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A novel finite-time leader-follower consensus control for a disturbed mechanical nonlinear system in presence of actuator saturation

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ABSTRACT
This paper presents a novel leader-follower consensus control for a particular class of nonlinear multi-agent mechanical systems in the presence of control input constraints and external disturbances which includes robot system dynamics with a wide range of potential applications in industry. In this case, one of the agents is selected as the leader to direct the other agents in such a way that the whole system can reach consensus within certain prescribed performance transient bounds. Due to the presence of disturbances in most practical systems, the effect of limited disturbance in the consensus control method has been investigated, and actuator saturation is included in the design process. A terminal sliding mode control method has been adapted to ensure the stability of the overall system and fast finite-time leader-follower consensus control. The simulation results of the multi-agent nonlinear robot system in MATLAB environment, in different scenarios with simultaneous consideration of actuator saturation and external disturbance, will show the efficiency of the proposed control method.

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KEYWORDS
Consensus control; disturbance; input constraint; multi-agent system; sliding mode control

1. Introduction

Cooperative control in multi-agent systems covers a wide range of applications in power systems [1], unmanned aerial vehicles [2], sensor networks [3], intelligent networks [4], biological systems [5], robotic teams [6], formation control [7], etc. [8,9]. Multi-agent systems (MASs) consensus means converging the modes of all agents to a common value by calling some control schemes for each agent in the group and the main idea of cooperative control is to design distributed controllers on each agent using its local neighbour information for achieving this goal. It means under a locally distributed protocol, agents can work together to achieve a consensus goal. In particular, under the idea of cooperation, agents in MASs only share information locally with their neighbours and try to reach some agreement [10,11].

Standard common overall activities under cooperative control contain consensus [12], synchronization [13,14], flocking [15], swarming [16] and many expansions have been already understood. The consensus approach commonly focuses on how a collection of autonomous agents can get to an arrangement on position, velocity or other certain quantity of criteria. Most of the planned MASs have single- or double-integrator dynamics [17,18].

In consensus control studies, the rate of convergence is an important issue. This significant performance indicator contains great interest in studying the effectiveness of the consensus protocols in the field of MASs. Most consensus methods focus on asymptotic convergence, where the settling time is limitless. However, numerous programmes require a fast convergence which is usually labelled as a finite-time control plan [19]. Finite time control permits beneficial properties such as disturbance rejection and robustness to uncertainty. Actuator saturation in the control signal is another common constraint that must be considered in the control design and neglecting it can greatly reduce system performance [20]. Therefore, the controller design under actuator saturation is quite practical.

Most consensus protocols are available for non-leader or fixed-leader modes. But sometimes the existence of a dynamic leader is necessary for its followers, as the leader-follower consensus control for MASs is discussed in [21,22] in the presence of communication time delay and uncertainty of dynamic parameters. Most consensus techniques have been designed for linear MASs with unlimited time convergence [23–25], but recent various studies have been performed for nonlinear MASs as well. Control approaches for nonlinear MAS with input constraints have been designed in [26–28]. Liu and Huang [29] have also proposed an adaptive mode control law for a class of uncertain nonlinear MASs.

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Certainly, MASs are affected by disturbances and noise [30,31]. New control techniques such as self-adaptive control [32–34], robust control [35–37], sliding mode control [38], etc. have been proposed to deal with disturbances in MASs, but most can cover a specific type of disturbance, i.e. the type of match, while different types of disturbances need to be considered in designing a consensus control approach. Covering input constraints is another important issue in designing a consensus control approach for MASs. Given the importance of MASs and the need for considering actuator saturation in obtaining a control signal as well as the network communication process between agents, finding effective coordination between independent agents is one of the main concerns to achievinghigh-quality overall consensus performance.

Among the various controllers, terminal sliding mode control is one of the most effective methods in covering the effects of disturbance and parameter uncertainty in a finite time [39,40] and this paper presents a new TSM-based method for leader-follower consensus control of MASs. In general, this paper presents a new consensus control technique for the MAS by combining adaptive and terminal sliding mode methods, and includes the following innovations simultaneously: (1) One of the major advantages of this paper is the design of a finite time consensus method for a nonlinear system; (2) Uncertainty in the model is considered in the design process of the consensus method; (3) External disturbances entering the MAS are another inconveniences considered in the consensus method design process; (4) Considering the saturation boundary at the same time as disturbance and uncertainty forms another function of the proposed consensus technique; (5) Achieving high convergence speed in a limited time is another function considered in this paper; and (6) Finally, the designed consensus technique has the ability to work in leader follower manner.

