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Finite-time Robust Trajectory Tracking Control of Unmanned Underwater Vehicles

Pengli Zhu[1], Yancheng Liu[1*], Youtao Zhao[1] and Jian Zhou[2]

[1]Marine Engineering College, Dalian Maritime University, Dalian, Liaoning, 116026, China

[2]Navigation College, Dalian Maritime University, Dalian, Liaoning, 116026, China

[*]Corresponding author's e-mail: liuyc3@126.com

Abstract. In this paper, the finite-time tracking control problem of unmanned underwater vehicle in complex environment is studied. By combining dynamic surface control with second-order sliding mode control, a finite-time dynamic surface sliding mode composite track tracking control scheme is designed. Ensure that the unmanned underwater vehicle track tracking system has high-quality track tracking performance such as fastness, accuracy, strong robustness and limited time convergence. Finally, the simulation experiment and the traditional PD control strategy tracking effect are compared and analyzed to verify the effectiveness and superiority of the proposed track tracking control method.

1. Introduction

In recent years, the trajectory tracking control problem of unmanned underwater vehicles (UUV) has been highly valued by scholars and researchers all over the world and has become a research hotspot. With the development of mathematical theory and control theory, many advanced theories have been deeply discussed and widely used in the field of trajectory tracking control [1-3].Unmanned underwater vehicle is an intelligent device with autonomous controller and various sensors, among which the efficient and reliable autonomous controller plays an important role in performing various dynamic and complex underwater tasks. Therefore, the research on the precise tracking and control of underwater vehicle is of great practical significance to maritime traffic safety.

Aiming at the tracking control problem of unmanned underwater vehicle, many scholars around the world have made great contributions in this direction, among which the main research methods are PID, reverse step design, sliding mode variable structure control, adaptive control, intelligent control and the control strategy combining them. Conte et al. [4] adopted the backstepping method to design a nonlinear control law to solve the ship's robust progressive tracking control problem under unified disturbance attenuation, and combined with the high-gain feedback robust design method to eliminate the influence of model perturbation. Hu et al.[5] proposed a weighted sliding mode and neural network fusion control system. Both sliding mode control and neural network control play a role in the control process, and the control weight is completed by a fuzzy supervisor. Kashif et al.[6] proposed a single input UUV tracking controller based on fuzzy logic. Kayacan et al.[7] proposed an adaptive neural fuzzy controller based on sliding mode learning method to solve the tracking control problem of spherical unmanned underwater vehicle, and the neural fuzzy network was used to ensure the asymptotic stability of the system.

In this paper, aiming at the UUV trajectory tracking control problem, this paper designs the composite trajectory tracking control algorithm based on the mathematical model, proposes a combination of two sliding mode control based on dynamic surface and trajectory tracking control scheme of dynamic surface finite time sliding mode control (FTDSMC). The stability of the control system is proved by the Lyapunov function, and compared with the traditional PD Control. Then compare and analyze the simulation experiment, and the simulation result demonstrate the effectiveness of the proposed control scheme.

2. Motion Modeling of UUV

It's necessary to study the movement law and establish a model suitable for describing the movement of UUVs in order to better determine the position, attitude and speed. Considering the complexity of the unmanned underwater vehicle and underwater environment degeneration and randomness, combining the mechanism modeling, the simulation control model in this paper is a UUV at low speed which is synergistic propulsion by five propeller, the five thruster configuration is shown in Figure 1. The five degrees of freedom include spatial translation, swaying and trim et al can be realized by the thrusters synergistic propulsion. The roll movement of six degrees of freedom can keep balance by the floater and without additional control. The system control input dimension is the same as the controlled state dimension, so the UUV system is full drive control system.

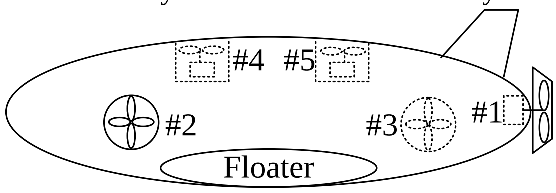

Fig. 1 Unmanned underwater vehicle

Considering the influence of system parameter uncertainty and unmodeled dynamics, the kinematics and dynamics model of UUV are as follows [8, 9]:

$$\dot{\boldsymbol{\eta}} = \boldsymbol{J}(\boldsymbol{\eta})\boldsymbol{v} \tag{1}$$

$$\boldsymbol{M}'\dot{\boldsymbol{v}} + \boldsymbol{C}'(\boldsymbol{v})\boldsymbol{v} + \boldsymbol{D}'(\boldsymbol{v})\boldsymbol{v} + \boldsymbol{g}'(\boldsymbol{\eta}) = \boldsymbol{\tau} + \boldsymbol{\tau}'_d \tag{2}$$

