Fast Terminal Sliding Mode Control based on Super-twisting Algorithm for Trajectory Tracking Control of Uncertain Nonlinear Systems

Hoang Duc Long

***Abstract*—This paper presents a new approach for designing a fast terminal sliding mode control based on the super-twisting algorithm for uncertain nonlinear systems. The proposed control combines the advantages of fast terminal sliding mode control and the super-twisting algorithm to achieve rapid convergence, robustness, and chattering reduction in the control of nonlinear systems. The fast terminal sliding mode control law is designed to drive the system state to a sliding surface in finite time, while the super-twisting algorithm provides effective control action near the sliding surface to further enhance system performance. The theoretical framework of the control design is presented, along with stability analysis using Lyapunov functions and simulation results with an inverted pendulum on a cart to demonstrate the effectiveness of the proposed approach. Comparative studies with the conventional sliding mode control method and the fast terminal sliding mode control highlight the superior performance of the fast terminal sliding mode control based on the super-twisting algorithm. The proposed control strategy shows promise for applications in uncertain nonlinear systems where fast and precise control is required.**

***Keywords*—Fast Terminal Sliding Mode Control, Super-twisting Algorithm, Uncertain Nonlinear Systems, Inverted Pendulum on Cart, Chattering Reduction, Lyapunov Function.**

I. INTRODUCTION

The control of uncertain nonlinear systems is a persistent and fundamental challenge in control engineering, arising in a wide range of applications including robotics, aerospace, automotive systems, and industrial automation [1-5]. These systems are often characterized by complex dynamics, external disturbances, and parametric uncertainties that make conventional linear control strategies inadequate for ensuring desired performance and stability [6-10]. To address these limitations, robust nonlinear control methodologies-particularly sliding mode control (SMC)-have been extensively studied and applied due to their inherent robustness to uncertainties and disturbances [11-15]. Classical SMC, while robust, suffers from several drawbacks, most notably the phenomenon of chattering caused by high-frequency switching in the control signal. This not only deteriorates control accuracy but can also lead to hardware degradation in practical implementations. To overcome this limitation, higher-order sliding mode (HOSM) techniques have been introduced, such as the nominal terminal sliding mode control (Nominal TSC) [16-20] and the fast terminal sliding mode control (Fast TSC) [21-25], among which the super-twisting algorithm (STA) [26-28] has gained prominence due to its ability to maintain robustness while generating a continuous control signal, thereby significantly reducing chattering.

The fast terminal sliding mode control is characterized by its ability to drive the system state to a sliding surface in finite time, leading to rapid stabilization and improved transient response [21-25]. This control strategy has been widely adopted in various applications due to its robustness and ability to handle uncertainties. However, traditional fast terminal sliding mode control methods may suffer from chattering, a phenomenon associated with high-frequency control switching near the sliding surface. To address this challenge and further enhance the performance of fast terminal sliding mode control for nonlinear systems, this paper proposes a novel control approach based on the super-twisting algorithm. The super-twisting algorithm is a second-order sliding mode control technique that offers improved robustness and chattering reduction compared to traditional sliding mode control methods [26-28]. By integrating the super-twisting algorithm with fast terminal sliding mode control, the author aims to leverage the benefits of both approaches to achieve superior control performance in nonlinear systems.

In this paper, the author presents the theoretical framework for the design of fast terminal sliding mode control based on the super-twisting algorithm. The key aspects of the control strategy will be discussed, including the formulation of the control law, stability analysis, and practical implementation considerations. Simulation results are provided to demonstrate the effectiveness of the proposed approach in controlling nonlinear systems and compare its performance with the nominal terminal sliding mode control and the fast terminal sliding mode control.

The main contributions of this work are as follows:

1. **Design of a novel sliding surface** that guarantees finite-time convergence of the system states to the desired trajectory.

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2. **Integration of the super-twisting algorithm** to generate continuous control effort, thereby addressing chattering while preserving robustness against uncertainties.
3. **Rigorous Lyapunov-based stability analysis**, establishing theoretical guarantees for the finite-time convergence and stability of the closed-loop system.
4. **Comprehensive simulation studies** using an inverted pendulum on a cart system to validate the performance of the proposed controller, including comparative analysis against Nominal TSC and Fast TSC approaches.

