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Adaptive Integral-Type Terminal Sliding Mode Tracker Based on Active Disturbance Rejection for Uncertain Nonlinear Robotic Systems With Input Saturation

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ABSTRACT This paper proposes an adaptive integral-type terminal sliding mode tracking control approach based on the active disturbance rejection for uncertain nonlinear systems subject to input saturation and external disturbances. Its main objective is to achieve zero tracking error in the presence of external disturbances, parametric uncertainties and input saturation; ubiquitous problems in most practical engineering systems. The proposed approach combines the robustness and chattering-free dynamics of adaptive integral-type sliding mode control with the estimation properties of a nonlinear extended state observer. It also assumes the bounds of the input saturation to be unknown. The asymptotic stability of the closed-loop system in the presence of disturbances, uncertainties and input saturation is proven using the Lyapunov theorem. The effectiveness of the proposed approach is assessed using a flexible-link robotic manipulator. The obtained results confirmed the robustness and god tracking performance of the proposed approach. Robustness, chattering-free dynamics and good tracking performance albeit input saturation are among the main features.

INDEX TERMS Active disturbance rejection, nonlinear system, terminal sliding mode control, input saturation, flexible-link manipulator.

I. INTRODUCTION

A. BACKGROUND AND MOTIVATION

It is well known that actuator constraints, internal and external disturbances, such as modeling errors, parameter variations, uncertain external dynamics, widely exist in many practical engineering systems. If not properly addressed, these issues have the potential to adversely affect the system's performance and even destroy the stability of the whole system. As a result, various control approaches have been proposed in the literature to overcome these issues [1]–[3]. These approaches can be classified into intelligent methods, classical approaches and combination of both. Among the classical approaches, we can list the Proportional-Integral-Derivative (PID) control [4]–[6], adaptive control [7], [8], backstepping control [9], [10] and Sliding Mode Control (SMC) [11]. Among the intelligent methods, neural networks [12]–[14] and fuzzy-logic approaches [15]–[17] are the most popular. In the approaches that combine the intelligent and classic methods, we can list adaptive neural network [18] and fuzzy sliding mode control [19]. The neural network approaches have some disadvantages such as ahigh computational burden and potential for overfitting [20]. The fuzzy methods, on the other hand, rely on fuzzy rules that are determined based on the knowledge of the experts of that field, and suffer from a lack of analytical tools for stability analysis [21].

Sliding mode control (SMC) is among the most effective robust control technique for nonlinear systems with uncertainties and external disturbances [22]. It offers advantages such as good tracking performance, fast response, robustness against external disturbances and uncertainties, and suitable transient response [23]–[25]. However, a major drawback

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of this approach are the high-frequency finite amplitude oscillations or chattering phenomena [26]. Some solutions have been already investigated such as use of hyperbolic tangent and saturation instead of sign function [27], [28] or the use of rigid body assumption. However, these methods are not practical for all control input signals [29]. Using the High-Order Sliding Mode Control (HOSMC) and Terminal Sliding Mode Control (TSMC) procedure, the chattering effects can be reduced [30]–[33]. In HOSMC, the integration approach yields a control signal with the reduced chattering phenomenon [34], [35]. Second-Order Sliding Mode Control (SOSMC) offers several advantages compared to the standard SMC such as chattering reduction, increased accuracy, finite time stability and extension of the relative degrees of switching variables [3], [36], [37]. In [38], a chattering-free output-feedback finite time controller is designed for vehicle active suspension systems with matched disturbances. In [39], pure-feedback uncertain nonlinear systems with dead-zone actuators and stochastic failures are controlled using an adaptive backstepping fault-tolerant method. An energy-efficiency-based adaptive tracking control technique is proposed in [40] for active suspension systems with a bioinspired nonlinearity. Recently, the Active Disturbance Rejection Control (ADRC) has been shown to provide good perform in rejecting external disturbances. Additionally, using the extended state observer (ESO) with control laws can compensate for the external disturbances and estimate the unknown dynamics in the ADRC method [41]. In [42], a tidal stream turbine was successfully controlled by cascading ADRC with second-order ADRC. The approach was shown to guarantee robustness, and properly eliminate disturbances and overshoots. In [43], the ADRC is used to reject the effects of harmonic disturbances with unknown frequencies and uncertainties. Therefore, the ADRC approach enhances the robust performance of the controlled system to external disturbances. Hence, by combining ADRC and TSMC, the time-derivative of the external disturbances does not require to be bounded [44]. Additionally, the robustness of the system against uncertainties and disturbances is increased.

B. LITERATURE REVIEW

The SOSMC and SMC techniques were compared in [45]. It was shown that increasing the bound of the unmodeled dynamics, resulted in an increase in the chattering amplitude in both methods. Therefore, the bound of the unmodeled dynamics and perturbation value should be taken into consideration in chattering control. The effect of the input saturation was not considered in [45]. Implementation of a TSMC approach to a robotic airship in [46], proved its ability to ensure finite-time convergence in tracking control. The design, however, did not consider uncertainties and input saturation and chattering was not completely eliminated. In [33], a novel HOSMC is designed for Single-Input-Single-Output (SISO) and multi-variable systems with existing unmodeled dynamics and disturbances. This approach can reduce the chattering, but it has not been extended for Multi-Input-Multi-Output (MIMO) and saturated system. In [47], the SOSMC approach is designed for nonlinear affine structures with quantized uncertainties according to the non-smooth sliding surface. In this method, the uncertainties were assumed to be known, the input saturation was not considered, and the chattering effect was not eliminated. In [48], the effects of output constraints were controlled using the SOSMC method, however, the uncertainty bounds were assumed to be known. Furthermore, increasing the values of the initial states exacerbated the chattering problem, and the switching surface and its time-derivative could not converge to zero. In [49], an adaptive discrete-time SOSMC scheme is examined for the tracking control of a combustion engine. This method was shown to decrease the inaccuracies in data sampling and reduce system model uncertainties compared to standard SMC. However, the effect of input saturation was not considered in that paper. An SOSMC method based on the combination of the time-based adaptation and switched policy was suggested in [50]. The design was based on three assumptions that are not general, and the state-dependent uncertainty, state-space partitioning and upper-lower bounds of uncertainties had to be defined. Additionally, it is necessary to consider system constraints such as unknown unmatched uncertainties to have a better assessment of real systems. In [51], [52], uncertain nonlinear systems with time delays were controlled using robust adaptive SMC approaches. In [53], the Integral Sliding Mode Control (ISMC) and ADRC were combined to control the effects of wind disturbance on quadrotors, but the uncertainty and input saturation are not modeled in system and the chattering effects are obvious in the results. In [54], an adaptive HOSMC is designed for stabilization of the nonlinear systems with unknown bounded uncertainty, it can ensure the finite time stability, but some other important system constrains have not been considered in this paper. In [55], as the most related research to our work, a Fast Terminal Sliding Mode Control (FTSMC) procedure based on ADRC is designed to control a lower limb exoskeleton in swing phase, where it had good performance in comparison with PID and ADRC in the experimental results. Nevertheless, input saturation has not been considered in this method. According to the previous works, the external disturbances, parameter uncertainties and input saturations are some problems that the electromechanical systems are struggling with. Many researches have been investigated to reduce the destructive effects of these problems in the systems' performance; however, to the best of our information, combination of unknown uncertainty, input saturation and external disturbance have not been considered in the literature and a general solution has not been provided to overcome these problems.

