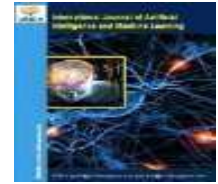




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Sliding Mode Control: Evolution, Advanced Strategies, and Future Research Directions

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Abstract

Sliding Mode Control (SMC) is a widely adopted nonlinear control methodology for systems affected by parameter uncertainties, external disturbances, and modeling inaccuracies. Originating from Variable Structure Control (VSC) in the late 1950s, SMC has evolved significantly to improve robustness, reduce chattering, enhance convergence performance, and address the challenges of modern engineering systems. This paper presents an overview of the evolution and advanced strategies of SMC, highlighting its fundamental concepts, mathematical formulation, stability characteristics, advantages, limitations, and practical applications. The development of classical first order SMC, higher-order SMC, terminal and non-singular terminal SMC, adaptive SMC, integral SMC, observer-based SMC, and disturbance observer-based SMC is discussed. Recent advancements, including intelligent SMC, learning-based SMC, fractional-order SMC, and event-triggered SMC, are also reviewed with emphasis on their role in improving adaptability and implementation efficiency. Furthermore, emerging applications of SMC in robotics, autonomous systems, renewable energy, power electronics, and cyber-physical systems are highlighted. The paper also identifies key research challenges, including chattering reduction, computational complexity, stability analysis of intelligent methods, and real-time implementation. Finally, future research directions are discussed toward developing more adaptive, efficient, and intelligent SMC frameworks for complex uncertain systems.

Keyword: Sliding Mode Control, Variable Structure Control, Nonlinear Control, Robust Control, Advanced Control Methods, Adaptive Control, Intelligent Control, Learning-Based Control, Survey.

1. Introduction

Control systems constitute the backbone of modern engineering applications, including industrial automation, robotics, aerospace systems, automotive engineering, power electronics, renewable energy systems, biomedical devices, marine systems, and autonomous vehicles. The primary objective of a control system is to ensure accurate reference tracking while maintaining stability, fast dynamic response, robustness, and high control precision. However, practical systems are inherently nonlinear and are often influenced by parameter uncertainties, external disturbances, modeling errors, actuator nonlinearities, time delays, and measurement noise. These challenges significantly limit the performance of conventional linear control methods and have motivated the development of robust nonlinear control strategies capable of maintaining satisfactory performance under uncertain operating conditions [1]–[8].

Among the various robust nonlinear control techniques, Sliding Mode Control (SMC) has emerged as one of the most effective approaches because of its inherent robustness, simple controller design, finite-time convergence, and strong disturbance rejection capability. Originating from the concept of Variable Structure Control (VSC) introduced by Emelyanov in the late 1950s and systematically developed by Utkin in the 1970s, SMC has evolved into a mature control framework with extensive theoretical foundations and practical significance [1]–[3]. The fundamental principle of SMC is to design a sliding manifold such that system trajectories are first driven toward the manifold and subsequently constrained to evolve along it. Once the sliding motion is established, the closed loop system exhibits remarkable insensitivity to matched uncertainties and external disturbances, making SMC particularly attractive for nonlinear and uncertain systems [4], [5], [9], [10].

Despite these advantages, classical first-order SMC suffers from the well-known chattering phenomenon caused by discontinuous switching control. Chattering can excite unmodeled dynamics, increase actuator wear, generate undesirable vibrations, and degrade control performance, thereby limiting the practical implementation of classical SMC. Consequently, reducing chattering while preserving robustness has remained one of the central research topics in SMC for several decades [11]–[13].

To address these limitations, numerous advanced SMC methodologies have been developed. These include higher

order sliding mode control, terminal and non-singular terminal sliding mode control, adaptive sliding mode control, integral sliding mode control, observer-based and disturbance observer-based sliding mode control, as well as fractional order and event-triggered sliding mode control. More recently, the integration of artificial intelligence and machine learning techniques has led to intelligent and learning-based SMC schemes capable of improving adaptability, uncertainty estimation, and implementation efficiency in increasingly complex engineering systems [5], [7], [14]–[16].

The continuous evolution of SMC has considerably broadened its application scope. Today, SMC is widely employed in robotic manipulators, autonomous and unmanned vehicles, spacecraft attitude control, renewable energy systems, electric motor drives, power electronic converters, industrial process control, biomedical engineering, and cyber-physical systems. These successful applications demonstrate the versatility and effectiveness of SMC in addressing complex nonlinear control problems under uncertain operating conditions [4], [10], [16], [17].

Although numerous review articles have focused on individual SMC techniques or specific application domains, a comprehensive survey that systematically traces the historical evolution of SMC while integrating recent developments in intelligent, learning-based, and data-driven control strategies remains limited. Furthermore, the rapid growth of advanced SMC variants has created the need for an updated review that consolidates their theoretical foundations, design methodologies, advantages, limitations, and emerging application areas within a unified framework.

This paper presents a comprehensive review of the evolution and advanced strategies of Sliding Mode Control (SMC). It begins by revisiting the fundamental concepts, mathematical formulation, and stability characteristics of classical SMC, followed by a systematic review of major developments, including higher order, terminal, adaptive, integral, observer-based, disturbance observer-based, fractional-order, event triggered, and intelligent SMC approaches. The advantages, limitations, and representative applications of these techniques are discussed, with particular emphasis on motor and robotic control. Finally, the paper identifies current research challenges and future directions, focusing on chattering reduction, computational efficiency, stability analysis of advanced SMC schemes, and their implementation in simulation.

The remainder of this paper is organized as follows. Section 2 presents the Foundations of Sliding Mode Control, including its basic principles, mathematical formulation, and stability concepts. Section 3 discusses First-Order Sliding Mode Control, covering its design methodology, advantages, and limitations. Section 4 reviews Higher-Order Sliding Mode Control and its major algorithms for chattering reduction. Section 5 focuses on Terminal Sliding Mode Control and its finite time convergence characteristics. Section 6 presents Fast and Non-Singular Terminal Sliding Mode Control, highlighting their improved convergence performance and elimination of singularity issues. Section 7 discusses Adaptive, Integral, and Dynamic Sliding Mode Control, emphasizing their enhanced robustness and disturbance rejection capabilities. Section 8 reviews Observer-Based Sliding Mode Control, while Section 9 presents Disturbance Observer-Based Sliding Mode Control for improved estimation and compensation of external disturbances. Section

10 discusses Advanced Sliding Mode Control Techniques, including event-triggered, intelligent, and learning-based SMC approaches, together with their emerging applications. Finally, Section 11 summarizes the major findings of this review and outlines current research challenges and future directions for the development of adaptive, efficient, and intelligent Sliding Mode Control strategies.

II. FOUNDATIONS OF SLIDING MODE CONTROL

The concept of Sliding Mode Control (SMC) originates from Variable Structure Systems (VSS), in which the controller structure changes according to the operating condition of the system. Unlike fixed-structure controllers that use a single control law for all operating conditions, VSS employs different control actions in different regions of the state space. This variable control structure provides flexibility in handling nonlinearities, parameter variations, and external disturbances, and forms the fundamental principle behind the development of Sliding Mode Control [1]–[3], [6], [8].

In a conventional state-feedback control system, the control input is generally expressed as

$$u(t) = Kx(t) \quad (1)$$

where K is the state-feedback gain matrix and $x(t)$ are the system state vector. Since the feedback gain remains fixed during operation, the control law does not change with variations in the operating conditions. As a result, the controller performance may deteriorate in the presence of parameter uncertainties, external disturbances, modeling errors, or changes in the system dynamics [9], [18], [19].

In contrast, Variable Structure Systems (VSS) employ a switching control law that changes according to the system state. The control input switches between different control structures based on a predefined switching function, thereby improving robustness against uncertainties and disturbances. A general switching control law can be expressed as,

$$u(t) = \begin{cases} u_1(x), & s(x) > 0 \\ u_2(x), & s(x) < 0 \end{cases} \quad (2)$$

where $u_1(x)$ and $u_2(x)$ are different control laws, and $s(x)$ represents the switching function. The switching function divides the state space into different regions and determines which control action should be applied. This switching mechanism enables the controller to modify its structure according to the operating condition, thereby improving robustness, disturbance rejection capability, and control performance [2]–[5].

A commonly used linear switching surface is defined as

$$s(x) = x_2 + \lambda x_1 \quad (3)$$

where x_1 and $x_2 = \dot{x}_1$ are the state variables, and $\lambda > 0$ is a positive design parameter. The switching surface specifies the desired dynamic behavior of the closed-loop system and guides the system trajectory toward the surface. Once the trajectory reaches the switching surface, it is constrained to move along it, thereby achieving the desired system performance. The selection of an appropriate switching surface plays a crucial role in determining the stability, convergence speed, robustness, and transient response of the closed-loop system [4], [5], [9], [10].

The general nonlinear system considered in Variable Structure Control can be represented as

$$\dot{x} = f(x) + g(x)u \quad (4)$$

where x represents the system state vector, u is the control input, $f(x)$ represents the nonlinear system dynamics, and $g(x)$ represents the input distribution matrix. This nonlinear affine representation is widely used in Sliding Mode Control because it provides a convenient framework for controller design, stability analysis, and robustness evaluation [3], [9], [18].

The main objective of Variable Structure Control (VSC) is to design a switching law that drives the system trajectory toward a predefined switching surface. Once the trajectory reaches this surface, the controller continuously switches between different control actions to keep the system states on or near the surface, thereby ensuring that the system output closely follows the desired reference value. This concept of driving and maintaining the system trajectory on a selected surface forms the fundamental principle of Sliding Mode Control [1]–[3], [5], [6], [8].

The switching concept of Variable Structure Systems can be easily illustrated using a vehicle speed control system, as shown in Fig. 1. The desired speed is compared with the actual vehicle speed to generate a speed error signal. When the error is large, a stronger control action is applied to reduce the error rapidly. As the vehicle speed approaches the desired value, the control effort is reduced to provide smoother operation and improved performance. Thus, the controller changes its behavior according to the system condition. This switching strategy represents the fundamental idea behind Variable Structure Systems and forms the basis for the development of modern Sliding Mode Controllers used in industrial applications [3], [4], [17].