Accordingly, this paper is set as follows. In Section 2, the problem formulation is stated. Section 3 shows the calculations for finite time. In Section 4, some simulation results are used to demonstrate the effectiveness of the proposed method. Finally, the conclusion is made in Section 5.

2. Proposed leader-follower consensus control method

This section provides the configuration of the new terminal sliding-mode technique for leader-follower consensus control of the MAS. Consider a class of multiple mechanical nonlinear systems as follows:

$$T_i\ddot{q}_i + C_i(q_i.\dot{q}_i)\dot{q}_i + N_i(q_i) + D_i = \tau_i \tag{1}$$

where $q_i \in R^m$, $i = 1.\dots.n$, indicates the state of the ith system, $\tau_i \in R^m$ specifies the saturated control input vector, $T_i \subset R^{m\times m}$ shows an inertia matrix, $C_i(q_i.\dot{q}_i)$ determines the centripetal and Coriolis matrix, $N_i(q_i)$ signifies the friction terms and D_i is a disturbance. Denote $v_i = \dot{q}_i$. System (1) can be transferred to

$$\begin{aligned}\dot{q}_i &= v_i\\ \dot{v}_i &= f_i(q_i.v_i) + g_iu_i + g_i\delta_i + \vartheta_i\end{aligned} \tag{2}$$

where $v_i \in R^m$ signifies the velocity.

$$\begin{aligned}f_i(q_i.v_i) &= -T_i^{-1}(C_i(q_i, v_i)v_i + N_i(q_i))\\ \vartheta_i &= -T_i^{-1}D_i\\ g_i &= -T_i^{-1}\end{aligned} \tag{3}$$

By considering the upper bound of input control as τ_{imax}, which is positive, $\delta_i = \tau_i - u_i$, the saturation function $sat(u_i)$ is stated as follows:

$$u_i = \begin{cases}\tau_{imax} & u_i > \tau_{imax}\\ u_i & |u_i| \le \tau_{imax}\\ -\tau_{imax} & u_i < -\tau_{imax}\end{cases} \tag{4}$$

The δ_i is the error affected by input saturation and it is used to solve the control input saturation problem. As the adaptive method has an omnipotent ability of approximation, it has been used to approximate δ_i here.

Two state error criteria, absolute and relative state errors, are considered for the problem of leader-follower consensus control in MASs. The absolute error is the state error of one follower agent in relation to the reference path (the leader state). The absolute state errors of the ith follower agent are described as follows:

$$\begin{aligned}e_{qi} &= q_i - q_0\\ e_{vi} &= v_i - \dot{q}_0\end{aligned} \tag{5}$$

The leader agent path q_0 and its derivatives are considered in a Ω_0 compact set described by $\Omega_0 = \left\{(q_0.\dot{q}_0.\ddot{q}_0)\,\middle|\,{q_0}^2 + \dot{q}_0^2 + \ddot{q}_0^2 \le c_1\right\}$, and c_1 is a positive constant.

The dynamic equations for the absolute errors e_{qi} and e_{vi} can be found by means of (2) as

$$\begin{aligned}\dot{e}_{qi} &= e_{vi}\\ \dot{e}_{vi} &= -\ddot{q}_0 + f_i(q_i.v_i) + g_iu_i + g_i\delta_i + \vartheta_i\end{aligned} \tag{6}$$

The relative state errors between the $i(i = 1.2.\dots.n)$th and $j(j = 1.2.\dots.n)$th follower agents are described as

$$\begin{aligned}r_{qij} &= q_i - q_j\\ r_{vij} &= v_i - v_j\end{aligned} \tag{7}$$