The remainder of the paper is structured as follows: The design of the conventional terminal sliding mode control is given in Section 2, and the design of the fast terminal sliding mode control is presented in Section 3. After that, the fast terminal sliding mode control based on the super-twisting algorithm simulation results is designed in Section 4. The proposed control is applied for an inverted pendulum on a cart in Section 5 and compared with nominal TSC and fast TSC to show the efficiency of the proposed method. Some conclusions about the proposed method are given in Section 6.

II. DESIGN OF CONVENTIONAL TERMINAL SLIDING MODE CONTROL

A nonlinear second-order system affected by unknown external disturbances is described as below [16-20]

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = f(\mathbf{x}) + g(\mathbf{x})u + d(t) \end{cases} \tag{1}$$

where the vector of state variables is $\mathbf{x} = [x_1 \quad x_2]^T$; $f(\mathbf{x})$ and $g(\mathbf{x})$ are nonlinear function with uncertainties; $d(t)$ denotes bounded unknown disturbances $\left(|d(t)| \le l_d\right)$.

Assume that the functions $f(\mathbf{x})$ and $g(\mathbf{x})$ include two parts: The nominal parts ($f_0(\mathbf{x})$ and $g_0(\mathbf{x})$) and the uncertain bounded parts ($\Delta f(\mathbf{x})$ and $\Delta g(\mathbf{x})$) as follows

$$f(\mathbf{x}) = f_0(\mathbf{x}) + \Delta f(\mathbf{x}) \tag{2}$$

$$g(\mathbf{x}) = g_0(\mathbf{x}) + \Delta g(\mathbf{x}) \tag{3}$$

The sliding function is selected as

$$s = \dot{e} + \beta e^{\frac{q}{p}} \tag{4}$$

where $e = x_1 - x_d$; $\beta > 0$; $p, q\,(p > q)$ are positive odd numbers.

The controller is designed as

$$u = -\frac{1}{g(\mathbf{x})}\left(f(\mathbf{x}) + \beta \frac{q}{p} e^{\frac{q}{p}-1}\dot{e} - \ddot{x}_d + (l_d + \gamma)\operatorname{sign}(s) \right) \tag{5}$$

where $\gamma > 0$.

Analysis of stability:

From (4) and (5),

$$\begin{aligned} \dot{s} &= \ddot{e} + \beta \frac{q}{p} e^{\frac{q}{p}-1}\dot{e} \\ &= f(\mathbf{x}) + g(\mathbf{x})u + d(t) - \ddot{x}_d + \beta \frac{q}{p} e^{\frac{q}{p}-1}\dot{e} \\ &= f(\mathbf{x}) - \left(f(\mathbf{x}) + \beta \frac{q}{p} x_1^{\frac{q}{p}-1} x_2 - \ddot{x}_d + (l_d + \gamma)\operatorname{sign}(s) \right) \\ &\quad + d(t) - \ddot{x}_d + \beta \frac{q}{p} e^{\frac{q}{p}-1}\dot{e} = d(t) - (l_d + \gamma)\operatorname{sign}(s) \end{aligned} \tag{6}$$

The Lyapunov function is selected as below

$$V = \frac{s^2}{2} \tag{7}$$

So that

$$\dot{V} = s\dot{s} = sd(t) - (l_d + \gamma)|s| \le -\gamma |s| \tag{8}$$

From (8), the sliding function s convergences to zero that leads to the nonlinear system (1) is stable at the equilibrium point. The finite-time t_s which the system (1) can reach the sliding surface is given by

$$t_s = \frac{p}{\beta(p-q)} |e(0)|^{\frac{p-q}{p}} \tag{9}$$

III. DESIGN OF GLOBAL FAST TERMINAL SLIDING MODE CONTROL

Considering the global fast terminal sliding surface as follows [21-25].

$$s = \dot{e} + \alpha e + \beta e^{\frac{q}{p}} \tag{10}$$

where $e = x_1 - x_d$; $\alpha, \beta > 0$ and $q, p\,(q < p)$ are positive odd numbers.

The global fast terminal sliding mode controller is designed as

$$u = -\frac{1}{g(\mathbf{x})}\left(\begin{aligned} & f(\mathbf{x}) + \alpha \dot{e} + \beta \frac{q}{p} e^{\frac{q}{p}-1}\dot{e} - \ddot{x}_d \\ & + \frac{\alpha}{2}s + \frac{\beta}{2^{\frac{q}{p}}} s^{2\frac{q}{p}-1} + l_d \operatorname{sign}(s) \end{aligned} \right) \tag{11}$$

Analysis of stability:

The Lyapunov function is chosen as (7). Therefore,

$$\dot{V} = s\dot{s} = -\alpha \frac{s^2}{2} - \beta \left(\frac{s^2}{2} \right)^{\frac{q}{p}} + sd(t) - l_d |s| \le -\alpha V - \beta V^{\eta} \tag{12}$$

where $0 < \eta = \dfrac{q}{p} < 1$.