Where $\boldsymbol{\eta} = [x, y, z, \theta, \psi]^{\mathrm{T}}$ is the positions and attitudes vector in the Geodetic Coordinate System, $\boldsymbol{v} = [u, v, w, q, r]^{\mathrm{T}}$ is the linear and angle velocities vector in the Motion Coordinate System, $\boldsymbol{J}(\boldsymbol{\eta})$ is the rotation matrix, $\boldsymbol{M}'$ is the inertia matrix, $\boldsymbol{C}'(\boldsymbol{v})$ is the Coriolis and centrifugal matrix, $\boldsymbol{D}'(\boldsymbol{v})$ is the drag forces matrix, $\boldsymbol{g}(\boldsymbol{\eta})$ is the restoring forces vector, $\boldsymbol{\tau}$ is the control torques vector applied to the underwater vehicles, $\boldsymbol{\tau}'_d$ is the time varying unknown external disturbances vector due to ocean currents and waves.

Considering that the tracking control problem of UUVs is usually studied in the Geodetic Coordinate System, the Lagrange dynamic model in GCS is constructed by establishing the kinematics model (1) and the dynamics model (2) are rewritten as

$$\boldsymbol{M}(\boldsymbol{\eta})\ddot{\boldsymbol{\eta}} + \boldsymbol{C}(\boldsymbol{v},\boldsymbol{\eta})\dot{\boldsymbol{\eta}} + \boldsymbol{D}(\boldsymbol{v},\boldsymbol{\eta})\dot{\boldsymbol{\eta}} + \boldsymbol{g}(\boldsymbol{\eta}) = \boldsymbol{\tau} + \boldsymbol{\tau}'_d \tag{3}$$

Where inertia matrix $\boldsymbol{M}(\boldsymbol{\eta}) = \boldsymbol{M}'\boldsymbol{J}^{-1}(\boldsymbol{\eta})$, fluid damping matrix $\boldsymbol{D}(\boldsymbol{v},\boldsymbol{\eta}) = \boldsymbol{D}'(\boldsymbol{v})\boldsymbol{J}^{-1}(\boldsymbol{\eta})$, Coriolis centripetal force matrix $\boldsymbol{C}(\boldsymbol{v},\boldsymbol{\eta}) = \left[\boldsymbol{C}'(\boldsymbol{v}) - \boldsymbol{M}'\boldsymbol{J}^{-1}(\boldsymbol{\eta})\dot{\boldsymbol{J}}(\boldsymbol{\eta})\right]\boldsymbol{J}^{-1}(\boldsymbol{\eta})$, resilience and moment vector $\boldsymbol{g}(\boldsymbol{\eta}) = \boldsymbol{g}'(\boldsymbol{\eta})$, Disturbing lumped term $\boldsymbol{\tau}'_d = \boldsymbol{d} - \Delta\boldsymbol{C}(\boldsymbol{v},\boldsymbol{\eta})\dot{\boldsymbol{\eta}} - \Delta\boldsymbol{D}(\boldsymbol{v},\boldsymbol{\eta})\dot{\boldsymbol{\eta}} - \Delta\boldsymbol{g}(\boldsymbol{\eta}) - \boldsymbol{l}(\boldsymbol{\eta},\dot{\boldsymbol{\eta}})$, $\boldsymbol{l}(\boldsymbol{\eta},\dot{\boldsymbol{\eta}})$ is unknown function, used to describe unmodeled dynamics.

For the dynamic model of unmanned underwater vehicle in the geodetic coordinate system, it has the following properties:

Property 1 The inertial matrix $\boldsymbol{M}$ is positively definite and bounded by real symmetry:

$$\boldsymbol{M}(\boldsymbol{\eta}) = \boldsymbol{M}^T(\boldsymbol{\eta}) > 0$$

$$\lambda_{M_1} \le \|\varsigma\|^2 \le \varsigma^T \boldsymbol{M}(\boldsymbol{\eta})\varsigma \le \lambda_{M_2} \|\varsigma\|^2 \tag{4}$$