C. CONTRIBUTION

The main contributions of this paper are as follows:

- An approach that combines the robustness and chattering-free dynamics of adaptive integral-type sliding mode control with the estimation properties of a nonlinear extended state observer to not only remove the effects of disturbances and uncertainties, but also drive the tracking error to zero, albeit input saturation.

- A design that considers non-symmetric input saturation, disturbances and unknown uncertainties with unknown bounds.
- A design that reduces the chattering effect, eliminates knowledge about uncertainties and guarantees finite time asymptotic stability of the closed-loop system.

D. PAPER ORGANIZATION

This remainder of the paper is organized as follows. The problem formulation along with some preliminaries are presented in section II. Section III details the designs of the extended state observer and control approaches. The performance of the proposed approach is assessed in section IV using a flexible-link manipulator. Some concluding remarks are finally provided in section VI.

II. PROBLEM FORMULATION AND PRELIMINARIES

Consider the uncertain nonlinear system described by the following equation:

$$\begin{cases} \dot{x}_k = x_{k+1} \quad for\ k = 1, 2, \ldots, n-1 \\ \dot{x}_n = h(x) + g(x)sat(u) + d(x, u, t) \end{cases} \tag{1}$$

where $x = [x_1, x_2, \ldots, x_n]$ is the system state, $h(x) \in R$ is a known nonlinear function, $g(x) \in R - \{0\}$, $sat(u) \in R$ is the saturated controller input vector, $d(x, u, t)$ denotes the unmatched uncertainty, un-modeled dynamics and external disturbances. Equation (1) is the state-space representation of dynamical models of physical (mechanical, electrical, thermal, hydraulic) systems with a set of state variables, nonlinear functions, saturated control input and external disturbances. The input saturation is defined as

$$sat(u) = \begin{cases} u_{max} & if\ u > u_{max} \\ u & if\ u_{min} < u < u_{max} \\ u_{min} & if\ u < u_{min} \end{cases} \tag{2}$$

Therefore, the input saturation is considered as $sat(u) = u + \Delta u$, where Δu is an unknown constant.

The main control objective is to obtain an appropriate controller law u, to force the output trajectory to follow the reference signal $r \in R$ in the presence of external disturbances, input constraint and unmatched uncertainty. The overall schematic of the proposed approach is illustrated in Figure 1. The tracking error is defined as

$$e_k = x_k - r_k \tag{3}$$

where the reference signal r_k is differentiable function of time. To solve the control problem at hand, the following assumptions and propositions are considered.

Assumption 1: The reference signal and its derivative are bounded, with:

$$sup_{t \geq t_0} \left\{ \left| r_k^{(k)}(t) \right| \right\} \leq \varepsilon_d \quad 0 \leq k \leq n+1 \tag{4}$$

where ε_d is a positive constant.

Assumption 2: The disturbances $\boldsymbol{d}(\boldsymbol{x}, \boldsymbol{u}, \boldsymbol{t})$ and $\dot{\boldsymbol{d}}(\boldsymbol{x}, \boldsymbol{u}, \boldsymbol{t})$ are continuously differentiable.

Remark 1: In this paper, the main idea is to combine a Nonlinear Extended State Observer (NESO) with a TSMC-based control approach. The NESO estimates the internal uncertainties and external perturbations, whereas the NESO compensates for system uncertainties. Hence, an accurate dynamic model is not essential for this method. Thus, the system dynamics can be simplified [53].

Proposition 1 [56]: Consider the differential system defined by:

$$\dot{x}(t) = h(x) + d(x, t), \tag{5}$$

where $h(x) : \chi \rightarrow \Re^n$ is a nonlinear function defined on χ, i.e., an open neighborhood of equilibrium point. If there exists a Lyapunov function on χ which can prove the asymptotic stability of the nominal system, then there exist positive constants $\xi_0, \delta, \aleph, \Phi$ and an open neighborhood of equilibrium, such that for every continuous $d : \Re_+ \times \chi \rightarrow \Re^n$,

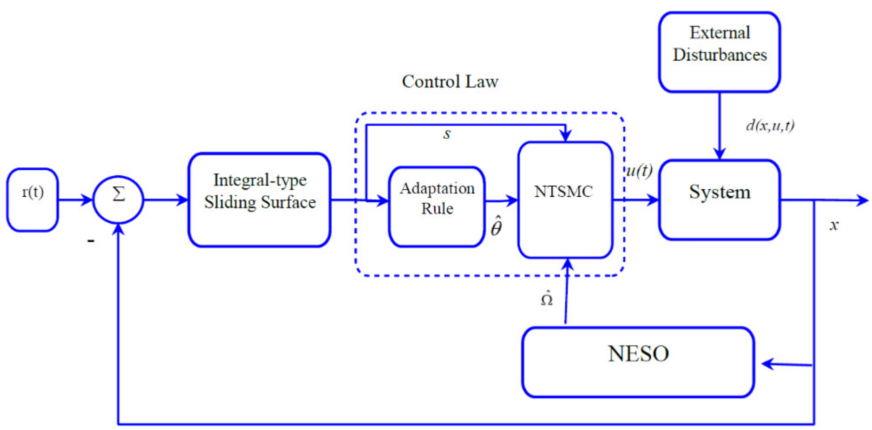

FIGURE 1. Overall schematic of the proposed approach.

the following inequality is satisfied:

$$\xi = \sup_{\Re_+ \times \chi} \|d(x, u, t)\| < \xi_0, \tag{6}$$

Then, any right maximally solution x of (5) satisfies $x(t) \in \Phi$ for all $t \in \Re_+$ and

$$\|x(t)\| \leq \delta \xi^{\gamma}, \quad t > \aleph, \tag{7}$$

where $\gamma = \frac{1-\varepsilon}{\varepsilon} > 1$.