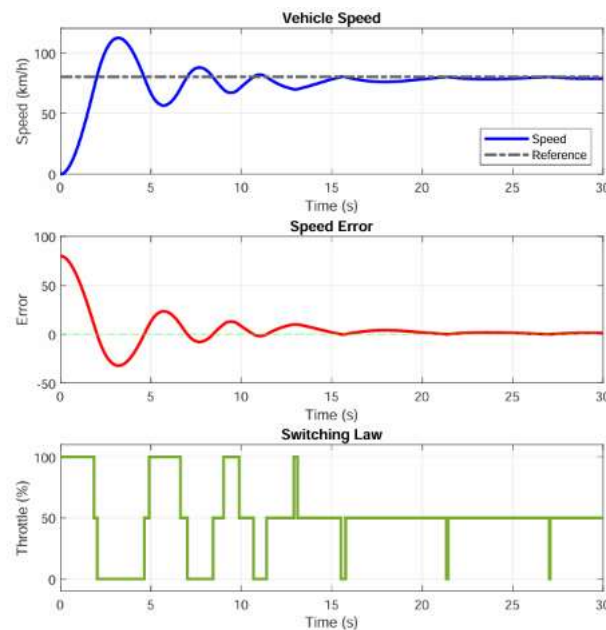


Fig. 1. Variable Structure Control for vehicle speed control.

Consider another example of an industrial furnace temperature control system, where the desired (reference) temperature is set to 100 °C. Based on the temperature error, a simple switching controller can be defined as

$$u = \begin{cases} 100\%, & e > 5^\circ\text{C} \\ 50\%, & 0 < e \leq 5^\circ\text{C} \\ 0\%, & e < 0 \end{cases} \quad (5)$$

When the temperature is much lower than the reference value, maximum heating power is applied to increase the temperature rapidly. As the temperature approaches the desired value, the heating power is reduced to avoid excessive overshoot. When the temperature exceeds the reference value, the heater is turned off. This example demonstrates how the controller modifies its action according to the system error. Although this controller illustrates the basic switching principle, practical Sliding Mode Controllers employ mathematically designed switching surfaces and stability conditions to guarantee robustness, stability, and finite-time convergence [3], [5], [11].

These examples demonstrate the basic idea of Variable Structure Systems, where the controller switches between different control actions depending on the system state. In Sliding Mode Control, this switching principle is further developed through the introduction of properly designed sliding surfaces, reaching laws, equivalent control concepts, and stability conditions that force the system trajectory toward the desired motion. The existence of a sliding mode depends on satisfying appropriate reaching conditions and maintaining the system trajectory on the sliding manifold despite parameter uncertainties and external disturbances [3]–[5], [9].

Although Variable Structure Systems provide a flexible control mechanism, direct switching between control laws may produce rapid oscillations near the switching surface. This behavior is known as chattering and represents one of the major challenges in the practical implementation of Sliding Mode Control. Chattering may excite unmodeled dynamics, increase actuator wear, generate unwanted vibrations, and degrade control performance. To address this issue, researchers have developed several advanced techniques, including boundary layer methods, higher-order Sliding Mode Control, super-twisting algorithms, adaptive Sliding Mode Control, and disturbance observer-based approaches while preserving robustness and finite-time convergence properties [10]–[14], [20].

The concepts presented in this section establish the theoretical foundation of Variable Structure Systems and Sliding Mode Control. They provide the basis for understanding switching surfaces, reaching conditions, equivalent control, invariance properties, Lyapunov stability, and robustness analysis, which are essential for the design of modern first-order, higher-order, adaptive, terminal, fixed-time, and intelligent Sliding Mode Controllers [3], [5], [7], [10], [16]. The next section introduces the mathematical formulation and design principles of First Order Sliding Mode Control, which serves as the foundation for many advanced SMC techniques developed in recent years.

III. FIRST-ORDER SLIDING MODE CONTROL

First-Order Sliding Mode Control (FOSMC) is the fundamental structure used for designing sliding mode controllers. It provides a systematic framework for selecting an appropriate sliding surface and designing a control law that forces the system states to follow the desired behavior. The main steps involved in FOSMC design include defining the tracking error, selecting the sliding surface, developing the control law, and verifying stability. FOSMC has been extensively studied due to its robustness against matched uncertainties and external disturbances in nonlinear systems [2]–[5], [9].

Consider the nonlinear system introduced in the previous section in the presence of an external bounded disturbance $d(t)$, which can be expressed as

$$\dot{x} = f(x) + g(x)u + d(t) \quad (6)$$

where $x \in \mathbb{R}^n$ is the system state vector, $u \in \mathbb{R}^m$ is the control input, $f(x)$ represents the nonlinear system dynamics, $g(x)$ denotes the input distribution matrix, and $d(t)$ represents a bounded external disturbance.

For setpoint tracking, the tracking error is defined as

$$e = x - x_d \quad (7)$$

where x_d is the desired state.

The sliding surface is designed to specify the desired error dynamics of the closed-loop system. Once the system trajectory reaches the sliding surface, the tracking error converges to zero according to the prescribed dynamics. For a second order tracking system, a commonly used linear sliding surface is given by

$$s = \dot{e} + \lambda e \quad (8)$$

where $\lambda > 0$ is a design parameter that determines the convergence rate of the tracking error. Linear sliding surfaces of this form are widely adopted due to their simplicity and effectiveness in achieving desired error dynamics during the sliding motion [4], [8], [9]. The desired sliding motion is obtained when

$$s = 0 \quad (9)$$

Under this condition, the system follows the dynamics defined by the sliding surface, and the tracking error approaches zero. The conventional FOSMC law is expressed as

$$u = u_{eq} - K \text{sign}(s) \quad (10)$$

where u_{eq} is the equivalent control, $K > 0$ is the switching gain, and the switching function is defined as

$$\text{sign}(s) = \begin{cases} 1 & s > 0 \\ 0 & s = 0 \\ -1 & s < 0 \end{cases} \quad (11)$$

The equivalent control maintains the system trajectory on the sliding surface, whereas the switching component provides the corrective action required to drive the sliding variable toward zero. This control structure ensures

robustness against bounded uncertainties and disturbances [3], [5], [6].

The stability of the FOSMC is commonly analyzed using Lyapunov stability theory. A suitable Lyapunov candidate function is selected as

$$V = \frac{1}{2} s^2 \quad (12)$$

where s denotes the sliding variable. Since $V > 0$ for $s \neq 0$ and $V = 0$ at $s = 0$, the Lyapunov function is positive definite. Differentiating Eq. (12) with respect to time gives

$$\dot{V} = s\dot{s} \quad (13)$$

To guarantee convergence of the system trajectory toward the sliding surface, the reaching condition is selected as

$$s\dot{s} < 0 \quad (14)$$

Consequently,

$$\dot{V} < 0 \quad (15)$$

which indicates that the Lyapunov function decreases monotonically with time. Therefore, the sliding variable converges asymptotically to zero, ensuring that the system trajectory reaches the sliding surface and remains stable under the specified conditions [3], [5], [9], [18]. The Lyapunov stability behavior of FOSMC is illustrated in Fig. 2.

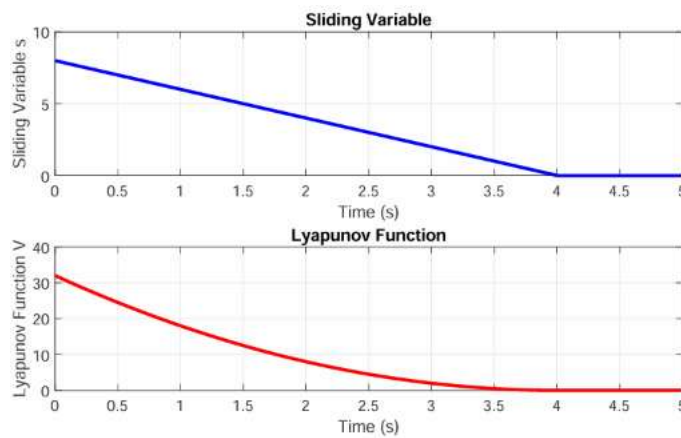


Fig. 2. Lyapunov stability analysis of FOSMC.

The transient performance of FOSMC is primarily determined by the reaching law, which governs the evolution of the sliding variable during the reaching phase. A commonly used reaching law is expressed as

$$\dot{s} = -K \text{sign}(s) \quad (16)$$

This reaching law forces the sliding variable to converge to zero in finite time and determines the convergence rate before the system trajectory reaches the sliding surface [2], [3], [21].

To illustrate the design procedure of FOSMC, consider the speed control of a DC motor. The tracking error is defined as $e = \omega - \omega_d$, where ω and ω_d denote the actual and desired motor speeds, respectively. The sliding surface is selected as

$$s = \dot{e} + 10e \quad (17)$$

and the control law is given by

$$u = u_{eq} - 20 \text{sign}(s) \quad (18)$$

The discontinuous switching term drives the system trajectory toward the sliding surface while providing robustness against disturbances and model uncertainties, thereby ensuring accurate speed tracking. Sliding mode controllers have been widely applied in DC motor drives due to their strong robustness against load variations and parameter uncertainties [3], [8]. The FOSMC application for the DC motor is showed in Fig. 3.

As another example, consider the stabilization of an inverted pendulum system. The error signal is expressed as $e = \theta - \theta_d$, where θ and θ_d denote the actual pendulum angle and the desired equilibrium angle, respectively. The corresponding sliding surface and control law are given by

$$s = \dot{e} + 5e \quad (19)$$

and

$$u = u_{eq} - 15 \text{sign}(s) \quad (20)$$

respectively.

Following the same FOSMC design principle, the controller drives the pendulum states toward the sliding surface and stabilizes the system around the desired equilibrium position despite disturbances and parameter uncertainties. The inverted pendulum is a widely used benchmark system for evaluating nonlinear stabilization and robust control techniques [5], [22]. Figure 4 illustrates the corresponding control example.