It should be considered that the $i(i = 1.2.\dots.n)$th agent may not achieve the absolute state errors and all relative state errors because the shared preferred q_0 is only accessible to a subset of group members, and each agent only has access to its neighbour information. Therefore, by using the weighted adjacency matrices A

and B, lumped state errors $\alpha_{qi} \in R^m$ and $\alpha_{vi} \in R^m$ are defined as

$$\alpha_{qi} = \sum_{j=1}^{n} a_{ij} r_{qij} + b_i e_{qi}$$
$$\alpha_{vi} = \sum_{j=1}^{n} a_{ij} r_{vij} + b_i e_{vi} \quad (8)$$

where a_{ij} indicates the element of matrix A. The $\alpha_{qi} \in R^m$ and $\alpha_{vi} \in R^m$ specify the sum of the absolute and relative state errors. The controller for each agent is settled based on $\alpha_{qi} \in R^m$ and $\alpha_{vi} \in R^m$.

A terminal sliding manifold $s_i \in R^m (i = 1.2.\dots.n)$ is stated as

$$s_i = \alpha_{vi} + \sigma_i \alpha_{qi} \quad (9)$$

where σ_i is a positive constant.

The first-time derivative of (9) is specified by

$$\begin{aligned} \dot{S}_i &= \sum_{j=1}^{n} a_{ij} \dot{r}_{ij} + b_i \dot{e}_{vi} + \sigma_i \alpha_{vi} \\ &= b_i \left(-\ddot{q}_0 + f_i(q_i.v_i) + g_i u_i + g_i \delta_i + \upsilon_i\right) \\ &\quad + \sum_{j=1}^{n} a_{ij} \dot{r}_{vij} + \sigma_i \alpha_{vi} \\ &= b_i (f_i(q_i.v_i) + g_i u_i) + b_i \left(\ddot{q}_0 + g_i \delta_i + \upsilon_i\right) \\ &\quad + \sum_{j=1}^{n} a_{ij} \dot{r}_{vij} + \sigma_i \alpha_{vi} \end{aligned} \quad (10)$$

By defining ω_i, $i = 1.2.\dots.$ as follows:

$$\omega_i = b_i \left(-\ddot{q}_o + g_i \delta_i + \upsilon_i\right) + \sum_{j=1}^{n} a_{ij} \dot{r}_{vij} + \sigma_i \alpha_{vi}.|\omega_i| < L_i \quad (11)$$

where L_i is the unknown upper bound of ω_i. Now $\dot{s}_i$ is rewritten as follows:

$$\begin{aligned} \dot{s}_i &= b_i (f_i(q_i.v_i) + g_i u_i) + \omega_i \\ i &= 1.2.\dots.n \end{aligned} \quad (12)$$

Now to prove the stability of the system and also to find the appropriate control signal, the Lyapunov function is nominated as follows:

$$V = \frac{1}{2} \sum_{i=1}^{n} (s_i^2 + \tilde{L}_i^2) \quad (13)$$

where

$$\tilde{L}_i = L_i - \hat{L}_i$$
$$i = 1.\dots.n$$

Above, $\hat{L}_i$ is the upper bound estimate of L_i.

It is obtained by deriving from the Lyapunov function

$$\begin{aligned} \dot{V} &= \sum_{i=1}^{n} \left(s_i \dot{s}_i + \tilde{L}_i \dot{\hat{L}}_i\right) \\ &= \sum_{i=1}^{n} \left(s_i (b_i (f_i(q_i.v_i) + g_i u_i) + \omega_i) - \tilde{L}_i \dot{\hat{L}}_i\right) \end{aligned} \quad (14)$$

Selecting the control signal as follows:

$$u_i = g_i^{-1} \left(-f_i(q_i.v_i) - \frac{1}{b_i} (k_i \mathrm{sign}(s_i) + \hat{L}_i \mathrm{sign}(s_i)\right) \quad (15)$$

where k_i, $i = 1.\dots.n$ are the controller signal gains. Now, by placing the control signal in the derivative of Lyapunov's function, the following can be obtained:

$$\begin{aligned} \dot{V} &= \sum_{i=1}^{n} \left(-s_i \mathrm{sign}(s_i) - \hat{L}_i s_i \mathrm{sign}(s_i) + s_i \omega_i - \tilde{L}_i \dot{\hat{L}}_i\right) \\ &\le \sum_{i=1}^{n} \left(-k_i |s_i| - \hat{L}_i |s_i| + L_i |s_i| - \tilde{L}_i \dot{\hat{L}}_i\right) \\ &\le \sum_{i=1}^{n} \left(-k_i |s_i| + \tilde{L}_i |s_i| - \tilde{L}_i \dot{\hat{L}}_i\right) \end{aligned} \quad (16)$$