Property 2 The derivative of inertia matrix $\dot{\boldsymbol{M}}$ and the coriolis centripetal force matrix $\boldsymbol{C}$ satisfy the property:

$$\varsigma^T \left[\dot{\boldsymbol{M}}(\boldsymbol{\eta}) - 2\boldsymbol{C}(\boldsymbol{v},\boldsymbol{\eta}) \right] \varsigma = 0 \Rightarrow \dot{\boldsymbol{M}}(\boldsymbol{\eta}) = 2\boldsymbol{C}(\boldsymbol{v},\boldsymbol{\eta}) \tag{5}$$

Property 3 The fluid damping matrix $\boldsymbol{D}$ satisfies the property:

$$\boldsymbol{D}(\boldsymbol{v},\boldsymbol{\eta}) > 0 \tag{6}$$

3. Controller Design

The text of ***Assumption 1*** In complex marine environment, the unknown disturbance terms of wind, wave and current are bounded, $\|\dot{\boldsymbol{\tau}}_d\| \le \omega_d$, the boundary ω_d is a standard vector.

In order to design a finite-time dynamic plane-slip tracking controller, some basic knowledge is introduced.

Consider the following system:

$$\dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x}),\ \boldsymbol{f}(0) = 0 \tag{7}$$

Where $\boldsymbol{x} = \left[x_1, x_2, \dots, x_n \right]^T \in \boldsymbol{R}^n$ is state vector. $\boldsymbol{f}(\boldsymbol{x}) = \left[f_1(\boldsymbol{x}), \dots, f_n(\boldsymbol{x}) \right]^T \in \boldsymbol{R}^n$ is continuous vector.

Lemma 1**[10]** Suppose there is a Lyapunov function $V(\boldsymbol{x})$ defined in $\boldsymbol{U} \subset \boldsymbol{R}^n$. And there is a positive real number $\kappa \in \boldsymbol{R}^+$ and $\iota \in (0,1)$, so that the following is true:

(1) For any non-zero $\boldsymbol{x}$, $V(\boldsymbol{x})$ is positive definite.

(2) If $\dot{V}(\boldsymbol{x}) + aV^b(\boldsymbol{x}) \le 0$, then the system is globally finite time stable, and the stabilization time $T(\boldsymbol{x}_0)$ depends on the initial state of $\boldsymbol{x}_0$, and defined as

$$T(\boldsymbol{x}_0) \le \frac{V^{1-b}(\boldsymbol{x}_0)}{a(1-b)} \tag{8}$$

Define variable $\boldsymbol{x}_1 = \boldsymbol{\eta}$ and $\boldsymbol{x}_2 = \dot{\boldsymbol{\eta}}$.Then, Lagrange dynamic model (3) of the UUV in complex environment can be written as

$$\begin{cases} \dot{\boldsymbol{x}}_1 = \boldsymbol{x}_2 \\ \dot{\boldsymbol{x}}_2 = \boldsymbol{F}(\boldsymbol{x}_1, \boldsymbol{x}_2) + \boldsymbol{G}(\boldsymbol{x}_1)\boldsymbol{\tau} + \boldsymbol{\tau}_d \end{cases} \tag{9}$$

Where $\boldsymbol{G}(\boldsymbol{x}_1) = \boldsymbol{M}^{-1}(\boldsymbol{\eta})$, $\boldsymbol{F}(\boldsymbol{x}_1, \boldsymbol{x}_2) = -\boldsymbol{M}^{-1}(\boldsymbol{\eta}) \left[\boldsymbol{C}(\boldsymbol{v},\boldsymbol{\eta})\dot{\boldsymbol{\eta}} + \boldsymbol{D}(\boldsymbol{v},\boldsymbol{\eta})\dot{\boldsymbol{\eta}} + \boldsymbol{g}(\boldsymbol{\eta}) \right]$, $\boldsymbol{\tau}_d = \boldsymbol{M}^{-1}(\boldsymbol{\eta})(\boldsymbol{\tau}'_d + \Delta\boldsymbol{\tau})$, $\Delta\boldsymbol{\tau} = \boldsymbol{\tau} - \boldsymbol{\tau}_c$.

On the basis, the Finite-Time Dynamic Surface Sliding Mode Control (FTDSMC) presented in this paper needs to use the following transformation:

$$\boldsymbol{e}_1 = \boldsymbol{x}_1(t) - \boldsymbol{x}_d(t),\ \boldsymbol{e}_2 = \boldsymbol{x}_2 - \boldsymbol{\sigma}_b,\ \boldsymbol{\varepsilon} = \boldsymbol{\sigma}_b - \boldsymbol{\sigma} \tag{10}$$

Where $\boldsymbol{x}_d(t) = \boldsymbol{\eta}_d(t)$ is the desired track, $\boldsymbol{e}_1$ is the tracking error, $\boldsymbol{e}_2$ is dynamic surface error, $\boldsymbol{\sigma}_b$ is the first order filter output, the input is $\boldsymbol{\sigma}$, $\boldsymbol{\varepsilon}$ is the first order filter output error.