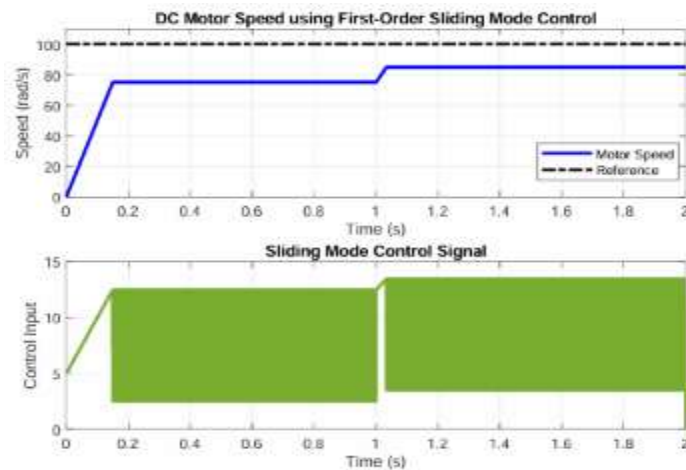


Fig. 3. DC motor speed control using FOSMC

Following the same FOSMC design principle, the controller drives the pendulum states toward the sliding surface and stabilizes the system around the desired equilibrium position despite disturbances and parameter uncertainties. The inverted pendulum is a widely used benchmark system for evaluating nonlinear stabilization and robust control techniques [5], [22]. Figure 4 illustrates the corresponding control example.

The above examples demonstrate the design methodology and operating principle of FOSMC. By combining an appropriately designed sliding surface with a discontinuous switching control law, FOSMC provides robust tracking performance and effective disturbance rejection for nonlinear systems. However, the discontinuous switching term in the conventional control law introduces high-frequency oscillations, commonly known as chattering. Chattering may excite unmodeled system dynamics, increase actuator wear, generate undesirable vibrations, and degrade the overall control performance in practical applications [3], [8], [23].

To overcome this limitation, several modified sliding mode control techniques have been proposed. One of the earliest and most widely adopted approaches is Boundary Layer Sliding Mode Control, which replaces the discontinuous signum function with a continuous approximation within a thin boundary layer around the sliding surface. This modification reduces chattering while preserving the robustness characteristics of classical sliding mode control [4], [6], [9]. The next section discusses the design principles and implementation of Robust Sliding Mode Control in detail.

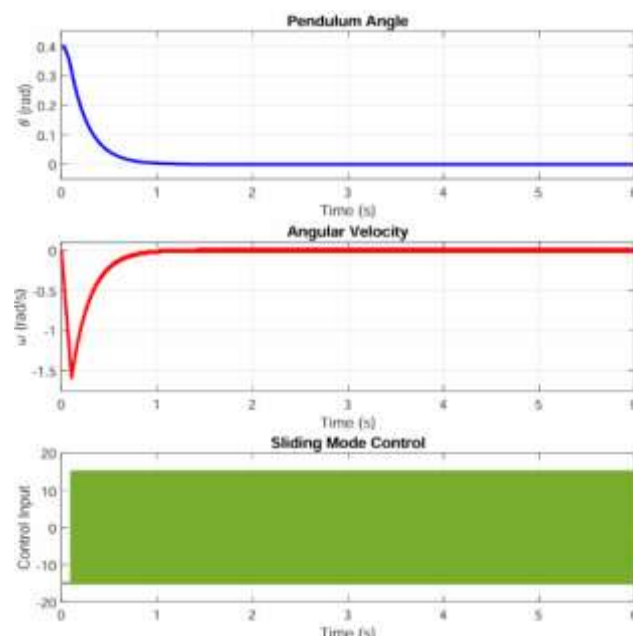


Fig. 4. Inverted pendulum stabilization using FOSMC.

IV. HIGHER-ORDER SLIDING MODE CONTROL

The previous sections presented the development of SMC from conventional FOSMC to BLSMC. Although BLSMC reduces chattering by replacing the discontinuous switching function with a continuous approximation, it cannot maintain the system trajectory exactly on the sliding surface. As a result, a compromise exists between tracking accuracy and smooth control action. To overcome this limitation and achieve high tracking accuracy with reduced chattering, Higher-Order Sliding Mode Control (HOSMC) was introduced [5], [11], [14], [24].

HOSMC extends the conventional sliding mode concept by enforcing convergence of the sliding variable and its higher order derivatives. In FOSMC, the discontinuous switching term directly appears in the control input, which may generate high frequency oscillations. In contrast, HOSMC applies the discontinuous action to higher-order derivatives of the sliding variable. This produces a smoother control signal while maintaining the robustness and finite-time convergence properties of SMC [11], [13], [25].

The general condition for an r th-order sliding mode is defined as

$$s = \dot{s} = \ddot{s} = \dots = s^{r-1}$$

(21)

where r denotes the order of the sliding mode. For the commonly used second-order sliding mode, the convergence requirement is expressed as

$$s = \dot{s} = 0 \quad (22)$$

The additional convergence condition enhances control input smoothness and reduces chattering in conventional first order sliding mode controllers. [5], [11], [24].

Among the different HOSMC approaches, the Super Twisting Algorithm (STA) is one of the widely used second order sliding mode techniques. The main advantages of STA are its continuous control output and its ability to achieve finite time convergence without requiring direct measurement of $\dot{s}$. Therefore, it is particularly suitable for practical systems where measurement noise and sensing limitations affect controller performance [10], [24], [25].

The Super-Twisting control law is expressed as

$$u = u_1 + u_2 \quad (23)$$

where

$$u_1 = -K_1 |s|^{\frac{1}{2}} \text{sign}(s) \quad (24)$$

and

$$\dot{u}_2 = -K_2 \text{sign}(s) \quad (25)$$

where $K_1 > 0$ and $K_2 > 0$ are controller gains. The first component provides continuous correction of the sliding variable, whereas the second component compensates for system uncertainties and guarantees finite-time convergence of the sliding variable [13], [25].

The stability analysis of HOSMC can be established using Lyapunov-based finite-time stability theory. Unlike conventional FOSMC, the Lyapunov function considers both the sliding variable and its higher-order dynamics. The controller gains are selected to satisfy the finite-time convergence condition

$$\dot{V} \leq -\alpha V^\beta \quad (26)$$

where $\alpha > 0$ and $0 < \beta < 1$. When this condition is satisfied, the sliding variable and its derivatives converge to zero within finite time, ensuring stability of the closed-loop system [13], [26], [27].

HOSMC has been successfully applied to various engineering applications due to its smooth control characteristics and strong robustness against disturbances and uncertainties. The previously considered examples of DC motor speed control and robotic manipulator position control are used here to demonstrate the effectiveness of HOSMC.

For the DC motor speed control example, the Super Twisting Sliding Mode Control (STSMC) law is designed as

$$u = -K_1 |s|^{\frac{1}{2}} \text{sign}(s) + v \quad (27)$$

with

$$\dot{v} = -K_2 \text{sign}(s) \quad (28)$$

The obtained DC motor speed response using STSMC is shown in Fig. 5. The controller compensates for load variations and provides accurate speed tracking. Compared with conventional FOSMC, the Super-Twisting controller generates smoother voltage signals, which reduces torque ripple, mechanical vibrations, and actuator stress.

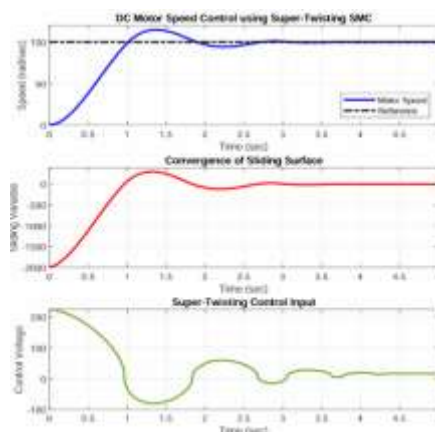


Fig. 5. DC motor speed control using STSMC.

Robotic systems require smooth torque generation to achieve accurate position tracking and avoid mechanical oscillations caused by discontinuous control actions. For this application, the HOSMC law is formulated as

$$u = u_{eq} - K_1 |s|^{\frac{1}{2}} \text{sign}(s) + v \quad (29)$$

Where $\dot{v} = -K_2 \text{sign}(s)$ (30)

The robotic manipulator position response using HOSMC is shown in Fig. 6. The controller achieves accurate position tracking while reducing torque oscillations and maintaining robustness against external disturbances and parameter variations.

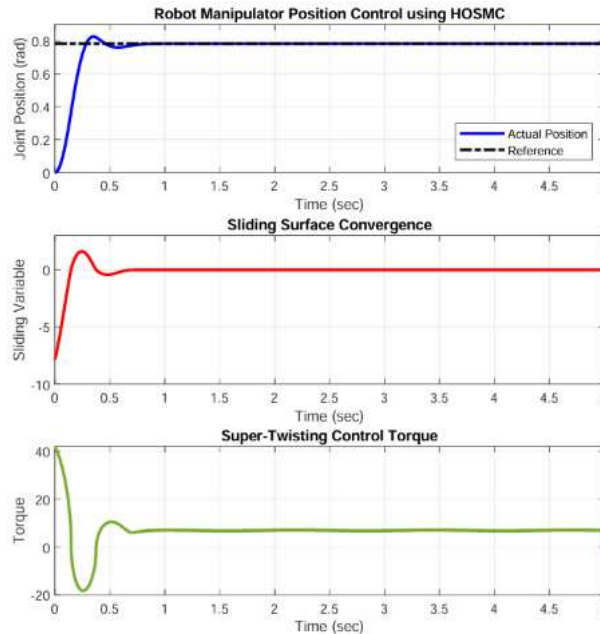


Fig. 6. Robotic manipulator position control using HOSMC.

Compared with classical FOSMC, HOSMC provides several advantages, including smoother control signals, reduced chattering, finite-time convergence, improved tracking performance, and better suitability for practical applications. These characteristics have enabled its successful implementation in robotics, aerospace systems, electric drives, and power electronic converters [5], [11].

Despite these advantages, HOSMC also presents several practical challenges. The controller design is more complex than conventional SMC because additional gains and internal variables must be selected to satisfy finite-time convergence conditions. Improper parameter selection may degrade the convergence rate, increase control effort, and affect the stability of the closed-loop system. Furthermore, the involvement of higher-order sliding variables and discontinuous terms in the controller structure may increase sensitivity to measurement noise and estimation errors, which can influence practical implementation [10], [11], [28].

Therefore, HOSMC provides an effective solution to the limitations of classical SMC by reducing chattering while preserving robustness, disturbance rejection capability, and finite-time convergence properties. The development of the Super-Twisting Algorithm, homogeneous control concepts, and finite-time stability theory has further advanced the design of sliding mode controllers [13], [24], [25], [27]. One such advancement is Terminal Sliding Mode Control (TSMC), which employs nonlinear sliding surfaces to achieve faster convergence and improved transient response. The design principles and applications of TSMC are discussed in the next section [5], [29], [30].