From (12), the $V(t)$ converges to the origin in the finite-time as

$$t_s = \frac{1}{\alpha(1-\eta)} \ln \frac{\alpha V^{1-\eta}(0) + \beta}{\beta} \tag{13}$$

IV. DESIGN OF FAST TERMINAL SLIDING MODE CONTROL BASED ON SUPER-TWISTING ALGORITHM

The fast terminal sliding surface is described as:

$$s = \dots \qquad (14)$$

$$\dots \qquad (15)$$

where constant parameters $0 < \lambda_i < 1,\ \alpha_i > 0$ for $i = 1,2$.

From (14) and (15),

$$\dots + \alpha \dots \qquad (16)$$

Take into account (2) and (3), (16) is rewritten

$$\dots + \alpha_2 | \dots + \Delta g(\mathbf{x}) u + d(t) \qquad (17)$$

Denote $\psi(\mathbf{x},t) = \Delta f(\mathbf{x}) + \Delta g(\mathbf{x}) u + d(t)$. The control law is designed

$$u = -\frac{1}{g_0(\mathbf{x})} \begin{pmatrix} f_0(\mathbf{x}) - \dots e \\ + \alpha_2 | \dots \end{pmatrix} \qquad (18)$$

After that

$$\dots) + v \qquad (19)$$

where v is designed based on the super-twisting algorithm as below

$$v = -k_1 \|s\|^{-\frac{1}{2}} s + w \qquad (20)$$

$$\dots \|^{-\frac{1}{2}} s \qquad (21)$$

Choosing the coefficients k_1 and k_2 that satisfied the following conditions

$$\begin{cases} k_1 > \max\left(\dfrac{4}{3}\delta,\ \dfrac{4\mu\delta + 16\delta\varepsilon^2 + \left(\mu + 4\varepsilon^2 + 3\varepsilon\delta\right)^2}{4\varepsilon(\mu + 3\varepsilon)}, \right) \\ k_2 = k_1 \dfrac{\varepsilon}{2} \end{cases} \qquad (22)$$

where $\alpha, \delta, \mu, \varepsilon$ are arbitrary positive constants.

Theorem 1: Consider the uncertain nonlinear system (1) with uncertain parameters and bounded unknown disturbances. The fast terminal sliding mode control based on the super-twisting algorithm (18) can guarantee the states of (1) converging to an equilibrium position in finite-time if the controller parameters satisfy the conditions (22).

Proof: A Lyapunov function is chosen as follows:

$$V = \left(\mu + 4\varepsilon^2\right)\|s\| + \|w\|^2 - 4\varepsilon \|s\|^{-\frac{1}{2}} w^T s \qquad (23)$$

After that,

$$\begin{aligned} \dot{V} = & \dots + 4\varepsilon^2\right)\left(k_1 - \delta\right) - 2\varepsilon k_2\Big)\|s\|^{\frac{1}{2}} \\ & -\varepsilon \|s\|^{-\frac{1}{2}} \|w\|^2 + \left(\mu + 4\varepsilon^2 - 2k_2 + k_1\varepsilon + 3\varepsilon\delta\right)\|w\| \\ & = -\|s\|^{-\frac{1}{2}} \mathbf{Q}^T \mathbf{\Omega} \mathbf{Q} \end{aligned} \qquad (24)$$

where

$$\mathbf{\Omega} := \begin{bmatrix} \left(\mu + 3\varepsilon^2\right)k_1 - \left(\mu + 4\varepsilon^2\right)\delta & -\dfrac{1}{2}\left(\mu + 4\varepsilon^2 + 3\varepsilon\delta\right) \\ * & \varepsilon \end{bmatrix} > 0;$$

$$\mathbf{Q} := \begin{bmatrix} \|s\|^{\frac{1}{2}} & \|w\| \end{bmatrix}^T$$

From (24), using Rayleigh's inequality to V, it can be obtained that

$$\dot{V} \dots ^{\frac{1}{\dots}} \qquad (25)$$

where $\xi > 0$.