The block diagram of the FTDSMC control system is shown in figure 2. The specific design process is as follows:

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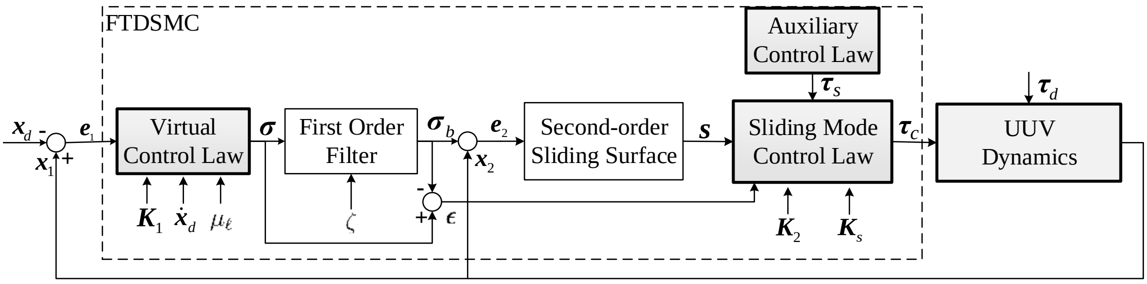

Fig.2 System block diagram of FTDSMC

Step 1: According to the formula (10), let $\boldsymbol{x}_2 = \boldsymbol{\sigma}_b$ is the virtual control law filter output, then the virtual control law $\boldsymbol{\sigma}$ can be designed as:

$$\boldsymbol{\sigma} = -\boldsymbol{K}_1 \tanh(\frac{\boldsymbol{e}_1}{\mu_l}) + \dot{\boldsymbol{x}}_d \tag{11}$$

Where $\mu_l > 0$ is a constant with small value, $\boldsymbol{K}_1 \in \boldsymbol{R}^{6\times6}$ is a positive definite diagonal matrix: $\tanh(\frac{e_1}{\mu_l}) = \left[\tanh(\frac{e_{11}}{\mu_l}), \tanh(\frac{e_{12}}{\mu_l}), \tanh(\frac{e_{13}}{\mu_l}), \tanh(\frac{e_{14}}{\mu_l}), \tanh(\frac{e_{15}}{\mu_l}), \tanh(\frac{e_{16}}{\mu_l})\right]^T$

To avoid differentiation of $\boldsymbol{\sigma}$, we introduce a new variable $\boldsymbol{\sigma}_b$ by the first order filter. This can be expressed as following:

$$\varsigma \dot{\boldsymbol{\sigma}}_b + \boldsymbol{\sigma}_b = \boldsymbol{\sigma}, \boldsymbol{\sigma}_b(0) = \boldsymbol{\sigma}(0) \tag{12}$$

Where $\varsigma > 0$ is the filtering time constant. According to the formula(9), the derivative of $\boldsymbol{e}_1$ can be expressed:

$$\dot{\boldsymbol{e}}_1 = \boldsymbol{x}_2 - \dot{\boldsymbol{x}}_d = \boldsymbol{e}_2 + \boldsymbol{\varepsilon} - \boldsymbol{K}_1 \tanh(\frac{e}{\mu_l}) \tag{13}$$

Step 2: According to (10) and (13),

$$\dot{\boldsymbol{e}}_1 = \boldsymbol{e}_2 + \boldsymbol{\varepsilon} - \boldsymbol{K}_1 \tanh(\frac{e_1}{\mu_l})$$
$$\dot{\boldsymbol{e}}_2 = \boldsymbol{F}(\boldsymbol{x}_1, \boldsymbol{x}_2) + \boldsymbol{G}(\boldsymbol{x}_1)\boldsymbol{\tau}_c + \boldsymbol{\tau}_d + \frac{\boldsymbol{\varepsilon}}{\varsigma} \tag{14}$$

We select two sliding mode variables:

$$\boldsymbol{\rho}_1 = \boldsymbol{e}_2$$
$$\boldsymbol{\rho}_2 = \dot{\boldsymbol{e}}_2 \tag{15}$$