V. TERMINAL SLIDING MODE CONTROL

The previous Sliding Mode Control methods mainly focused on improving robustness, reducing chattering, and enhancing practical implementation. However, many engineering applications require faster error convergence, shorter settling time, and improved transient response. Terminal Sliding Mode Control (TSMC) was developed to address these requirements by introducing nonlinear terms into the sliding surface. The nonlinear sliding manifold modifies the error dynamics and enables the tracking error to converge to zero within finite time, providing faster convergence compared with conventional linear sliding surfaces [29]–[32].

In conventional SMC, the sliding surface is commonly designed using a linear combination of the tracking error and its derivative. Although this approach ensures stable error convergence, the convergence rate is mainly determined by the selected linear parameters. TSMC improves the convergence characteristics by incorporating nonlinear power terms into the sliding manifold. These nonlinear terms enhance the convergence rate near the equilibrium point and provide improved transient performance. For the nonlinear system defined in Eq. 6, the terminal sliding surface is defined as

$$s = \dot{e} + \alpha |e|^{\frac{p}{q}} \text{sign}(e) \quad (31)$$

where $\alpha > 0$ is a design parameter, and p and q are positive odd integers satisfying

$$0 < \frac{p}{q} < 1 \quad (32)$$

The fractional power term determines the convergence characteristics of the tracking error. Due to the selected range of p/q , the error decreases rapidly as the system approaches the desired equilibrium point, resulting in finite-time convergence [30], [31].

When the sliding condition ($s = 0$) is reached, the error dynamics become

$$\dot{e} = -\alpha|e|^{p/q}\text{sign}(e) \quad (33)$$

This nonlinear error equation provides finite-time convergence because the power term satisfies $0 < p/q < 1$. Therefore, the tracking error reaches zero within a finite settling time instead of following the asymptotic convergence behavior of linear sliding surfaces.

The control design of TSMC follows the equivalent and switching control used in conventional SMC. The stability of the closed-loop system can be verified using the Lyapunov analysis introduced in the previous sections. For finite-time convergence, the controller is designed to satisfy the condition given in Eq. (26).

where $\alpha > 0$ and $0 < \beta < 1$. Under this condition, the sliding variable converges to zero within finite time, which guarantees stable system operation [29].

The fast convergence capability of TSMC makes it suitable for high-performance engineering applications requiring rapid response and precise tracking. For the DC motor speed control case, the terminal sliding surface is selected as

$$s = \dot{e} + 5|e|^{0.5}\text{sign}(e) \quad (34)$$

and the control input is designed using the equivalent and switching control structure given in Eq. 10. The corresponding control configuration is shown in Fig. 7. The nonlinear sliding surface accelerates the convergence of the tracking error. Improves the transient response while maintaining accurate speed regulation under load variations and parameter uncertainties. Terminal sliding mode approaches have been widely investigated for electric drive systems due to their finite-time convergence capability and robustness against disturbances [29]–[31], [33].

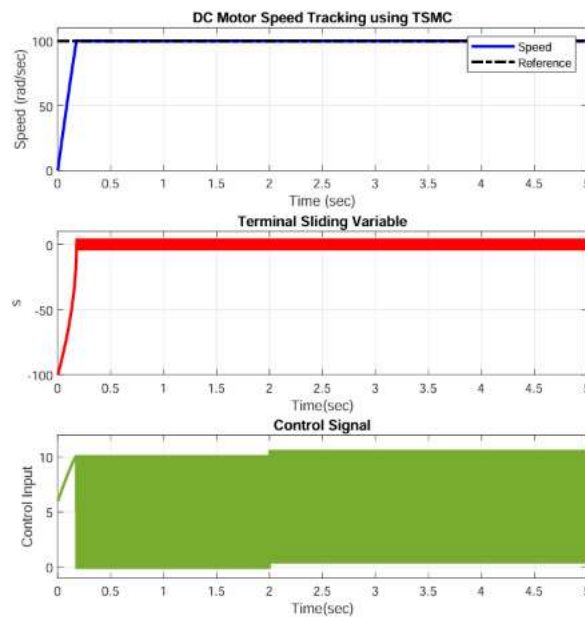


Fig. 7. DC motor speed control using TSMC.

Similarly, TSMC can be applied to robotic manipulator control, where fast and accurate trajectory tracking is required. The terminal sliding surface can be defined as

$$s = \dot{e} + 3|e|^{0.5}\text{sign}(e) \quad (35)$$

The control input is formulated based on the TSMC principle. The resulting robotic manipulator control response is shown in Fig.8. The nonlinear sliding manifold improves joint position convergence and provides robustness against uncertain payloads, friction effects, and external disturbances. Therefore, TSMC is an effective approach for robotic motion control applications requiring fast transient response and high tracking accuracy [29], [33], [34].

Although TSMC provides faster convergence than conventional linear sliding mode approaches, its nonlinear formulation may introduce singularity problems in certain controller structures, particularly when the tracking error approaches zero. Moreover, the switching component can still produce undesirable oscillations in practical implementations. These limitations have motivated the development of improved terminal sliding mode techniques, such as Fast Terminal Sliding Mode Control (FTSMC) and Non-Singular Terminal Sliding Mode Control (NTSMC), which provide faster convergence while avoiding singularity issues and enhancing control performance [29], [35], [36]. The design principles of these advanced terminal sliding mode techniques are presented in the next section.

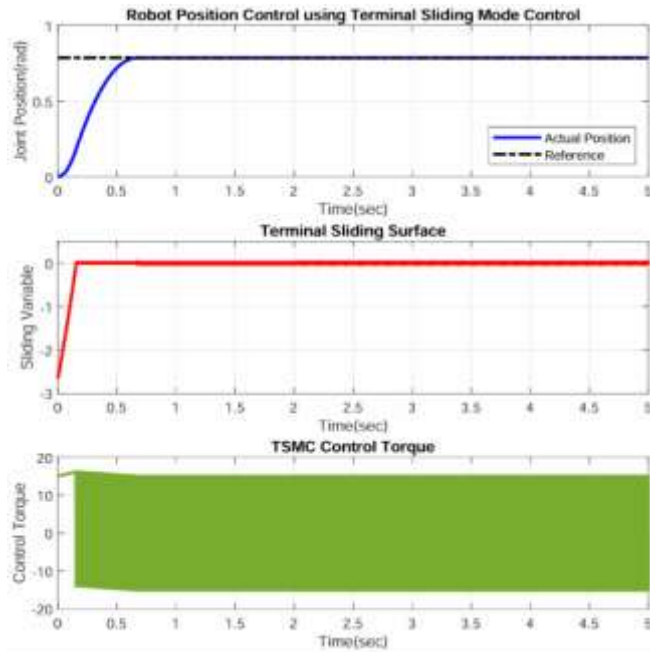


Fig. 8. Robotic manipulator position control using TSMC.

VI. FAST AND NON-SINGULAR TERMINAL SLIDING MODE CONTROL

Terminal Sliding Mode Control improves the convergence speed of conventional sliding mode control by employing nonlinear sliding surfaces that guarantee finite-time convergence. Despite these advantages, classical TSMC has several limitations that restrict its practical application. The convergence rate may be unsatisfactory when the initial tracking error is large because the nonlinear terminal term dominates the transient response. In addition, certain terminal sliding surfaces may introduce singularity near the equilibrium point, resulting in excessively large control inputs and implementation difficulties. To address these issues, Fast Terminal Sliding Mode Control (FTSMC) and Non-Singular Terminal Sliding Mode Control (NTSMC) were developed. These approaches improve the transient response, eliminate singularity problems, and preserve the finite-time convergence and robustness characteristics of TSMC [5], [29]–[31], [34], [35], [62].

FTSMC enhances the conventional terminal sliding surface by incorporating an additional linear error term. For the nonlinear system described in Eq. 6, the FTSMC sliding surface is defined as

$$s = \dot{e} + \alpha e + \beta |e|^{p/q} \text{sign}(e) \quad (36)$$

where $\alpha > 0$ and $\beta > 0$ are controller gains, and p and q are positive odd integers satisfying $1 < p/q < 2$.

The linear component dominates when the tracking error is large, providing rapid error reduction during the transient phase. As the tracking error decreases, the nonlinear terminal term becomes dominant and guarantees finite time convergence to the equilibrium point. Consequently, FTSMC combines the fast transient response of linear sliding mode control with the finite-time convergence property of TSMC [5], [34], [35].

The control input of FTSMC follows the equivalent plus switching control structure introduced in Eq. 10. The controller stability can be established using the Lyapunov framework presented. By selecting suitable controller parameters such that

$$\dot{V} \leq -cV^\gamma \quad (37)$$

where $c > 0$ and $0 < \gamma < 1$, the sliding variable converges to zero within finite time, thereby guaranteeing finite-time stability of the closed-loop system [5], [11], [27], [36].

Although FTSMC improves convergence speed, it does not completely solve the singularity problem of some terminal sliding surfaces. This problem occurs when the controller formulation contains negative powers of the tracking error or its derivatives. To overcome this issue, Non-Singular Terminal Sliding Mode Control introduces a modified sliding surface that remains bounded throughout the system operation.

A commonly used NTSMC sliding surface is expressed as

$$s = e + \frac{1}{\alpha} \dot{e}^{p/q} \quad (38)$$

$$\text{where } 1 < \frac{p}{q} < 2 \quad (39)$$

and $\alpha > 0$.

Unlike conventional terminal sliding surfaces, this formulation avoids singular behavior near the equilibrium point while maintaining fast convergence. The corresponding control law can be written as

$$u = u_{eq} - K|s|^\eta \text{sign}(s) \quad (40)$$

where

$$0 < \eta < 1 \quad (41)$$

The nonlinear switching term provides robustness against uncertainties and disturbances while reducing

unnecessary control effort near the desired operating condition.

The advantages of FTSMC and NTSMC have been demonstrated in a wide range of high-performance control applications. For the DC motor speed control example, the fast terminal sliding surface is selected as

$$s = \dot{e} + 5e + 3|e|^{0.5}\text{sign}(e) \quad (42)$$

and the corresponding control law is expressed as

$$u = u_{eq} - K|e|^{0.5}\text{sign}(s) \quad (43)$$

The resulting speed response obtained using FTSMC is shown in Fig. 9. The inclusion of the linear and nonlinear terms in the sliding surface improves the transient response, accelerates error convergence, and reduces the settling time while preserving the finite-time convergence property of terminal sliding mode control [5], [34], [35]. The additional linear term enhances the transient response during large speed variations and reduces the settling time compared with conventional TSMC.