From (25), it can be concluded that the control law (18) and the conditions (22) guarantee the states of the system (1) convergence to an equilibrium point in a finite-time

$$t_s = 2\xi^{-1} V^{\frac{1}{2}}(0) \qquad (26)$$

□

V. SIMULATION RESULTS

In this section, the proposed controller will be applied for an inverted pendulum on a cart that is illustrated in Fig. 1.

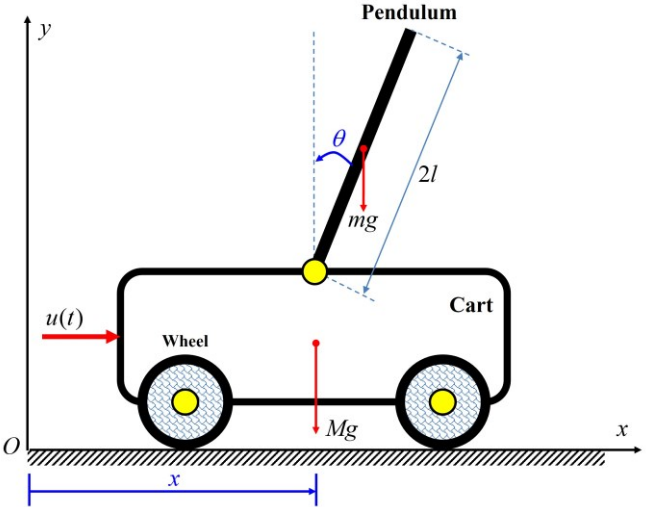

Fig. 1. Model of Inverted Pendulum on Cart.

The mathematic model of the inverted pendulum model is described in the state-space model as below [22]

$$\begin{cases} \dot{\dots} \\ \dot{\dots} + g(\mathbf{x})u + d(t) \end{cases} \qquad (27)$$

where θ is the pendulum angle from vertical (down) (rad); x is cart position coordinate (m); m_c is mass of the cart (kg); m is mass of the pendulum (kg); $2l$ is length of the pendulum (m); g is the gravity acceleration $(kg.m^2)$; u is the control law; $f(\mathbf{x})$ and $g(\mathbf{x})$ are defined

$$f(\mathbf{x}) = f_0(\mathbf{x}) + \Delta f(\mathbf{x}) = \frac{g\sin x_1 - \dfrac{mlx_2^2 \cos x_1 \sin x_1}{m_c + m}}{l\left(\dfrac{4}{3} - \dfrac{m\cos^2 x_1}{m_c + m}\right)} + \Delta f(\mathbf{x})$$

$$g(\mathbf{x}) = g_0(\mathbf{x}) + \Delta g(\mathbf{x}) = \frac{\dfrac{\cos x_1}{m_c + m}}{l\left(\dfrac{4}{3} - \dfrac{m\cos^2 x_1}{m_c + m}\right)} + \Delta g(\mathbf{x})$$

with uncertain parameters $\Delta f(\mathbf{x})$ and $\Delta g(\mathbf{x}) \le 1$ and the external disturbance $d(t) = \sin(t)$.The parameters of the inverted pendulum on cart are used in the simulation: $m_c = 1(kg)$; $m = 0.1(kg)$; $l = 0.5(m)$; $g = 9.81(m/s^2)$. The parameters of controllers: $\alpha = 1$, $\beta = 1$, $p = 7$, $q = 5$, $l_d = 1.1$, $\gamma = 5$, $\alpha_1 = 2$, $\alpha_1 = 1.5$, $\lambda_1 = \lambda_2 = 0.5$, $k_1 = 5$, $k_2 = 1.5$. The desired angle of the inverted pendulum is considered into two cases of tracking trajectories: $\theta_d(t) = 0$ and $\theta_d(t) = \sin t$. The outputs ($\theta(t)$ and $\dot{\theta}(t)$) and the control law ($u(t)$) of Case 1 are illustrated in Fig. 2, Fig.3 and Fig. 4. The outputs ($\theta(t)$ and $\dot{\theta}(t)$) and the control law ($u(t)$) of Case 2 are illustrated in Fig. 5, Fig. 6 and Fig. 7.

In the two cases, the response of the outputs ($\theta(t)$ and $\dot{\theta}(t)$) with the fast terminal sliding mode control based on a super-twisting algorithm are the better results than the response of the nominal terminal sliding control and the fast terminal sliding mode control (Fig. 2,3,5,6). The control laws in two cases of Fast TSC-STA are higher than other algorithms, but the chattering in this case is significantly reduced (Fig. 4, 7).