Proposition 2 [57]: If $x \in \chi \subset R^n$, $\dot{x} = h(x)$, $h : R^n \to R^n$ is a locally Lipschitz and continuous nonlinear functional on an open neighborhood D of origin, and $V : \chi \to R$ is Lyapunov function on $\chi \backslash \{0\}$ satisfying $\dot{V} + \alpha V^{\varepsilon} \leq 0$ on $N \backslash \{0\}$, therefore, the finite-time stable equilibrium of the system $\dot{x} = h(x)$ is the origin.

The Lyapunov functional V converges to zero in finite time and the settling time is

$$t_s = \frac{V(t_0)^{1-\varepsilon}}{\alpha(1-\varepsilon)} \tag{8}$$

where α and $0 < \varepsilon < 1$ are positive scalars and t_0 is the initial time.

III. MAIN RESULTS

A. NONLINEAR EXTENDED STATE OBSERVER DESIGN

In this section, the external disturbances and uncertainties are considered as an extended state. By considering Assumption 2, Eq. (1) can be re-written as:

$$\begin{aligned} \dot{x}_k &= x_{k+1} \quad for\ k = 1, 2, \ldots, n-1 \\ \dot{x}_n &= x_{n+1} + g(x)\, sat(u) \\ \dot{x}_{n+1} &= \Omega(t) \end{aligned} \tag{9}$$

where $\Omega(t) = h(x) + d(x, u, t)$. The nonlinear extended state observer (NESO) is designed based on the first state estimation error as follows:

$$\begin{cases} \tilde{e}_1 = \hat{x}_1 - x_1 \\ \dot{\hat{x}}_k = \hat{x}_{k+1} - \delta^{n-1} \omega_k (\frac{\tilde{e}_1}{\delta^n}) \quad for\ k = 1, 2, \ldots, n-1 \\ \dot{\hat{x}}_n = \hat{x}_{n+1} - \omega_n (\frac{\tilde{e}_1}{\delta^n}) + g(\hat{x})\, sat(u) \\ \dot{\hat{x}}_{n+1} = \delta^{-1} \omega_{n+1} (\frac{\tilde{e}_1}{\delta^n}) \end{cases} \tag{10}$$

where $\omega_k(\tilde{e}), \ldots, \omega_{n+1}(\tilde{e})$ can be linear or nonlinear functions and δ is a positive small constant. The dynamics of the NESO error is given by:

$$\begin{cases} \frac{\dot{\tilde{e}}_k}{\delta^{n+1-k}} = \frac{\tilde{e}_{k+1}}{\delta^{n-k}} - \delta^{n-1} \omega_k (\frac{\tilde{e}_1}{\delta^n}) \quad for\ k = 1, 2, \ldots, n-1 \\ \dot{\tilde{e}}_n = \tilde{e}_{n+1} - \omega_n (\frac{\tilde{e}_1}{\delta^n}) \\ \dot{\tilde{e}}_{n+1} = \Omega - \delta^{-1} \omega_{n+1} (\frac{\tilde{e}_1}{\delta^n}) \end{cases} \tag{11}$$

To obtain the ADRC law based on the Adaptive TSMC (ATSMC) and reach the finite time stability in tracking, the following proposition is considered.

Assumption 3: The following conditions should be satisfied:

3-a $|d(x, t)| + |x_k(t)| < \rho$ where ρ is a positive constant.

3-b There exist continuous and positive-definite functions ν and μ such that:

- $\ell_1 \|x\|^2 < \nu(x) < \ell_2 \|x\|^2,\ \ell_3 \|x\|^2 < \mu(x) < \ell_4 \|x\|^2$
- $\sum_{k=1}^{n} \frac{\partial \nu}{\partial x_k} (x_{k+1} - \omega_k(x_1)) - \frac{\partial \nu}{\partial x_{n+1}} \omega_{n+1}(x_1) \leq -\mu(x)$
- $\left| \frac{\partial \nu}{\partial x_{n+1}} \right| \leq \Im \|x\|$

where $x = (x_1, \ldots, x_{n+1})$, $k = 1, \ldots, n$, and $\Im$ is a positive constant.

3-c For unknown differentiable function h, d, positive constant c_0, j and positive integer k, the following inequality is satisfied: $|u| + |h| + |\dot{d}| + \left|\frac{\partial h}{\partial t}\right| + \left|\frac{\partial h}{\partial x_i}\right| \leq c_0 + \sum_{j=1}^{n} c_j |x_j|^k$

Proposition 3 [58]: Consider the NESO (10). The estimation errors converge to zero while $\boldsymbol{\delta}$ goes to the origin

Proof: Considering an extra state variable $x_{n+1} = h + d$, system (1) is rewritten as

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = x_3 \\ \quad \vdots \\ \dot{x}_n = x_{n+1} + g(x)\, sat(u) \\ \dot{x}_{n+1} = \Omega(t) \end{cases}$$

where $\Omega = h(x) + d(x, u, t)$.

From Assumption 3-a and 3-b, for all $t \geq 0$, there is a constant $M > 0$ such that

$$\begin{aligned} &\frac{d}{ds} h(s, x_1(s), \ldots x_n(s)) |_{s=\delta t} + \dot{d}(\delta t) \\ &= \frac{\partial}{\partial t} h(\delta t, x_1(\delta t), \ldots x_n(\delta t)) \\ &\quad + \sum_{i=1}^{n} x_{i+1}(\delta t) \frac{\partial}{\partial x_i} h(\delta t, x_1(\delta t), \ldots x_n(\delta t)) \\ &\quad + u(\delta t) \frac{\partial}{\partial x_n} h(\delta t, x_1(\delta t), \ldots x_n(\delta t)) + \dot{d}(\delta t) \leq M \end{aligned}$$

By considering $\psi_i(t) = \frac{e_i(\delta t)}{\delta^{n+1-i}}$,

$$\begin{cases} \dot{\psi}_i(t) = \psi_2(t) - \omega_1(\psi_1(t)) \\ \quad \vdots \\ \dot{\psi}_n(t) = \psi_{n+1}(t) - \omega_n(\psi_1(t)) \\ \dot{\psi}_{n+1}(t) = -\omega_{n+1}(\psi_1(t)) + \delta \Delta(t) \end{cases}$$

and Assumption 3-c, finding the derivative of $\nu(\psi(t))$ along the $\psi(t)$, it yields $|e(t)| \to 0$.