And then define a second-order sliding surface:

$$\boldsymbol{s} = \boldsymbol{\lambda}\boldsymbol{\rho}_1 + \boldsymbol{\rho}_2 + \gamma \int_0^t (\boldsymbol{\lambda}\boldsymbol{\rho}_1 + \boldsymbol{\rho}_2) d\tau \tag{16}$$

Where $\lambda \in \boldsymbol{R}^{6\times6}$ and $\gamma \in \boldsymbol{R}^{6\times6}$ is positive definite diagonal matrix.
FTDSMC control law is designed as:

$$\boldsymbol{\tau}_c = \boldsymbol{G}^{-1}(-\boldsymbol{F} - \varsigma^{-1}\boldsymbol{\varepsilon} + \boldsymbol{\tau}_s) \tag{17}$$

Where $\boldsymbol{\tau}_s$ can be determined by the following equation:

$$\dot{\boldsymbol{\tau}}_s = -\lambda \boldsymbol{\rho}_2 - \boldsymbol{K}_2 \operatorname{sgn}(\boldsymbol{s}) - \gamma(\boldsymbol{\lambda}\boldsymbol{\rho}_1 + \boldsymbol{\rho}_2) - \boldsymbol{K}_s \boldsymbol{s} \tag{18}$$

Where $\boldsymbol{K}_2 \in \boldsymbol{R}^{6\times 6}$ and $\boldsymbol{K}_s \in \boldsymbol{R}^{6\times 6}$ is positive definite diagonal matrix.

According to the definition of the sliding mode variable $\boldsymbol{\rho}_1$ and $\boldsymbol{\rho}_2$, the derivative can be expressed as:

$$\begin{cases} \dot{\boldsymbol{\rho}}_1 = \boldsymbol{\rho}_2 \\ \dot{\boldsymbol{\rho}}_2 = \dot{\boldsymbol{\tau}}_d - \boldsymbol{\lambda}\boldsymbol{\rho}_2 - \boldsymbol{K}_2 \operatorname{sgn}(\boldsymbol{s}) - \gamma(\boldsymbol{\lambda}\boldsymbol{\rho}_1 + \boldsymbol{\rho}_2) - \boldsymbol{K}_s \boldsymbol{s} \end{cases} \tag{19}$$

Then the derivative expression of the sliding surface is expressed as:

$$\dot{\boldsymbol{s}} = \dot{\boldsymbol{\tau}}_d - \boldsymbol{K}_2 \operatorname{sgn}(\boldsymbol{s}) - \boldsymbol{K}_s \boldsymbol{s} \tag{20}$$

4. Stability Analysis

For the UUV dynamic model in the complex environment(9), we adopt the track tracking controller(17) and virtual control law(11) to guarantee the tracking error $\boldsymbol{e}_1$**,** filter output error $\boldsymbol{\varepsilon}$ and sliding mode surface $\boldsymbol{s}$ tend to the area within the finite time T .

Proof: Substituting (11) into (13), $\dot{\boldsymbol{e}}_1$ can be rewritten as:

$$\dot{\boldsymbol{e}}_1 = \boldsymbol{\varepsilon} - \boldsymbol{K}_1 \tanh(\frac{\boldsymbol{e}_1}{\mu_l}) \tag{21}$$

According to the definition of filter output error $\boldsymbol{\varepsilon}$ and Equation (12), $\dot{\boldsymbol{\varepsilon}}$ can be expressed as the following:

$$\dot{\boldsymbol{\varepsilon}} = -\frac{\boldsymbol{\varepsilon}}{\varsigma} + \boldsymbol{K}(\cdot) = -\frac{\boldsymbol{\varepsilon}}{\varsigma} + \mu_l^{-1} diag\left[\boldsymbol{K}_{1i} \operatorname{sech}^2(\frac{\boldsymbol{e}_{1i}}{\mu_l})\right]\dot{\boldsymbol{e}}_1 - \ddot{\boldsymbol{x}}_d \tag{22}$$

Consider the following Lyapunov function:

$$V = \frac{1}{2}\boldsymbol{s}^T\boldsymbol{s} + \frac{1}{2}\boldsymbol{e}_1^T\boldsymbol{e}_1 + \frac{1}{2}\boldsymbol{\varepsilon}^T\boldsymbol{\varepsilon} \tag{23}$$