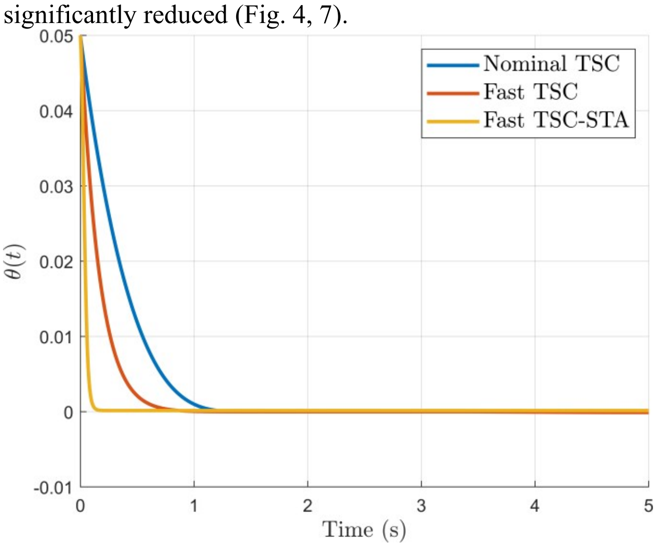

Fig. 2. The angle of the inverted pendulum in Case 1.

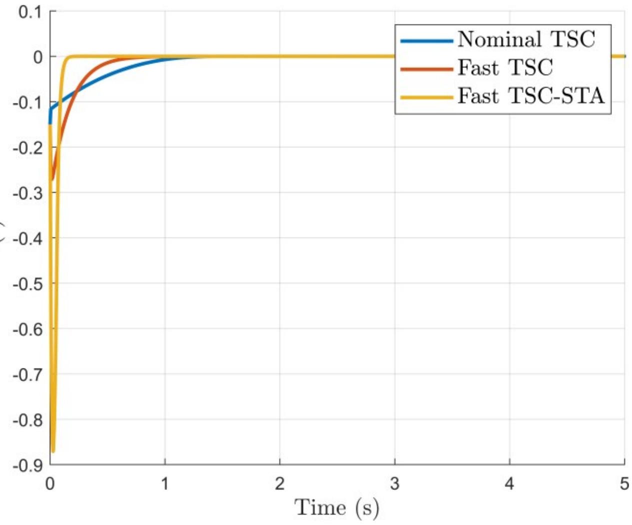

Fig. 3. The angular acceleration of the inverted pendulum in Case 1.

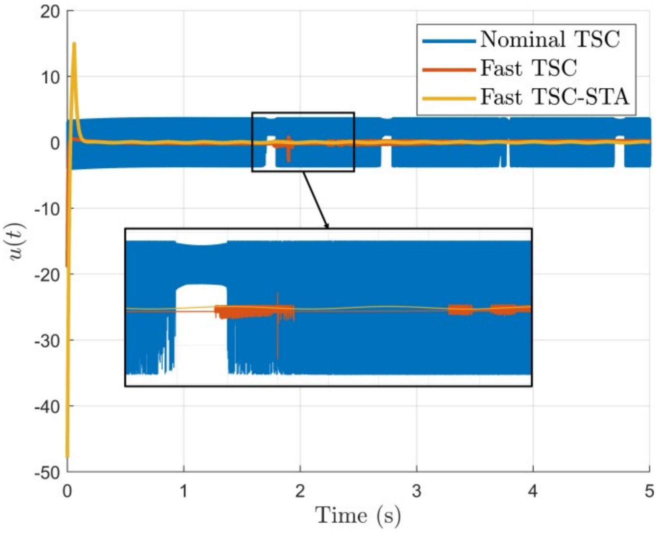

Fig. 4. The control law in Case 1.