B. CONTROL LAW DESIGN

The main objective of the ATSMC designed is to ensure robustness against uncertainties and disturbances, compensate for the effects of saturation and unknown uncertainties, eliminate chattering and attain finite time stability. First of all, the sliding manifold is considered as

$$s = \lambda e_n(t) + \int_0^t (\beta_n |e_n(\tau)|^{\frac{q_n}{p_n}} sgne_n(\tau) + \ldots + \beta_1 |e_1(\tau)|^{\frac{q_1}{p_1}} sgne_1(\tau))d\tau \quad (12)$$

where $\lambda, \beta_n, \ldots, \beta_1$ are positive constants, $q_1, \ldots, q_n$ and $p_1, \ldots, p_n$ are odd positive integers with $q < p$ and e is tracking error. If the trajectory of tracking error reaches the switching surface (12), error converges to zero asymptotically.

By using the output of NESO, the control law, considering the input saturation, is defined as:

$$u = -(\lambda g(x))^{-1} \left\{ \lambda \left(\hat{\Omega} - \dot{r}_n \right) + \beta_n |e_n(t)|^{\frac{q_n}{p_n}} sgne_n(t) + \ldots + \beta_1 |e_1(t)|^{\frac{q_1}{p_1}} sgne_1(t) + \theta sgn\, s + K |s|^z sgns + \int \eta sgns\, dt \right\} \quad (13)$$

The reaching phase of the control law is obtained from the following equation:

$$u_{eq} = -(\lambda g(x))^{-1} \left\{ \lambda(\hat{\Omega} - \dot{r}_n) + \beta_n |e_n(t)|^{\frac{q_n}{p_n}} sgne_n(t) + \ldots + \beta_1 |e_1(t)|^{\frac{q_1}{p_1}} sgne_1(t) \right\} \quad (14)$$

and the sliding phase input is designed as

$$u_s = -(\lambda g(x))^{-1} \left\{ \theta \; sgn\, s + K |s|^z sgns + \int \eta \; sgn\, s\, dt \right\} \quad (15)$$

where K denotes a positive constant and $\theta > |\lambda g(x)\Delta u|$. Finding the unknown bounds of the uncertainty and input saturation is practically difficult; therefore, to compensate for the unknown bounds, θ is estimated by an estimation parameter $\hat{\theta}$ which is designed by the adaptive approach defined by the following equation:

$$\dot{\hat{\theta}} = \zeta |s|, \quad (16)$$

with $0 < \zeta < 1$, the reachability criterion of switching surface is satisfied and the term s converges to zero. Therefore, the control law is updated to

$$u = -(\lambda g(x))^{-1} \left\{ \lambda(\hat{\Omega} - \dot{r}_n) + \beta_n |e_n(t)|^{\frac{q_n}{p_n}} sgn\; e_n(t) + \ldots + \beta_1 |e_1(t)|^{\frac{q_1}{p_1}} sgn\; e_1(t) + \hat{\theta} sgn\, s + K |s|^z sgn\, s + \int \eta sgn\, s\, dt \right\} \quad (17)$$

Theorem 1: Assume the uncertain nonlinear system (1) and integral-type terminal switching surface (12). The parametric uncertainties are considered bounded and Assumptions 1-2 are satisfied. Then, using TABLE 1, TABLE 2 and applying controller (17) to nonlinear system (1), all the signals of the closed-loop system are bounded and asymptotically stable.

Proof: The Lyapunov candidate function is considered as

$$V = 0.5 \left(s^2 + (\hat{\Omega} - \Omega)^2 + \zeta^{-1} \tilde{\theta}^2 \right), \quad (18)$$

where the estimation error variable is

$$\tilde{\theta} = \hat{\theta} - \theta, \quad (19)$$

By differentiating $\tilde{\theta}$ and using (16), one has

$$\dot{\tilde{\theta}} = \zeta |s|. \quad (20)$$

Calculating time-derivative of (18) and substituting (20) into it, gives

$$\dot{V} = s\dot{s} + (\hat{\Omega} - \Omega)(\dot{\hat{\Omega}} - \dot{\Omega}) + (\hat{\theta} - \theta) |s|, \quad (21)$$

The time derivative of sliding manifold (12) is substituted into (21), then the following equation is obtained:

$$\dot{V} = s(\lambda \dot{e}_n(t) + \beta_n |e_n(t)|^{\frac{q_n}{p_n}} sgne_n(t) + \cdots + \beta_1 |e_1(t)|^{\frac{q_1}{p_1}} sgne_1(t)) + (\hat{\Omega} - \Omega)(\dot{\hat{\Omega}} - \dot{\Omega}) + (\hat{\theta} - \theta) |s|. \quad (22)$$

The differentiation of the tracking error of n-th state is obtained by substituting (9) into (3) as

$$\dot{e}_n(t) = \dot{x}_n - \dot{r}_n = x_{n+1} + g(x)\, sat(u) - \dot{r}_n, \quad (23)$$

where r_n is reference signal of n-th state. Considering the input saturation of equation (2) and substituting (23) in (22) yields:

$$\dot{V} = s(\lambda(x_{n+1} + g(x)(u + \Delta u) - \dot{r}_n) + \beta_n |e_n(t)|^{\frac{q_n}{p_n}} sgne_n(t) + \cdots + \beta_1 |e_1(t)|^{\frac{q_1}{p_1}} sgne_1(t)) + (\hat{\Omega} - \Omega)(\dot{\hat{\Omega}} - \dot{\Omega}) + (\hat{\theta} - \theta) |s|. \quad (24)$$

Substituting the adaptive nonsingular terminal sliding mode tracker (17) into (24), yields:

$$\dot{V} \leq -s(\hat{\theta} sgn\, s + K |s|^z sgns + \int \eta sgn\, s\, dt) - \left| \Omega - \delta^{-1} \omega_{n+1} (\frac{\tilde{e}_1}{\delta^n}) \right| \left| (\dot{\hat{\Omega}} - \dot{\Omega}) \right| + (\hat{\theta} - \theta) |s|. \quad (25)$$