Adopting the Matrix Young Inequality to Equation (20), (21) and (22), the derivative of V with respect to time can be organized into:

$$\dot{V} \le \boldsymbol{s}^T\left[\boldsymbol{G}\dot{\boldsymbol{\tau}}_d + \dot{\boldsymbol{G}}\boldsymbol{\tau}_d - \boldsymbol{K}_2 \operatorname{sgn}(\boldsymbol{s}) - \boldsymbol{K}_s\boldsymbol{s}\right] - \boldsymbol{e}_1^T\boldsymbol{K}_1 \tanh(\frac{e}{\mu_l}) + \boldsymbol{e}_1^T\boldsymbol{\varepsilon} - \frac{\|\boldsymbol{\varepsilon}\|^2}{\varsigma} + \frac{1}{2}\|\boldsymbol{\varepsilon}\|^2\|\boldsymbol{K}(\cdot)\|^2 + \frac{1}{2} \tag{24}$$

According the *Assumption 1*, under complex marine environment, the unknown disturbance terms of wind, wave and current $\dot{\tau}_d$ are bounded as $\|\dot{\boldsymbol{\tau}}_d\| \le \omega_d$. The filter constants are $\varsigma^{-1} = \varsigma_0^2 + \frac{1}{2} + \frac{\boldsymbol{M}_B^2}{2} + \mu^*$, where μ^* is positive constant, so we can get:

$$\dot{V} \le -\alpha_1\|\xi_1\|^2 - \varphi_1\|\xi_1\| + \varpi_1 - \lambda_{\min}(\boldsymbol{K}_2) - 1 \ \|\boldsymbol{s}\| + \frac{\varpi_d^2}{2} \tag{25}$$

Where $\alpha_1 = \min(2\lambda_{\min}(\boldsymbol{K}_2) - 2, 2\mu^*)$, $\varphi_1 = \min(\sqrt{2}\lambda_{\min}(\boldsymbol{K}_1), 2\sqrt{2}\varsigma_0)$, $\xi_1 = \left[\frac{\boldsymbol{e}_1^T}{\sqrt{2}}, \frac{\boldsymbol{\varepsilon}^T}{\sqrt{2}}\right]^T$.

Let the controller parameter $\boldsymbol{K}_2$ which satisfy the inequality $\lambda_{\min}(\boldsymbol{K}_2) > 1$, and get the following formula

$$\dot{V} \le \varpi - \varphi\|\xi\| \tag{26}$$

By the definition of the variable ξ, $V = \|\xi\|^2$. The following results can be obtained.

$$\dot{V} = \varpi - \varphi\sqrt{V} \tag{27}$$

If $\|\xi\| > \varpi / \varphi$, $\dot{V} < 0$, this means that the gradual decrease of V drives the trajectory of the closed-loop system to reach the range $\|\xi\| > \varpi / \varphi$, so that the trajectory of the closed-loop system is ultimately bounded:

$$\lim_{t\to\infty} \xi \in \quad \|\xi\| > \varpi / \varphi \tag{28}$$

According to *Lemma 1*, the system states ξ tend to ϖ / φ in finite time. It can be seen that sliding surface parameters $\boldsymbol{\rho}_1$ and $\boldsymbol{\rho}_2$ can be made close to zero and the sliding surface $\boldsymbol{s} = 0$ by properly selecting design parameters. This completes the proof.

5. Simulation Experiment

In order to verify the effectiveness and superiority of the proposed trajectory tracking control strategy, the parameters of the underwater vehicle developed by Tokyo University of Marine Science and technology [11] were used for simulation analysis. In a complex Marine environment, in order to achieve the high-precision tracking control target, the disturbance term $\boldsymbol{\tau}_d$ of wind, wave, current and the desired track $\boldsymbol{\eta}_d$ of UUV are given as follows:

$$\boldsymbol{\tau}_d = \begin{bmatrix} 2+6\sin(4t-\pi/3) \\ 3+2\cos(2t-\pi/6) \\ 5+4\sin(3t-\pi/4) \\ 4+2\cos(0.5t-\pi/4) \\ 3+2\sin(0.5t+\pi/6) \end{bmatrix} \quad \boldsymbol{\eta}_d(t) = \begin{bmatrix} \sin(0.01t) \\ \cos(0.02t) \\ 2\sin(0.01t)+\cos(0.01t) \\ -0.2\cos(0.01t)+0.1\sin(0.01t) \\ 0.2\cos(0.01t)-0.2\sin(0.01t) \end{bmatrix} \tag{29}$$