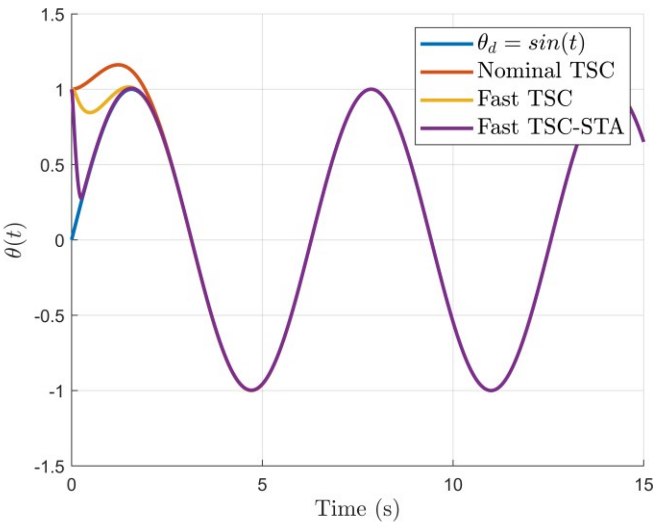

Fig. 5. The angle of the inverted pendulum in Case 2.

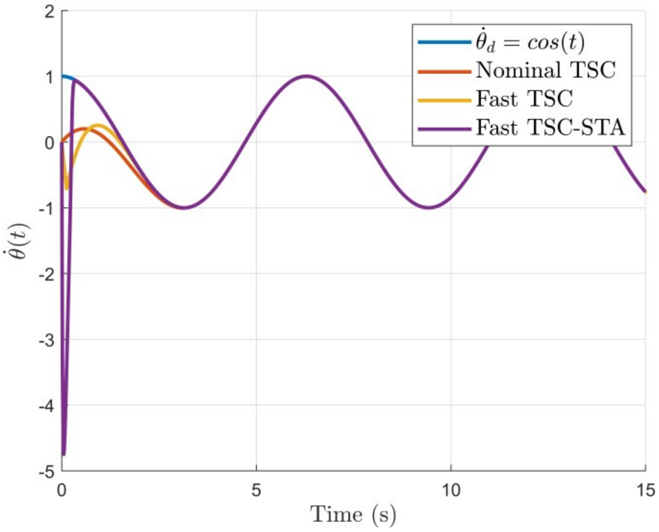

Fig. 6. The angular acceleration of the inverted pendulum in Case 2.

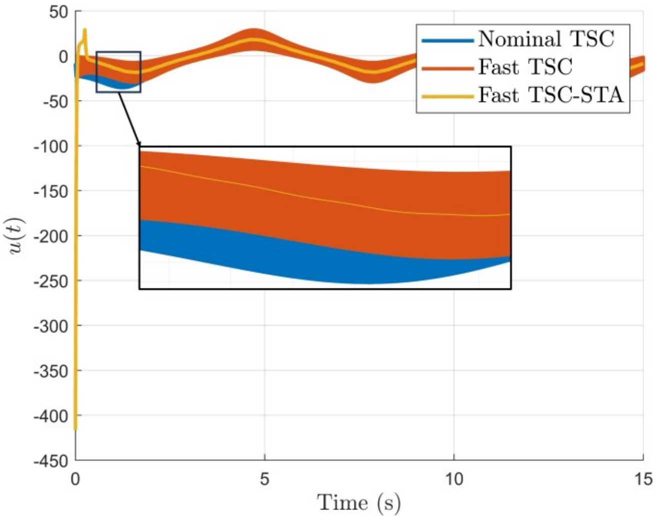

Fig. 7. The control law in Case 2.

VI. CONCLUSIONS

This paper presented a novel fast terminal sliding mode control (FTSMC) approach based on the super-twisting algorithm for trajectory tracking of uncertain nonlinear systems. The proposed method leverages the finite-time convergence of FTSMC and the chattering attenuation capability of the super-twisting algorithm, yielding a robust control strategy with improved tracking accuracy and reduced steady-state error. Rigorous Lyapunov-based stability analysis established the finite-time convergence of the system states, and simulation results on an inverted pendulum system validated the theoretical findings. Comparative studies demonstrated that the proposed controller outperforms conventional sliding mode and standard FTSMC approaches in terms of convergence speed, robustness, and control smoothness.

In the future, the author will focus on several directions related to this research. First, experimental validation on hardware platforms such as robotic manipulators or autonomous vehicles will be pursued to evaluate real-time performance under sensor noise and actuator limitations. Second, the extension of the proposed control scheme to higher-order and multi-input multi-output (MIMO) systems will be investigated. Additionally, adaptive or learning-based mechanisms could be integrated to estimate and compensate for unknown system parameters or time-varying disturbances online. Finally, hybrid control architectures that combine the proposed method with optimization-based approaches, such as model predictive control (MPC), may further enhance performance in complex, constraint-driven environments.

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