Now, using Proposition 3, the estimation error of NESO converges to zero and one achieves

$$\dot{V} \leq -(K |s|^{z+1} + \eta s \int sgn\, s\, dt + \hat{\theta} |s|) \quad (26)$$

Hence, the Lyapunov function'stime-derivative is negative. This completes the proof. □

C. CHATTERING-FREE ATSMC LAW

To further eliminate chattering, we derive in this section a control approach using the time-derivative of the sliding surface, thereby removing chattering using the integration of the sign function. The sliding manifold is designed as

$$s = k_p e_1(t) + k_i \int_0^t e_1(\tau)^{q/p} d\tau + k_d \dot{e}_1, \tag{27}$$

where k_p, k_i, k_d are positive constants, q and p denote two positive odd integers with $q < p$. The control law is obtained from the following equation:

$$\begin{aligned} \dot{u} = &-(k_d g(x))^{-1}\{k_p(\hat{\Omega} + g(x)u_{eq} - \dot{r}_1) - b\dot{s} + k_i e^{q/p} \\ &+ k_d(\dot{\hat{\Omega}} + \dot{g}(x)u_{eq} - \ddot{r}_1) + (k_p g(x) + k_d \dot{g}(x))u_S \\ &+ m_1 |\dot{s}| \, sgn(\dot{s}) + m_2 |\dot{s}|^\alpha \, sgn(\dot{s}) + \hat{\theta} sgn(\dot{s})\} \end{aligned} \tag{28}$$

where $\theta \geq |s| + |k_p w_u + k_d \dot{w}_u|$, the estimation of θ is obtained from $\dot{\hat{\theta}} = \zeta \, |\dot{s}|$, b indicates a positive coefficient which leads to descending s, $m_1, m_2 > 0$ and $0 < \alpha < 1$. The reaching and switching control laws are defined as

$$\begin{aligned} \dot{u}_{eq} = &(k_d g(x))^{-1} \Big(b\dot{s} - k_p(\hat{\Omega} + g(x)u_{eq} - \dot{r}_1) \\ &- k_i e^{q/p} - k_d(\dot{\hat{\Omega}} + \dot{g}(x)u_{eq} - \ddot{r}_1)\Big) \end{aligned} \tag{29}$$

$$\begin{aligned} \dot{u}_S = &-(k_d g(x))^{-1} \big((k_p g(x) + k_d \dot{g}(x))u_S \\ &+ m_1 |\dot{s}| \, sgn(\dot{s}) + \theta sgn(\dot{s}) + m_2 |\dot{s}|^\alpha \, sgn(\dot{s})\big) \end{aligned} \tag{30}$$

Theorem 2: The uncertain nonlinear system (1) and the integral-type terminal sliding surface (27) are considered. Assume that the uncertainties $d(x, u, t)$ and $\dot{d}(x, u, t)$ are bounded, with unknown bounds. Then, the terminal sliding tracking control law (28) satisfies the asymptotical stability of the system (1).

Proof: Consider the estimation error as (19). Differentiating $\tilde{\theta}$ and using $\dot{\hat{\theta}} = \zeta \, |\dot{s}|$, one has

$$\dot{\hat{\theta}} = \ell^{-1} |\dot{s}| . \tag{31}$$

The following equation should be considered:

$$\begin{aligned} \ddot{s} + b\dot{s} = &k_p(\hat{\Omega} + g(x)u + d(x, u, t) - \dot{r}_n) + k_i e^{q/p} \\ &+ k_d(\dot{\hat{\Omega}} + \dot{g}(x)u + \dot{d}(x, u, t) - \ddot{r}_n) + k_d g(x)\dot{u}. \end{aligned} \tag{32}$$

Replacing the adaptive terminal sliding tracker (28) into (32), we achieve

$$\begin{aligned} \ddot{s} = &k_p d(x, u, t) + k_d \dot{d}(x, u, t) - \hat{\theta} sgn(\dot{s}) \\ &- m_1 |\dot{s}| \, sgn(\dot{s}) - m_2 |\dot{s}|^\alpha \, sgn(\dot{s}). \end{aligned} \tag{33}$$

The Lyapunov function is considered as

$$\dot{V}_2 = 0.5 \left(s^2 + \dot{s}^2 + \ell \tilde{\theta}^2\right), \tag{34}$$

where taking the time-derivative of (34) gives

$$\dot{V}_2 = s\dot{s} + \dot{s}\ddot{s} + \ell \tilde{\theta} \dot{\tilde{\theta}} = (s + \ddot{s})\dot{s} + (\hat{\theta} - \theta) |\dot{s}| \tag{35}$$

Now, using (33) and (35), one achieves

$$\begin{aligned} \dot{V}_2 &= (k_p \, d(x, u, t) + k_d \dot{d}(x, u, t) - \hat{\theta} sgn(\dot{s}) - m_1 |\dot{s}| \, sgn(\dot{s}) \\ &\quad - m_2 |\dot{s}|^\alpha \, sgn(\dot{s}) + s)\dot{s} + (\hat{\theta} - \theta) |\dot{s}| \\ &= \left(k_p \, d(x, u, t) + k_d \dot{d}(x, u, t)\right) \dot{s} - \hat{\theta} |\dot{s}| - m_1 |\dot{s}|^2 \\ &\quad - m_2 |\dot{s}|^{\alpha+1} + s\dot{s} + (\hat{\theta} - \theta) |\dot{s}| \end{aligned} \tag{36}$$

Since $s \leq |s|$ and $(k_p d(x, u, t) + k_d \dot{d}(x, u, t))\dot{s} \leq |k_p d(x, u, t) + k_d \dot{d}(x, u, t)| \, |\dot{s}|$, Eq. (36) is written as

$$\begin{aligned} \dot{V}_2 \leq &\left(\left|k_p d(x, u, t) + k_d \dot{d}(x, u, t)\right| + |s| - \hat{\theta}\right) |\dot{s}| \\ &- m_1 |\dot{s}|^2 - m_2 |\dot{s}|^{\alpha+1} \left(\hat{\theta} - \theta\right) |\dot{s}| \end{aligned} \tag{37}$$

where by addition and subtraction of term $\theta \, |\dot{s}|$ to Eq. (37), we obtain

$$\begin{aligned} \dot{V}_2 &\leq \left(\left|k_p d(x, u, t) + k_d \dot{d}(x, u, t)\right| + |s| - \hat{\theta}\right) |\dot{s}| \\ &\quad - m_1 |\dot{s}|^2 - m_2 |\dot{s}|^{\alpha+1} + \left(\hat{\theta} - \theta\right) |\dot{s}| + \hat{\theta} |\dot{s}| - \theta |\dot{s}| \\ &= -\left(\theta - \left|k_p d(x, u, t) + k_d \dot{d}(x, u, t)\right| - |s|\right) |\dot{s}| - m_1 |\dot{s}|^2 \\ &\quad - m_2 |\dot{s}|^{\alpha+1} - \hat{\theta} |\dot{s}| + \hat{\theta} |\dot{s}| + \theta |\dot{s}| - \theta |\dot{s}| \leq -m_1 |\dot{s}|^2 \\ &\quad - m_2 |\dot{s}|^{\alpha+1} < 0 \end{aligned} \tag{38}$$

