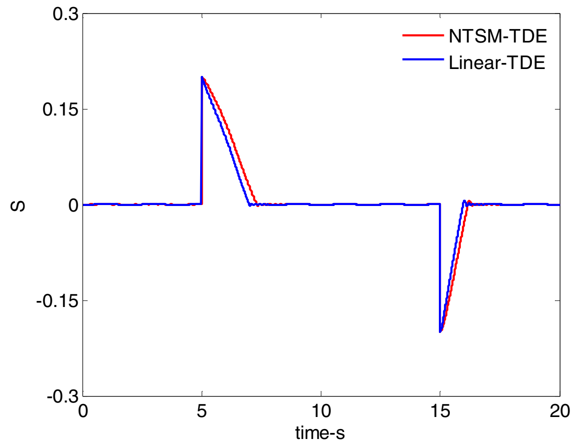

Fig. 8. Sliding manifold of our proposed controller and Linear-TDE with under square desired trajectory

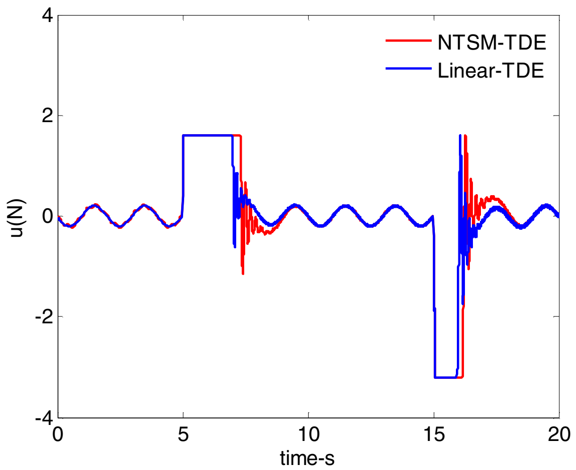

Fig. 9. Control input of our proposed controller and Linear-TDE under square desired trajectory

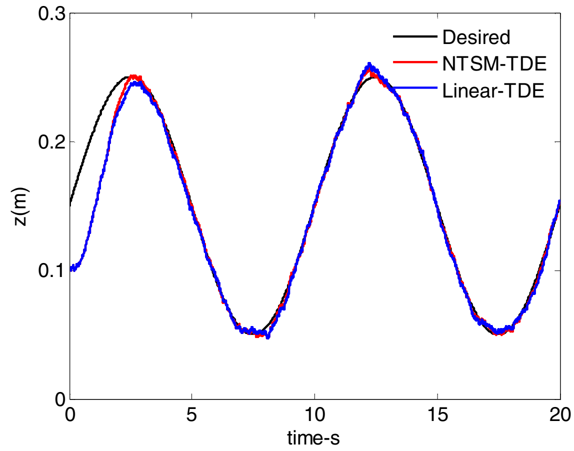

Fig. 10. Tracking performance of our proposed controller and Linear-TDE with noise

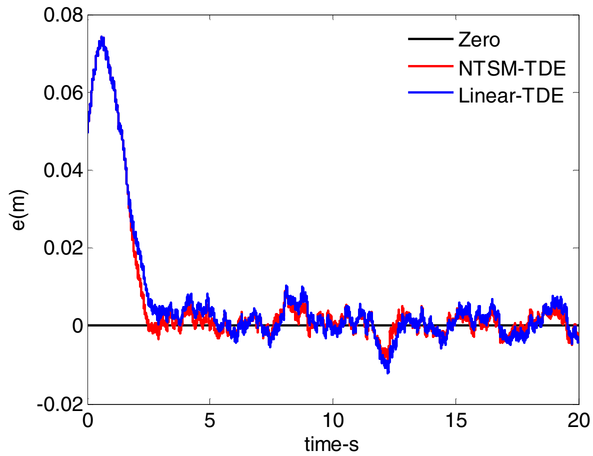

Fig. 11. Tracking error of our proposed controller and Linear-TDE with noise

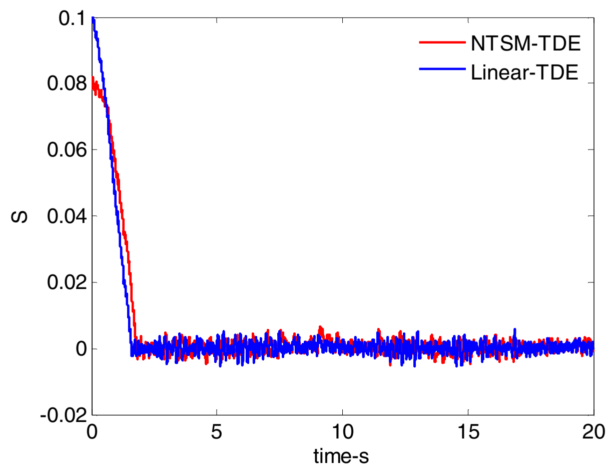

Fig. 12. Sliding manifold of our proposed controller and Linear-TDE with noise

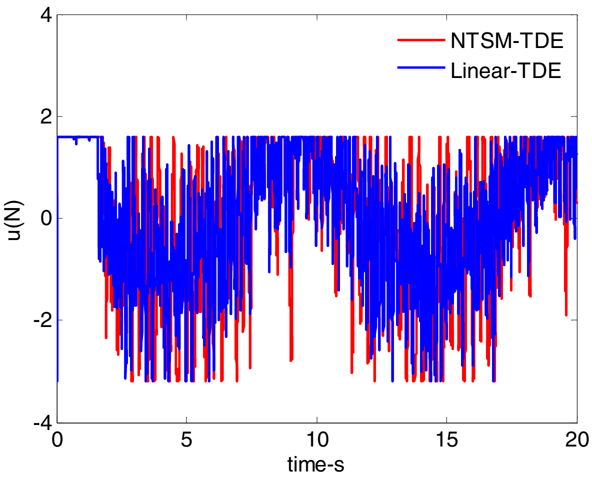

Fig. 13. Control input of our proposed controller and Linear-TDE with noise

Therefore, it can be concluded from the simulation results that both controllers can provide with satisfactory trajectory tracking control performance under external time-varying disturbance and measurement noise. And our proposed controller can ensure better control performance than the Linear-TDE method.

V. Conclusion

In this paper, we proposed a TDE-based NTSM controller for the depth control of ROVs. The proposed controller mainly contains two terms: a TDE term used to constitute the base of the whole control scheme and appromately compensate the lumped unkown system dyanmcis; a NTSM term used to obtain satisfactory control performance under the exsiting TDE error. The proposed method is model-free thanks to TDE and can ensure good trajectory tracking perforamnce due to NTSM. Stablity of the closed-loop system is analyzed using Lyapunov theory. And corresponding numerical simulations results have verified the effectiveness of our proposed method.

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