In order to prove the superiority of FTDSMC control strategy in this paper, compared with traditional PD control strategy, PD controller can be expressed as follows:

$$\boldsymbol{\tau}_{PD} = \boldsymbol{k}_p \boldsymbol{e}_1 + \boldsymbol{k}_d \boldsymbol{e}_2 \tag{30}$$

Where $\boldsymbol{\tau}_{PD}$ is the output vector of PD controller, $\boldsymbol{e}_1$ is the feedback error vector, $\boldsymbol{e}_2$ is the derivative of feedback error vector, $\boldsymbol{k}_p$ is the proportionality coefficient, $\boldsymbol{k}_d$ is the differential time constant. Relevant parameters of PD controller are selected as follows:

$$\boldsymbol{k}_p = \begin{bmatrix} 150 & 0 & 0 & 0 & 0 \\ 0 & 125 & 0 & 0 & 0 \\ 0 & 0 & 100 & 0 & 0 \\ 0 & 0 & 0 & 300 & 0 \\ 0 & 0 & 0 & 0 & 300 \end{bmatrix} \quad \boldsymbol{k}_d = \begin{bmatrix} 100 & 0 & 0 & 0 & 0 \\ 0 & 50 & 0 & 0 & 0 \\ 0 & 0 & 50 & 0 & 0 \\ 0 & 0 & 0 & 200 & 0 \\ 0 & 0 & 0 & 0 & 200 \end{bmatrix} \tag{31}$$

Simulation experiment is conducted on the basis of the above parameters, compared with the PD control strategy, the expected and actual unidimensional path tracking simulation results of the Unmanned Underwater Vehicle is shown in Figure 3 and Figure 5, the solid blue line is expected track, the red dotted line is the actual path. We can get from the figures, the FTDSMC control strategy can be rapid accurately track the desired track, has strong superiority compared to the traditional PD control.

Figure 4 and Figure 6 are the dynamic curve of the track error. By comparing the simulation curves of the two control strategies, it can be seen that the FTDSMC control strategy can ensure the tracking error to be arbitrarily small, while the PD controller can only ensure the convergence to the region near zero. In addition, it can be clearly seen from Figure 4 that the tracking error tends to be within the ideal error range in a limited time, which reflects the good tracking performance of the control algorithm proposed in this paper.