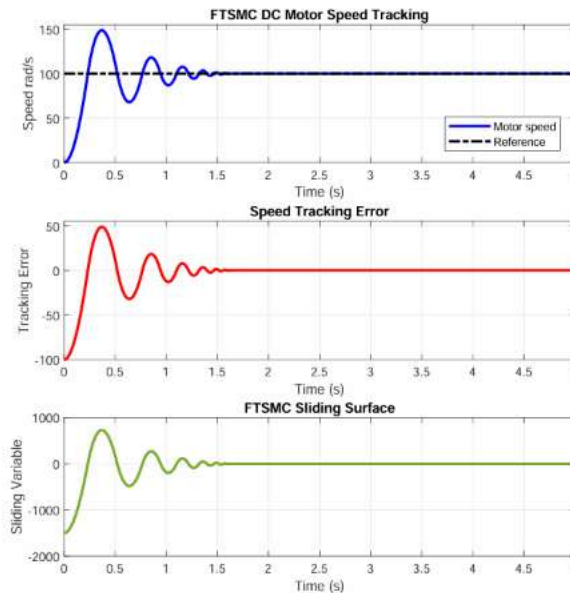


Fig. 9. DC motor speed control using FTSMC.

NTSMC is also well suited for robotic manipulator control, where accurate position tracking is required in the presence of payload variations and external disturbances. The non-singular sliding surface is defined as below and the control input is designed according to Eq. (43). The resulting position tracking performance of the robotic manipulator is presented in Fig. 10.

The modified sliding surface removes the singularity problem while providing fast position convergence and robustness against parameter variations and external disturbances.

The above examples show that FTSMC and NTSMC improve the performance of conventional TSMC by addressing its main limitations. FTSMC increases convergence speed through the addition of a linear term, whereas NTSMC eliminates singularity problems through a modified terminal sliding surface. These features make them suitable for applications such as robotics, electric drives, aerospace systems, autonomous vehicles, and nonlinear electromechanical systems.

However, the performance of FTSMC and NTSMC depends strongly on the proper selection of the sliding surface parameters and controller gains. In addition, practical implementation may still be influenced by measurement noise, sampling effects, actuator limitations, and residual chattering. These challenges have motivated the development of more advanced sliding mode control techniques, such as Adaptive Sliding Mode Control, Integral Sliding Mode Control, and Dynamic Sliding Mode Control, which further improve robustness, disturbance rejection, and control performance under uncertain operating conditions [3]–[5], [10]. The design principles and applications of these sliding mode control methods are discussed in the following sections.

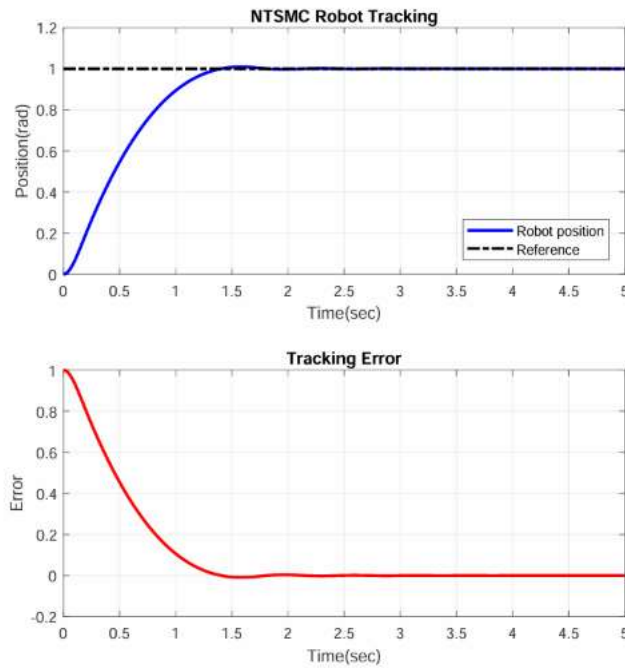


Fig. 10. Robotic manipulator position control using NTSMC.

VII. ADAPTIVE, INTEGRAL, AND DYNAMIC SLIDING MODE CONTROL

The previous sections presented several developments of Sliding Mode Control aimed at improving convergence speed, reducing chattering, and enhancing practical implementation. Nevertheless, these methods generally rely on controller gains selected according to assumed uncertainty bounds and disturbance levels. In many practical applications, including robotic manipulators, electric drives, aerospace systems, autonomous vehicles, and industrial processes, system parameters may vary during operation and external disturbances are often unknown or difficult to estimate accurately. Under such conditions, fixed controller gains may lead to conservative designs or degraded control performance. To address these challenges, several advanced SMC techniques have been developed, including Adaptive Sliding Mode Control (ASMC), Integral Sliding Mode Control (ISMC), and Dynamic Sliding Mode Control (DSMC). These approaches improve robustness and tracking performance by reducing the dependence on prior knowledge of uncertainty bounds and enhancing the controller's ability to accommodate time-varying uncertainties [37]–[40].

A. Adaptive Sliding Mode Control (ASMC)

ASMC extends the conventional SMC framework by adjusting the switching gain online according to the system operating conditions. Unlike fixed-gain controllers, ASMC continuously updates the switching gain based on the evolution of the sliding variable, thereby providing sufficient control effort only when required. This adaptive mechanism improves robustness against unknown disturbances and parameter variations while reducing excessive control effort and chattering [37]–[40]. The adaptive control law is expressed as

$$u = u_{eq} - K(t)\text{sign}(s) \quad (44)$$

where $K(t)$ denotes the adaptive switching gain. A commonly used adaptation law is given by

$$\dot{K} = \gamma|s| \quad (45)$$

where $\gamma > 0$ is the adaptation coefficient.

When the system is subjected to large disturbances or significant parameter variations, the sliding variable increases in magnitude, causing the adaptive mechanism to increase the switching gain and strengthen the control action. As the system states approach the sliding surface, the gain variation gradually decreases, thereby reducing unnecessary control effort and mitigating chattering. Consequently, ASMC provides improved tracking performance and robustness without requiring accurate prior knowledge of disturbance bounds or model uncertainties [38]–[40].

The effectiveness of ASMC can be observed in motor speed control, where motor parameters and load conditions may change during operation. Using the sliding variable formulation introduced in previous sections,

$$s = \dot{e} + 10e \quad (46)$$

the adaptive control law is selected as expressed in Eq. 44, with the adaptive gain updated according to

$$\dot{K} = 5|s| \quad (47)$$

The ASMC based motor speed control scheme is implemented, and the corresponding speed response is shown in Fig. 11. The adaptive gain mechanism allows the controller to automatically increase or decrease the control action according to the operating condition. This improves speed control performance under load variations and uncertain motor parameters compared with fixed gain SMC.

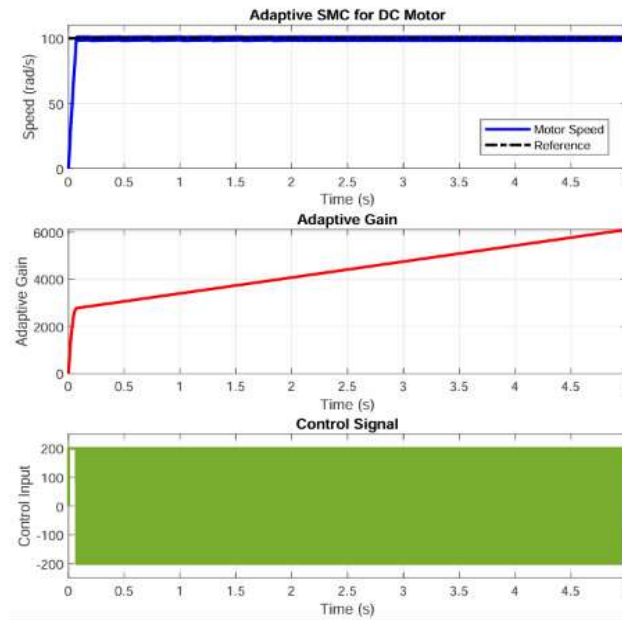


Fig. 11. DC motor speed regulation using ASMC.

B. Integral Sliding Mode Control (ISMC)

Integral Sliding Mode Control improves tracking accuracy and disturbance rejection by incorporating an integral term into the sliding variable. Unlike conventional SMC, the integral component establishes the sliding motion from the initial instant, thereby eliminating the reaching phase and enhancing robustness against matched uncertainties and external disturbances. In addition, the accumulated error reduces steady state tracking error and improves the disturbance rejection capability of the closed-loop system [10], [41], [42].

The integral sliding surface is defined as

$$s = \dot{e} + \lambda e + k_i \int_0^t e(\tau) d\tau \quad (48)$$

where $k_i > 0$ denotes the integral gain.

The integral term improves steady-state accuracy and compensates for constant and slowly varying disturbances. Consequently, ISMC is well suited for applications requiring high-precision tracking, such as robotic manipulators, servo systems, motion control, and aerospace applications [10], [41].

For the robotic manipulator position control example, the integral sliding surface is defined as

$$s = \dot{e} + 8e + 2 \int_0^t e(\tau) d\tau \quad (49)$$

and the control law is designed as

$$u = u_{eq} - 20\text{sign}(s) \quad (50)$$

The position tracking response of the robotic manipulator using ISMC is shown in Fig. 12. The integral term improves disturbance rejection and compensates for persistent uncertainties and parameter variations, thereby enhancing tracking accuracy and robustness during system operation [5], [41], [42]. The integral action improves position tracking by compensating for accumulated errors and external disturbances. Therefore, ISMC provides better accuracy for applications requiring precise trajectory following.