Thus, because of the parameter-tuning TSMC input (28), it is concluded that the Lyapunov function (34) decreases gradually and the reachability condition of the sliding surface is guaranteed. □

It is worth noting that the range of the control parameters is determined based on the Lyapunov stability, and their values are fine-tuned using a trial and error approach. Therefore, using this method, the asymptotic stability of the closed-loop system in the presence of disturbances, uncertainties and input saturations is guaranteed, the NESO estimates the un-modeled dynamics and the integral-type sliding surface can remove the chattering effects.

IV. SIMULATION RESULTS

The effectiveness of the proposed approach is assessed in this section using the flexible-link manipulator depicted in Figure 2.

The above flexible link manipulator is a highly nonlinear, under-actuated and non-minimum phase system represented by:

$$\begin{cases} \ddot{q}_r = -M_r^{*^{-1}} \left(C_r^* + K_f^* q_f\right) + M_r^{*^{-1}} \tau \\ \ddot{q}_f = -M_f^{-1}[M_{fr}\ddot{q}_r + C_f + K_f q_f] \end{cases} \tag{39}$$

where q_r and q_f are the generalized coordinate vectors associated with base movement and flexibility, τ is the input torque, $M_r^*, C_r^*, K_f^*, K_f, M_f, M_{fr}, C_f$ are dynamical matrices and scalars [59]. The extended form of the dynamical model can be written as

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = x_3 + g(x) \, sat(u) \\ \dot{x}_3 = \dot{\Omega} \end{cases} \tag{40}$$

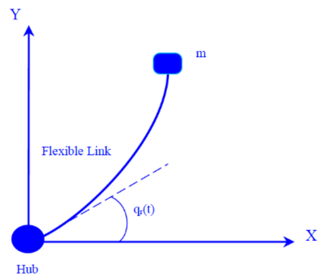

FIGURE 2. The flexible link manipulator.

with $x_1 = q_r, x_2 = \dot{q}_r, g(x) = M_r^{*^{-1}}, u = \tau$ and $x_3 = \Omega = -M_r^{*^{-1}}\left(C_r^* + K_f^* q_f\right) + d(x,t)$ where x_1, x_2, x_3 are the system states, $g(x) \in R - \{0\}$ is the input gain, $sat(u) \in R$ is the saturated controller input vector, $d(x,t)$ denotes the unmatched uncertainty, un-modeled dynamics and external disturbances.

A. EXAMPLE 1

In this part, the disturbance and uncertainty are considered as $d(x,t) = 0.1cos\,t + 0.3\sin x_1$, the initial values of system are $(x_1, x_2, x_3) = (1, 1, 1)$ and the input saturation is not symmetric and is considered as

$$sat(u) = \begin{cases} 10 & if\ u > 10 \\ u & if\ -10.5 < u < 10 \\ -10.5 & if\ u < -10.5 \end{cases} \tag{41}$$

By considering $r_1 = \sin(t)$ as reference signal, the tracking error is $e = q_r - q_{rd}$. The nonlinear extended state observer is designed as:

$$\begin{cases} \tilde{e}_1 = \hat{x}_1 - x_1 \\ \dot{\hat{x}}_1 = \hat{x}_2 - \delta cos3(\frac{\tilde{e}_1}{\delta^2}) \\ \dot{\hat{x}}_2 = \hat{x}_3 - 0.2cos5(\frac{\tilde{e}_1}{\delta^2}) + g\left(\hat{x}\right) sat\ (u) \\ \dot{\hat{x}}_{n+1} = 0.4\delta^{-1}cos7(\frac{\tilde{e}_1}{\delta^2}) \end{cases} \tag{42}$$

Therefore, by using two suggested methods, the control inputs (17) and (28) are applied to the flexible-link manipulator system IV-A. For comparison purposes, we also consider the FTSMC approach proposed in [1]. The control parameters are determined according to the following conditions: b indicates a positive coefficient which leads to descending s, $0 < \alpha < 1, \lambda, \beta_2, \beta_1, m_1, m_2, \eta, K$ are positive constants, q and p are odd positive integers with $q < p$. K_i, K_p, K_d should be positive, $0 < \zeta < 1$, therefore $\ell \geq 1$. The control parameters are provided in Table 1. The obtained results are illustrated in Figures 3 through 7, which show the state trajectory, error trajectory, control input, switching surface and disturbance estimation error, respectively. Figure 3 shows that all three methods enable the states to track the sine function suitably, however the ATSMC achieves the tracking performance much faster than the other two approaches.

TABLE 1. Control parameters of example 1.

Parameters	Values	Parameters	Values
K_p	15	m_1	4
K_i	30	m_2	0.8
K_d	0.15	α	0.1
p	9	ℓ	1
q	1	λ	0.1
β_1	25	β_2	5
K	15	θ	5
η	4	z	0.1

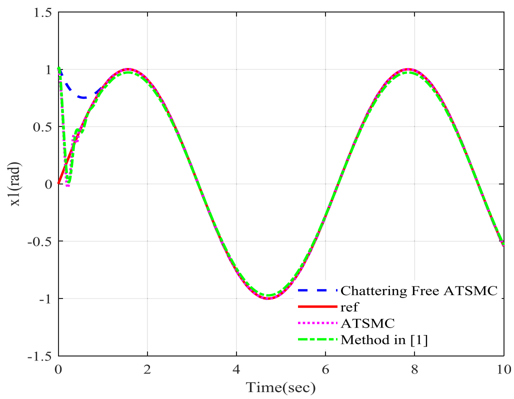

FIGURE 3. State trajectory of x_1 in example 1.