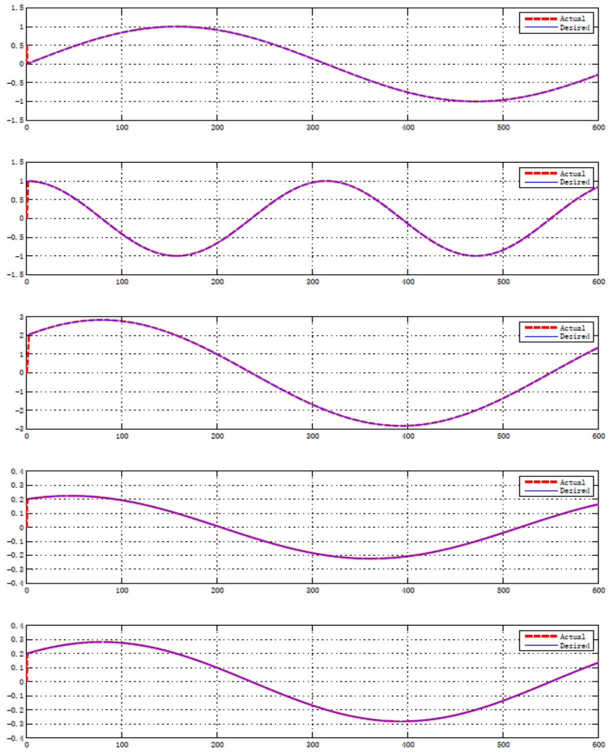

Fig.3 Comparisons on separate trajectory for FTDSMC

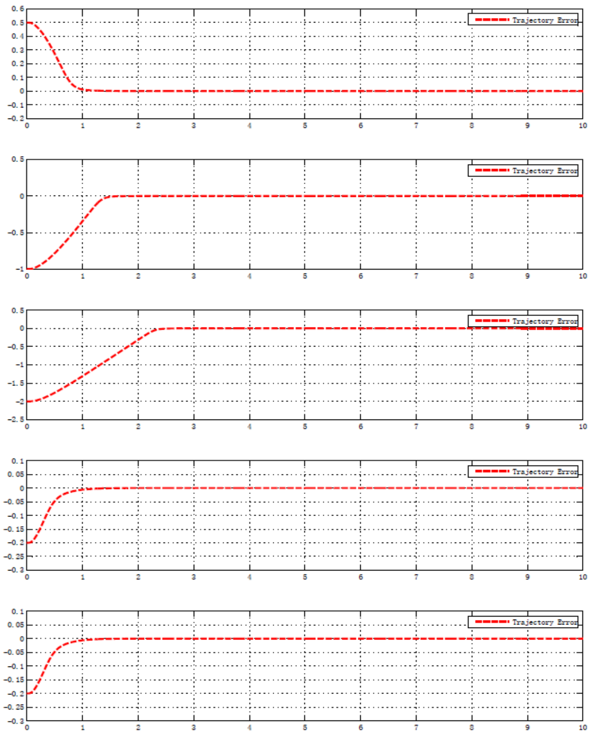

Fig.4 Comparisons on tracking errors for FTDSMC

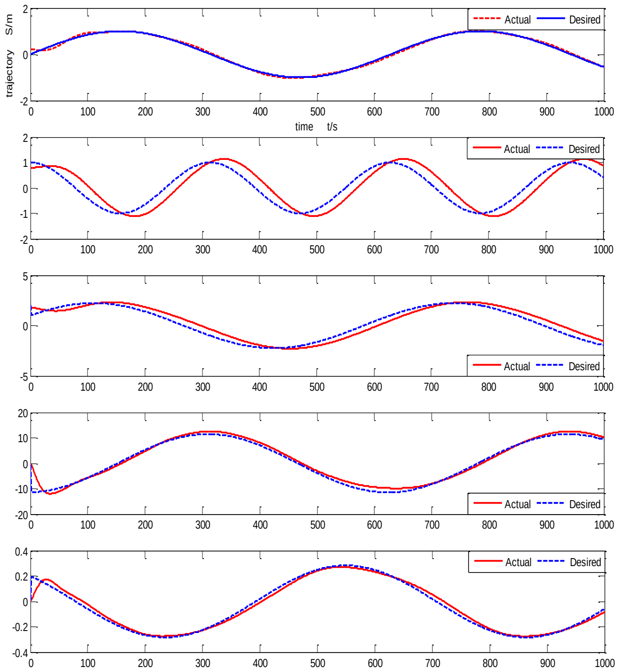

Fig.5 Comparisons on separate trajectory for PD control

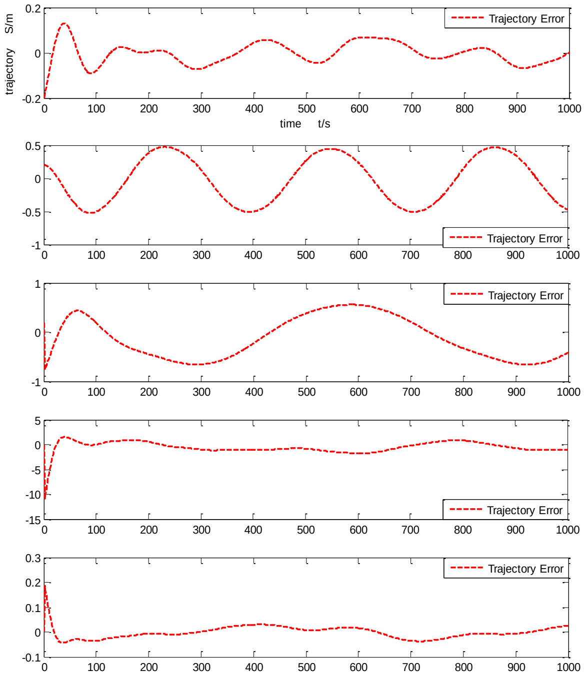

Fig.6 Comparisons on tracking errors for PD control

6. Conclusion

In this paper, to solve the problem of high-precision three-dimensional track tracking control of UUV, a finite-time dynamic surface sliding mode composite track tracking control scheme is proposed considering the uncertainties and unknown external disturbances of the system. Combining dynamic surface control with second-order sliding mode control design method, a second-order sliding mode surface is designed to realize the finite-time track tracking control of the UUV under complex marine environment. The combination of dynamic surface and second-order sliding mode control reduces the need for gain of sliding mode control. Finally, the feasibility and effectiveness of the proposed control strategy are verified by simulation experiment, and verified by comparison with PD control strategy. From the simulation results, the effectiveness of the proposed FTDSMC scheme is indicated.

Acknowledgments

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