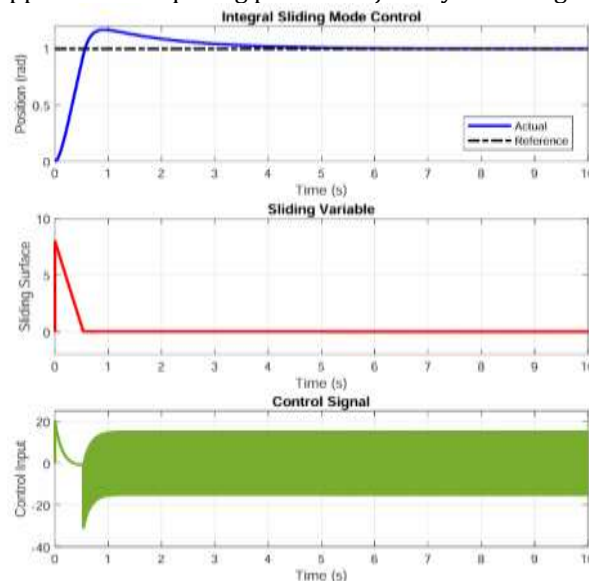


Fig. 12. Robotic manipulator position control using ISMC.

C. Dynamic Sliding Mode Control (DSMC)

DSMC introduces an additional dynamic component into the control structure between the switching mechanism and the actuator input. The primary objective of DSMC is to smooth the control signal, reduce chattering effects, and maintain the robustness and disturbance rejection characteristics of conventional SMC. By incorporating a dynamic compensator or filter, the discontinuous switching action is modified before being applied to the plant, resulting in improved control performance in practical systems with actuator limitations and measurement noise [10], [33], [37], [63].

Unlike conventional SMC, where the switching control directly influences the actuator input, DSMC employs an intermediate dynamic system to generate the actual control signal. This approach reduces abrupt control variations while preserving the ability of the sliding mode controller to reject matched uncertainties and external disturbances. A general dynamic compensator can be described as

$$\begin{aligned} \dot{z} &= h(z, s) \\ u &= z \end{aligned} \quad (51)$$

where z represents the internal dynamic state of the compensator and $h(\cdot)$ defines the dynamic update law. The compensator dynamics are designed such that the control input remains sufficiently smooth while ensuring convergence of the sliding variable toward the desired sliding surface [3], [5], [8]. The introduction of dynamic compensation provides an additional degree of freedom in controller design. The filtering effect of the dynamic element reduces high-frequency oscillations caused by the discontinuous switching term, thereby improving actuator performance and reducing mechanical stress. DSMC has been successfully applied in systems requiring smooth control action, including robotic manipulators, electric drives, aerospace systems, and precision motion control applications [10], [33], [37].

Dynamic Sliding Mode Control introduces an additional dynamic element between the switching mechanism and the actuator input. The main purpose of DSMC is to generate smoother control signals while preserving the disturbance rejection capability of SMC. A general dynamic compensator is described as

$$\dot{z} = -\alpha z + \beta \text{sign}(s) \quad (53)$$

where z represents the additional controller state and $\alpha, \beta > 0$ are design parameters.

The control input is then defined as

$$u = u_{eq} - Kz \quad (54)$$

The dynamic compensator modifies the switching signal before applying it to the actuator. As a result, sudden variations in the control input are reduced, which improves actuator operation and system reliability. The implementation of the general DSMC scheme for robotic manipulator position control is presented in Fig. 13.

The use of an additional dynamic element makes DSMC suitable for practical systems where actuator limitations and smooth control signals are important considerations [5], [43]. Therefore, mentioned controller-oriented approaches significantly extend the capability of conventional Sliding Mode Control (SMC) by addressing several practical challenges encountered in nonlinear and uncertain systems. Adaptive Sliding Mode Control (ASMC) enables online adjustment of controller parameters to accommodate time-varying uncertainties, Integral Sliding Mode Control (ISMC) enhances disturbance rejection by eliminating the reaching phase and improving tracking accuracy, whereas Dynamic Sliding Mode Control (DSMC) improves control smoothness through the introduction of additional dynamic compensation while mitigating chattering [3], [5], [43].

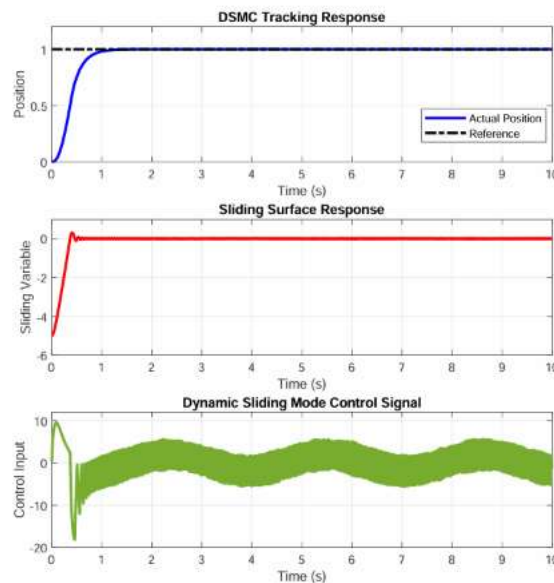


Fig.13. Robotic manipulator position control using DSMC

These developments have considerably broadened the applicability of SMC to robotics, electric drives, aerospace systems, renewable energy conversion and other complex engineering applications operating under uncertain environments. Despite these advancements, the effectiveness of ASMC, ISMC, and DSMC depends on the proper selection of adaptation laws, integral gains, and dynamic compensator parameters. More importantly, these approaches generally assume that all system states required for feedback are directly measurable. In many

practical systems, however, several state variables cannot be measured because of sensor limitations, implementation cost, measurement noise, or physical constraints. Consequently, integrating state estimation techniques with sliding mode control has become an important research direction, leading to the development of Observer-Based Sliding Mode Control (OBSMC), which enables robust output-feedback control using estimated system states rather than direct state measurements [4], [5], [44].

VIII. OBSERVER-BASED SLIDING MODE CONTROL (OBSMC)

The performance of conventional Sliding Mode Control (SMC) relies on the availability of all system states for feedback. However, in many practical applications, complete state measurement is not always possible. Observer-Based Sliding Mode Control (OBSMC) addresses this limitation by integrating a state observer with the conventional SMC framework to estimate unavailable states from measurable outputs and the mathematical model of the system. The estimated states are then utilized for feedback control, enabling robust output feedback implementation while preserving the robustness and disturbance rejection characteristics of conventional SMC [4], [5], [11], [44]–[46], [61]. Therefore, OBSMC has become an important extension of SMC for nonlinear uncertain systems.

The dynamics of an uncertain nonlinear system can be represented by Eq. 6 as

$$\dot{x} = f(x) + Bu + d(x), \quad y = Cx$$

Since only the output variables are available for measurement, an observer is designed to estimate the unavailable states. A general state observer can be expressed as

$$\dot{\hat{x}} = f(\hat{x}) + Bu + L(y - \hat{y}) \quad (55)$$

$$\text{where} \quad \hat{y} = C\hat{x} \quad (56)$$

$\hat{x}$ denotes the estimated state vector and L represents the observer gain matrix. The estimation error is defined as

$$e = x - \hat{x} \quad (57)$$

and the observer parameters are selected such that the estimation error converges to zero,

$$\lim_{t \rightarrow \infty} e(t) = 0 \quad (58)$$

For finite time observers, the estimation error can converge within a finite settling time, which improves the transient response of the overall control system [5], [11]. After convergence of the observer, the estimated states can be directly used in the sliding mode controller.

The sliding surface is constructed using the estimated states as

$$s = C_s \hat{x} \quad (59)$$

where C_s is the sliding surface matrix. The corresponding observer-based sliding mode control law is given by Eq. 10

$$u = ueq - K \text{sign}(s)$$

Thus, OBSMC achieves robust output-feedback control by replacing unavailable measured states with their estimated values.

The development of OBSMC has evolved through several important contributions. Walcott and Zak [45] introduced robust nonlinear state observers for uncertain systems, providing the foundation for observer-based control of nonlinear plants. Drakunov [46] proposed the equivalent-control-based sliding mode observer, which enabled robust state estimation using sliding mode principles. Edwards and Spurgeon [4] further developed sliding mode observers and demonstrated their effectiveness for uncertain systems with matched disturbances. Later, Levant [11] introduced higher-order sliding mode observers and differentiators, providing finite-time estimation with reduced sensitivity to measurement noise.

Different observer structures have been employed in OBSMC depending on the system requirements. Luenberger observers are widely used for linear systems because of their simple structure and computational efficiency. Kalman filters provide optimal state estimation for systems affected by stochastic noise. High gain observers provide fast convergence for nonlinear systems but may amplify measurement noise when high observer gains are selected. Sliding Mode Observers (SMOs) have received considerable attention because they maintain the robustness characteristics of SMC and provide accurate estimation under parameter uncertainties and external disturbances [4], [5], [11].

To illustrate the working principle of OBSMC, a DC motor system is considered, where the rotor position is available for measurement while the rotor speed is unavailable. The motor dynamics can be represented in state-space form as

$$\dot{x} = Ax + Bu, \quad y = Cx \quad (60)$$

where

$$x = \begin{bmatrix} \theta \\ \omega \end{bmatrix} \quad (61)$$

with θ representing the rotor position and ω representing the rotor speed. The system matrices are selected as

$$A = \begin{bmatrix} 0 & 1 \\ 0 & -2 \end{bmatrix} \quad B = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \quad C = [1 \quad 0] \quad (62)$$

Since only the rotor position is measured, a Luenberger observer is employed to estimate the rotor speed. The observer is designed as

$$\dot{\hat{x}} = f(\hat{x}) + Bu + L(y - C\hat{x}) \quad (63)$$

where the observer gain matrix is selected as

$$L = \begin{bmatrix} 15 \\ 60 \end{bmatrix} \quad (64)$$

The sliding surface is constructed using the estimated states as

$$s = \lambda \hat{\theta} + \hat{\omega} \quad (65)$$

where λ is a design parameter that determines the convergence characteristics of the sliding variable. The control input is obtained as

$$u = -K \text{sign}(s)$$

In this example, the observer reconstructs the unavailable rotor speed using the measured position, and the estimated states are used to generate the sliding control input. Thus, the OBSMC scheme provides the advantages of full-state feedback SMC while requiring only position measurement. The simulation results are shown in Fig. 14.