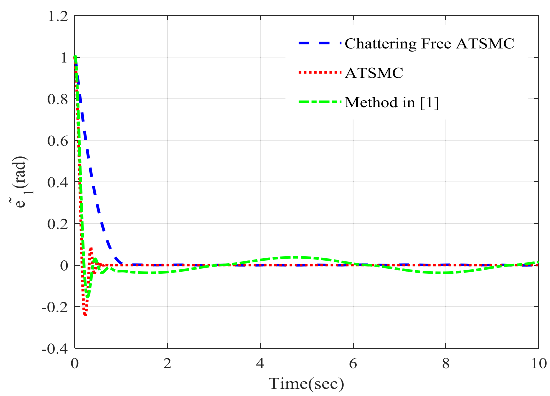

FIGURE 4. Tracking error in example 1.

Figure 4 shows that the state error converges to zero. Figure 5 depicts the dynamics of the control input. Note that the ATSMC displays some chattering dynamics, however the magnitude of those high frequency oscillations is very smaller compared to the method in [1]. The amplitude of the control input using the integral-type chattering free ATSMC is the smallest, but it has high undershoot at the start time. Figure 6 shows that the switching surface converges to the origin in the ATSMC method, whereas the integral-type chattering-free ATSMC and method of [1] display some errors. Figure 7 shows that the disturbance observer estimates the disturbances well in both of methods. The integral-type chattering-free ATSMC, however, has higher overshoot than ATSMC.

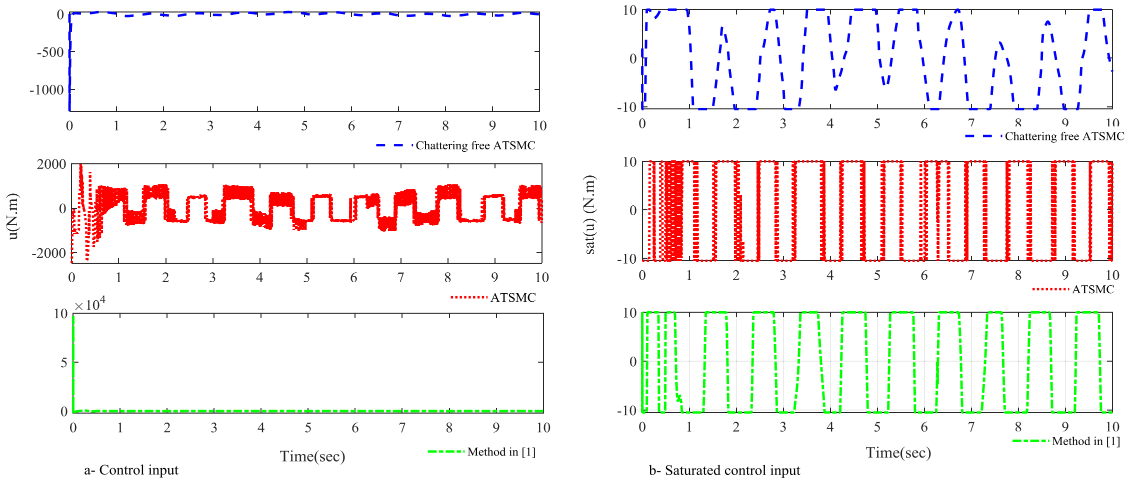

FIGURE 5. Control signals in example 1.

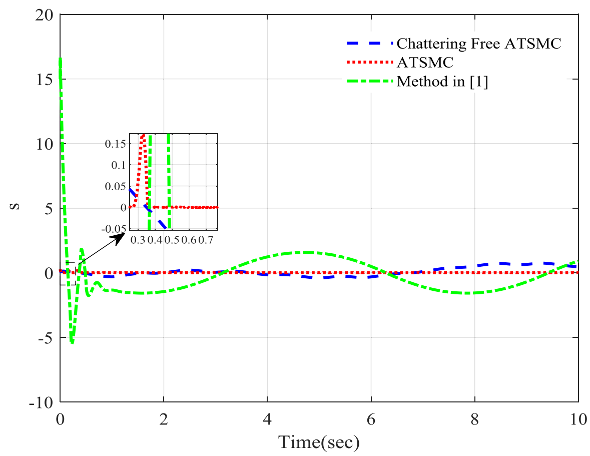

FIGURE 6. Sliding surface in example 1.

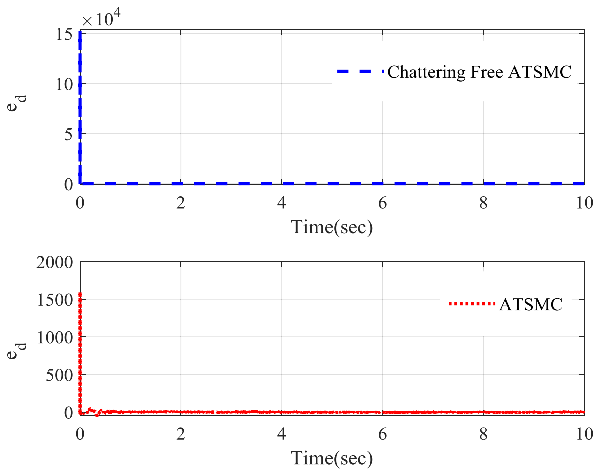

FIGURE 7. Error of disturbance estimation in example 1.

Based on the above results, we can confirm that the proposed design yields good tracking performance and reduced chattering albeit the presence of input saturation are external disturbances.

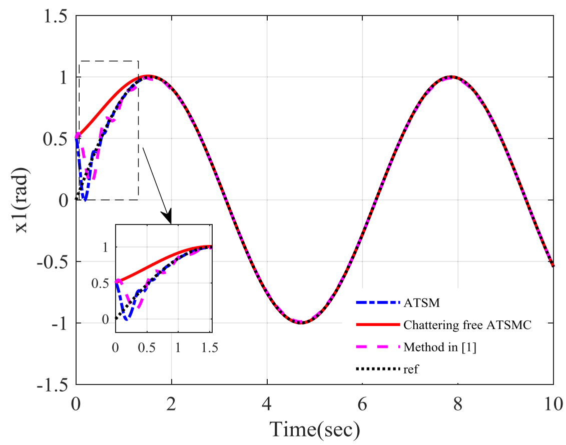

FIGURE 8. State trajectory of x_1 in example 2.

TABLE 2. Control parameters of example2.

Parameters	Values	Parameters	Values
K_p	6.95	m_1	1
K_i	6.99	m_2	100
K_d	0.031	α	0.1
p	5	ℓ	1
q	3	λ	0.2
β_1	12.5	β_2	2.5
K	15	θ	5
η	4	z	0.11

B. EXAMPLE 2

Now, the disturbance and initial values are changed to $d(x,t) = 1\,cos\,t + 3\sin x_1$, $(x_1, x_2, x_3) = (0.5, 0.5, 0.5)$ and the input saturation is not symmetric and is considered as

$$sat(u) = \begin{cases} 2 & if\ u > 2 \\ u & if\ -2.5 < u < 2 \\ -2.5 & if\ u < -2.5 \end{cases} \tag{43}$$

It is clear that, in this example, the system disturbance is increased ten-fold, the input saturation is reduced by almost

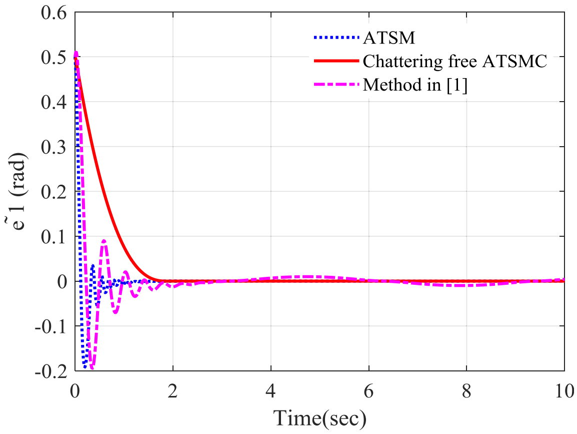

FIGURE 9. Tracking error in example 2.

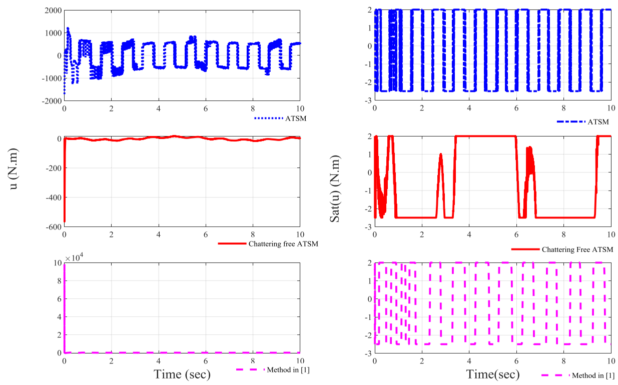

FIGURE 10. Control signals in example 2.

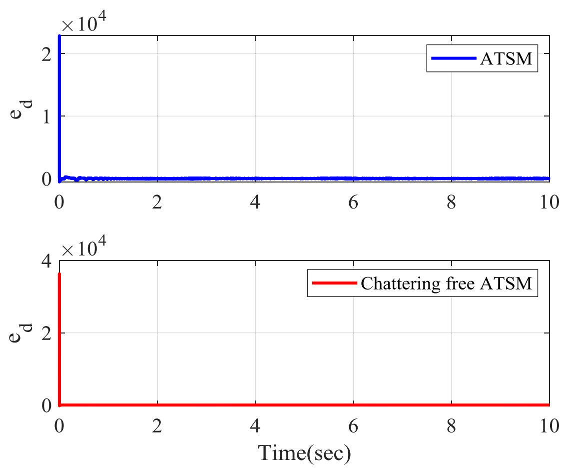

FIGURE 11. Error of disturbance estimationin example 2.

one-fifth and the initial values are halved. The suggested methods are applied to dynamics equation of flexible link manipulator (39). Other condition of problem is as same as example 1. The control parameters are illustrated in Table 2. The simulation results are shown in Figures 8 through 11. As it is seen in the figures, by changing the initial conditions, increasing the disturbances and further limiting the bounds of the input saturation, the tracking performance is faster and the oscillations are fewer than those obtained by the method in [1]. Figure 9 shows that the tracking error in the suggested methods converge to zero. As it is seen in Figure 10, the amplitude of the control inputs are much smaller than those of method [1]. High magnitude of control input may negatively impact electromechanical systems. Additionally, the practical implementing of high magnitude control inputs is too difficult and almost impossible in real systems. Figure 12 shows that the sliding surface in the suggested approach converges to zero with a much faster rate than that of method [1].

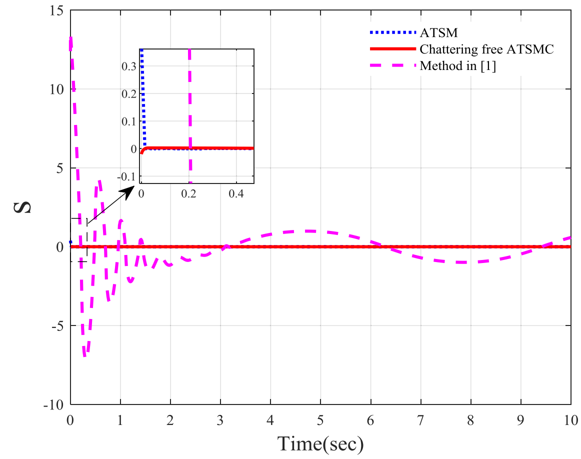

FIGURE 12. Sliding surface in example 2.

V. CONCLUSION

This paper proposed an approach that combines the robustness and chattering-free dynamics of adaptive integral-type sliding mode control with the estimation properties of a nonlinear extended state observers for nonlinear systems with uncertainties, external disturbances and input saturation. Two types of adaptive terminal sliding mode control schemes based on the nonlinear extended state observer were derived. By designing an estimation parameter in the control law, the effects of the non-symmetric input saturation and unknown uncertainty bounds are controlled. System stability was proven using the Lyapunov theorem. Implementation of the proposed design to a flexible-link manipulator confirmed its ability to reduce chattering, alleviate the impacts of the external disturbances, and achieve the finite time stability. Our future work will focus on extending the proposed integral-type ATSMC method to uncertain nonlinear systems with input saturation and time-varying delays and exploring the event-triggered implementations.

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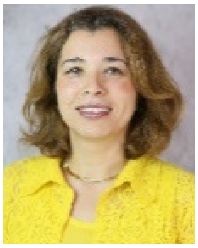

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