Observer-based SMC has been widely applied in practical engineering systems. In induction motor drives, sliding mode observers are used to estimate rotor speed and flux variables for sensorless control. In permanent magnet synchronous motor drives, OBSMC improves speed regulation by reconstructing unmeasured electrical and mechanical states. In robotic manipulators, observers estimate joint velocities to achieve accurate trajectory tracking under payload variations and nonlinear dynamics. Similarly, OBSMC has been applied in autonomous vehicles and UAV systems to estimate vehicle states and attitude variables in the presence of external disturbances [4], [5], [44].

Although OBSMC reduces sensor requirements and improves robustness, its performance strongly depends on observer convergence, parameter selection, and model accuracy. Moreover, OBSMC mainly focuses on reconstructing unavailable states and does not directly estimate unknown disturbances or lumped uncertainties. This limitation has motivated the development of Disturbance Observer-Based Sliding Mode Control (DO-SMC), where an additional disturbance observer is incorporated to estimate and compensate for unknown disturbances within the sliding mode control framework. The DO-SMC approach is discussed in the following section.

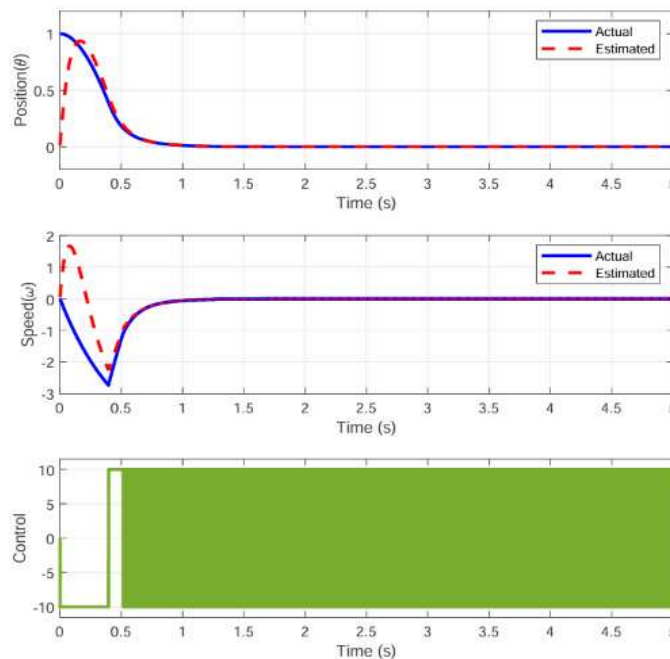


Fig.14. OBSMC for a DC motor control.

IX. DISTURBANCE OBSERVER-BASED SLIDING MODE CONTROL (DO-SMC)

Although Observer-Based Sliding Mode Control (OBSMC) improves the practical implementation of SMC by estimating unavailable system states, unknown disturbances and lumped uncertainties may still degrade the control performance. Conventional SMC can reject these disturbances by increasing the switching gain; however, a large switching gain increases the chattering phenomenon and may excite unmodeled high frequency dynamics. To overcome this limitation, Disturbance Observer-Based Sliding Mode Control (DO-SMC) incorporates a disturbance observer into the SMC framework to estimate unknown disturbances online and compensate for their effects before they affect the system behavior.

Consequently, the required switching gain can be reduced while maintaining robustness and tracking performance [47]–[50]. Consider the uncertain nonlinear system as

$$\dot{x} = f(x) + Bu + d \quad (66)$$

where d represents the lumped disturbance including external disturbances, parameter uncertainties, friction effects, and unmodeled dynamics. Unlike conventional SMC, where disturbances are considered as unknown bounded terms, DOSMC estimates the disturbance and compensates for it within the control input.

A general disturbance observer can be expressed as

$$\hat{d} = Q(s)[\dot{x} - f(x) - Bu] \quad (67)$$

Where $\hat{d}$ is the estimated disturbance and $Q(s)$ represents a stable filter used to obtain accurate disturbance estimation while reducing measurement noise. The estimated disturbance is incorporated into the sliding mode control law as

$$u = u_{eq} - B^{-1}\hat{d} - K \operatorname{sign}(s) \quad (68)$$

Since the disturbance effect is compensated by the disturbance observer, the switching term mainly compensates for the estimation error. Therefore, a smaller switching gain can be selected, resulting in reduced chattering and smoother control action.

Different disturbance observer structures have been developed depending on system requirements. Classical disturbance observers (DOBs) were initially developed for linear systems and slowly varying disturbances using nominal models and filtering techniques [48]. Nonlinear disturbance observers (NDOs) extend this concept to nonlinear systems by improving disturbance estimation under nonlinear dynamics and parameter uncertainties [49]. Finite-time disturbance observers (FTDOs) provide faster disturbance estimation by guaranteeing convergence within a finite settling time, which is beneficial for high-performance motion control applications [50]. Extended State Observers (ESOs), commonly used in Active Disturbance Rejection Control (ADRC), estimate unknown disturbances by considering them as additional system states [51]. Recent studies have combined disturbance observers with higher-order sliding mode techniques to improve estimation accuracy, convergence speed, and robustness against measurement noise [47].

To demonstrate the effectiveness of DO-SMC, a single link robotic manipulator position control system is considered. The objective is to achieve accurate trajectory tracking in the presence of unknown disturbances caused by payload variations, friction, and external interaction forces. The robot dynamics are described as

$$J\ddot{q} + B\dot{q} + mgl \sin(q) = \tau + d \quad (69)$$

where q denotes the joint position, $\dot{q}$ represents the joint velocity, J is the inertia, B is the viscous friction coefficient, $mgl \sin(q)$ represents the gravitational torque, τ is the control torque, and d denotes the unknown disturbance torque.

The tracking error is defined as $e = q - q_d$, where q_d represents the desired joint position. The sliding variable is selected as $s = \dot{e} + \lambda e$. The equivalent control component is obtained from the nominal robot dynamics as

$$\tau_{eq} = J\ddot{q}_d + B\dot{q} + mgl \sin(q), \quad (70)$$

where $\ddot{q}_d$ is the desired joint acceleration. Since the disturbance torque is unknown, a disturbance observer is introduced as

$$\dot{\hat{d}} = z \quad (71)$$

where the observer state is updated using

$$z = -Lz + L(\tau_{eq} - B\dot{q} - mgl \sin(q)) \quad (72)$$

where L represents the disturbance observer gain. The final DO-SMC control torque is designed as

$$\tau = \tau_{eq} - \hat{d} - K \operatorname{sign}(s) \quad (73)$$

The disturbance observer compensates for unknown disturbances, while the sliding mode term provides robustness against disturbance estimation errors. In the simulation, the robot manipulator is subjected to an external disturbance torque expressed as

$$d = 2 \sin(2t) \quad (74)$$

The disturbance observer estimates this unknown torque online, and the estimated disturbance is compensated through the control input. The position tracking response, disturbance estimation performance, and control torque are presented in Fig. 15. The simulation results demonstrate that DO-SMC achieves accurate trajectory tracking despite external disturbances. The disturbance observer successfully estimates the unknown disturbance torque, which reduces the required switching gain and improves control smoothness compared with conventional SMC. Therefore, DO-SMC provides enhanced disturbance rejection while preserving the robustness characteristics of sliding mode control.

DO-SMC has been widely applied in various engineering systems. In permanent magnet synchronous motor (PMSM) drives, disturbance observers estimate unknown load torque variations to improve speed regulation and tracking accuracy. In power electronic converters, disturbance estimation compensates for input voltage fluctuations and load variations while reducing switching oscillations.

In robotic manipulators, DO-SMC improves trajectory tracking by compensating for friction, payload uncertainties, and external interaction forces. Similarly, wind energy conversion systems use disturbance observers to estimate aerodynamic torque variations, while autonomous vehicles employ disturbance estimation to compensate for road slope, tire-road interaction variations, and environmental disturbances [47], [50].

Compared with conventional SMC, DO-SMC provides improved disturbance rejection, better tracking accuracy, reduced steady-state error, and lower chattering. However, its performance depends on disturbance observer design, estimation bandwidth, and parameter tuning. A high observer bandwidth may increase sensitivity to measurement noise, whereas inaccurate disturbance estimation can reduce compensation effectiveness. Despite these limitations, DO-SMC has become an important robust control approach by combining disturbance estimation capability with the robustness of sliding mode control. Further developments have focused on improving adaptability, reducing communication requirements, and incorporating learning mechanisms, leading to advanced sliding mode control techniques such as intelligent learning-based SMC and event-triggered SMC,

which are discussed in the following section.

X. ADVANCED SLIDING MODE CONTROL TECHNIQUES

The previous sections presented the evolution of Sliding Mode Control (SMC) from classical formulations to advanced robust control strategies. First-Order Sliding Mode Control (FOSMC) established strong robustness against matched uncertainties and external disturbances.

Boundary Layer and Higher-Order Sliding Mode Control (HOSMC) approaches improved practical implementation by reducing chattering and generating smoother control signals. Terminal-based approaches enhanced transient performance through finite-time convergence, while Adaptive, Integral, and Dynamic Sliding Mode Control methods improved disturbance compensation and adaptability under uncertain operating conditions [3], [5], [8], [10], [11].

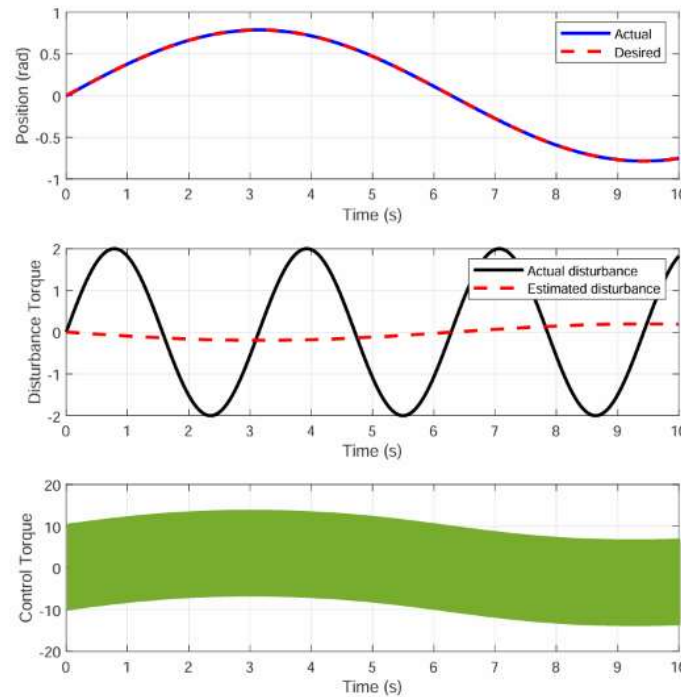


Fig. 15. DOSMC for robot manipulator position tracking.

However, modern engineering systems, including autonomous vehicles, robotic platforms, smart grids, renewable energy systems, and cyber-physical systems, involve complex nonlinearities, uncertain operating conditions, communication constraints, and rapidly varying environments. These characteristics make accurate mathematical modeling difficult and may degrade the performance of conventional model-based controllers. Consequently, advanced SMC frameworks integrating artificial intelligence, fractional calculus, learning mechanisms, and network-based strategies have been developed to improve adaptability, estimation capability, and control efficiency [16], [52], [53].

The developed approaches, including Intelligent Sliding Mode Control (ISMC), Event-Triggered Sliding Mode Control (ETSMC), Fractional Order Sliding Mode Control (FOSMC α), and Learning-Based Sliding Mode Control (LB-SMC), extend conventional SMC toward intelligent and distributed control architectures. These techniques maintain the inherent robustness and disturbance rejection capability of SMC while addressing challenges related to uncertainty estimation, communication limitations, and complex system dynamics [5], [10], [53], [54]. Since the nonlinear system formulation, tracking error definition, and fundamental sliding surface design have been presented in previous sections, the present section discusses the additional features introduced by advanced SMC methods, with emphasis on Intelligent Sliding Mode Control and Event Triggered Sliding Mode Control.

A. Intelligent Sliding Mode Control

Intelligent Sliding Mode Control combines the robustness of conventional SMC with artificial intelligence-based estimation and compensation techniques, including neural networks, fuzzy logic systems, reinforcement learning, and optimization algorithms. Unlike conventional model-based SMC approaches that require accurate system dynamics and predefined uncertainty bounds, intelligent SMC employs online estimators to approximate unknown dynamics and external disturbances. This improves adaptability and control performance for nonlinear systems with time-varying uncertainties [52], [54], [60]. The general intelligent SMC law can be expressed as

$$u = u_{eq} - K \operatorname{sign}(s) + u_{AI} \quad (75)$$

where u_{AI} represents the compensation generated by the intelligent estimator. The unknown disturbance can be approximated as

$$u_{AI} \approx d(t) \quad (76)$$

By estimating uncertain dynamics online, the required switching gain can be reduced, resulting in improved

tracking performance and reduced chattering effects. Intelligent SMC has been widely investigated for autonomous systems, robotic platforms, and nonlinear uncertain systems where accurate mathematical modeling is difficult [16], [55], [56].

For example, autonomous vehicles operate under uncertain conditions due to variations in vehicle parameters, road characteristics, and external disturbances. Learning-based intelligent SMC improves lateral tracking performance by incorporating neural-network-based disturbance estimation. The lateral tracking error is defined as

$$e = y - y_d \quad (77)$$

where y represents the vehicle lateral position and y_d denotes the desired trajectory.

The sliding surface is selected as

$$s = \dot{e} + 5e \quad (78)$$

The intelligent control law is formulated as

$$u = u_{eq} - 15\text{sign}(s) + u_{NN} \quad (79)$$

where u_{NN} represents the neural network compensation term. The neural-network-based Intelligent Sliding Mode Control structure for autonomous vehicle disturbance compensation is shown in Fig. 16.

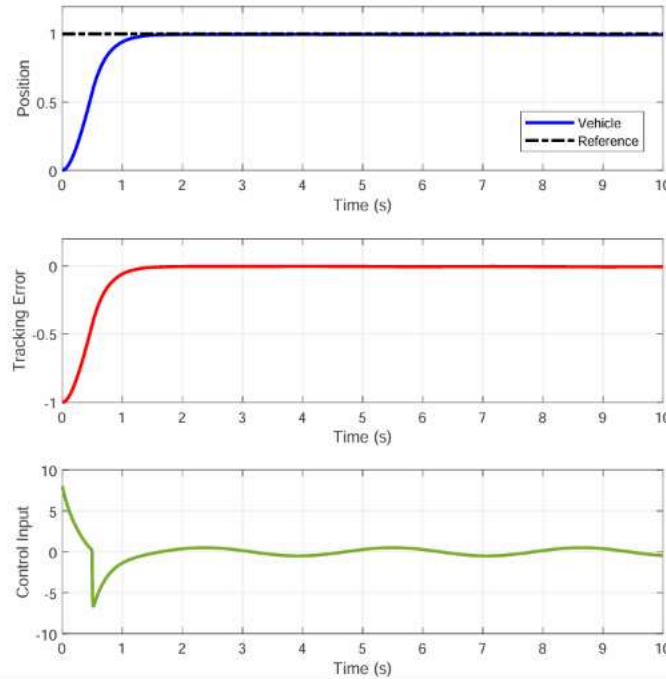


Fig.16. NN-based Intelligent Sliding Mode Control structure for autonomous vehicle disturbance compensation.

B. Event-Triggered Sliding Mode Control

Event-Triggered Sliding Mode Control addresses the limitations of conventional continuous-update control strategies in networked and digitally implemented systems. Although conventional SMC provides strong robustness, network-based applications introduce additional constraints related to communication bandwidth, computational resources, and energy consumption. Event-triggered SMC updates the control input only when a predefined condition is satisfied, thereby reducing unnecessary communication while preserving stability and tracking performance [57]–[59].

A general triggering condition can be expressed as

$$\|e(t)\| \geq \sigma \|x(t)\| \quad (80)$$

where $\sigma > 0$ represents the triggering parameter. When the triggering condition is not satisfied, the previous control input is maintained as

$$u(t) = u(t_k) \quad (81)$$

where t_k denotes the latest triggering instant.

Event-triggered SMC is particularly suitable for networked robotic systems. Industrial robotic manipulators often operate through communication networks with limited bandwidth, where reducing control transmissions is important. The sliding surface is selected as

$$s = \dot{e} + 8e \quad (82)$$

The control update is triggered when

$$|e| \geq 0.02 \quad (83)$$

Otherwise, the previous control input is maintained. The event triggered SMC framework for robotic manipulator position control is presented in Fig. 17. Advanced Sliding Mode Control techniques represent a recent stage in the evolution of robust sliding mode methodologies. Intelligent Sliding Mode Control and learning-based SMC approaches improve adaptability by employing online estimation of unknown system dynamics and external disturbances. Event-triggered SMC enhances communication efficiency by reducing unnecessary control updates in networked systems. These developments have significantly expanded the application scope of SMC toward autonomous vehicles, robotic systems, renewable energy systems, smart grids, and cyber-physical systems [5],

[10], [16], [52].

Despite these advantages, advanced SMC methods introduce several design challenges. Intelligent and learning-based controllers require sufficient training data, computational resources, and appropriate learning mechanisms to achieve reliable online adaptation. Event-triggered SMC requires careful selection of triggering conditions to maintain system stability while reducing communication requirements. Therefore, achieving an appropriate balance among robustness, adaptability, computational efficiency, and practical implementation remains an important research challenge [53], [54], [59].

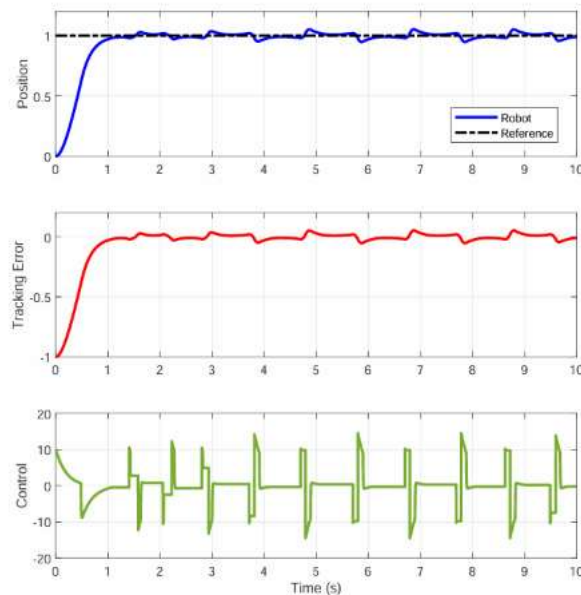


Fig.17. Event-triggered Sliding Mode Control framework for robotic manipulator position tracking.

Overall, advanced Sliding Mode Control techniques provide a transition from conventional robust control approaches toward intelligent, adaptive, and networked control frameworks. The integration of artificial intelligence, learning mechanisms, and event-based strategies creates new opportunities for future developments in safe AI-based control, digital twins, distributed autonomous systems, and intelligent engineering applications. Figures 16 and 17 present representative examples of intelligent disturbance compensation and communication efficient Sliding Mode Control implementations, respectively.

XI. CONCLUSION AND FUTURE RESEARCH DIRECTIONS

This paper presented an overview of the evolution and advanced developments in Sliding Mode Control (SMC), starting from the early concepts of Variable Structure Systems (VSS) to modern robust, observer-based, and intelligent control strategies. Over the years, SMC has evolved into a powerful nonlinear control methodology due to its inherent robustness, stability, and disturbance rejection capability for uncertain systems. The continuous development of SMC has mainly focused on improving the limitations of conventional approaches, particularly chattering reduction and convergence performance. Advanced techniques such as Boundary Layer SMC, Higher Order SMC, Super-Twisting SMC, and Terminal SMC have improved control smoothness and transient response. Furthermore, Adaptive SMC, Integral SMC, Observer-Based SMC, and Disturbance Observer-Based SMC have enhanced the practical implementation of SMC by addressing parameter variations, unavailable states, and unknown disturbances. Recent advancements in Intelligent SMC, Fractional-Order SMC, Event-Triggered SMC, and Learning-Based SMC have expanded the application of SMC toward complex systems including robotics, autonomous vehicles, renewable energy systems, and cyber-physical systems. However, challenges related to residual chattering, controller complexity, computational cost, and the reliable implementation of intelligent techniques remain important research issues.

Future research directions will focus on developing more adaptive, efficient, and intelligent SMC frameworks by integrating artificial intelligence, reinforcement learning, digital twins, and data-driven approaches while maintaining stability, robustness, and real-time implementation capability. The continuous evolution of Sliding Mode Control demonstrates its strong potential as a key robust control methodology for addressing the challenges of future complex and uncertain systems.

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