Now by selecting the adaptive law as follows:

$$\dot{\hat{L}}_i = \lambda_i |s_i|.\lambda_i > 1.i = 1.\dots.n \quad (17)$$

where λ_i are adaptive law adjustment gains. We will have

$$\dot{V} \le \sum_{i=1}^{n} (-k_i |s_i| - (\lambda_i - 1) |\tilde{L}_i| |s_i|) \quad (18)$$

By defining

$$\begin{aligned} &\theta_1 = \min_i(k_i).\theta_2 = \min_i((\lambda_i - 1)|s_i|) \\ &\theta = \min(\theta_1.\theta_2) \end{aligned} \quad (19)$$

Thus, the derivative of the Lyapunov function is simplified as follows:

$$\dot{V} \le -\theta \left(\sum_{i=1}^{n} |s_i| + |\tilde{L}_i|\right) \quad (20)$$

$$\dot{V} \le -\sqrt{2}\theta V^{\frac{1}{2}} \quad (21)$$

Finally, by setting $c = \sqrt{2}\theta$, $d = 0.5$ and applying Lemma 1 [41], it is proven that $s_i = \dot{s}_i = 0.\ i = 1.\dots.n$ are always fulfilled for $t \ge T_r$ where T_r is estimated by

$$T_r \le \frac{\sqrt{\sum_{i=1}^{n} (s_i^2(.) + (L_i(.) - \hat{L}_i(.))^2)}}{\min\left(\min_j(k_i).\min_j(\lambda_i - 1)|s_i|\right)} \quad (22)$$

3. Numerical results

In this section, the capabilities of the proposed control method are shown by simulating a MAS with four robots. The modified terminal sliding mode method has been implemented on the robot system with the aim of robust leader-follower consensus control and a MATLAB simulation environment has been used for this purpose. Two scenarios are considered for simulation and the results are compared with the fast terminal sliding mode, robust adaptive sliding mode and Chebyshev neural network terminal sliding mode methods of [6, 37, 42]. The matrices of the robot in (1) are as follows:

$$M = \begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}$$
$$C = \begin{bmatrix} cos(q_1) & c_1\dot{q}_2 \\ c_2\dot{q}_2 & sin(q_2) \end{bmatrix} \quad (23)$$
$$N = \begin{bmatrix} n_1\dot{q}_1 & 0 \\ 0 & n_2\dot{q}_2 \end{bmatrix}$$

The system parameters are as follows:

$$m_1 = m_2 = 5$$
$$c_1 = c_2 = 2 \quad (24)$$
$$n_1 = n_2 = 3$$

The initial positions are set to (−3, 1), (−5, 0.5), (−6, −1) and (−4, −0.5) for four robots, respectively. Also,

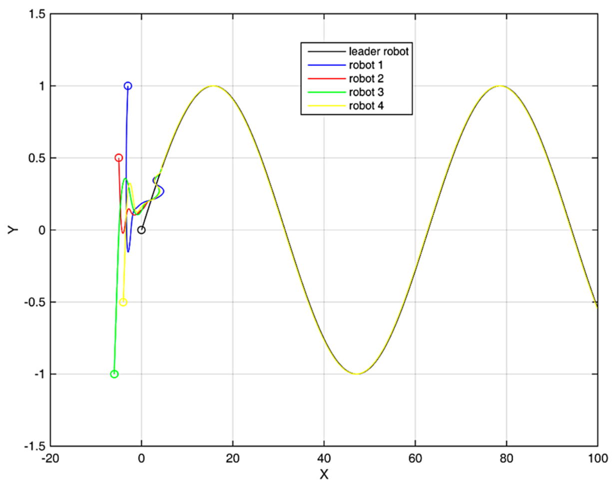

Figure 1. States of four mechanical robots in the leader-follower case in scenario 1.

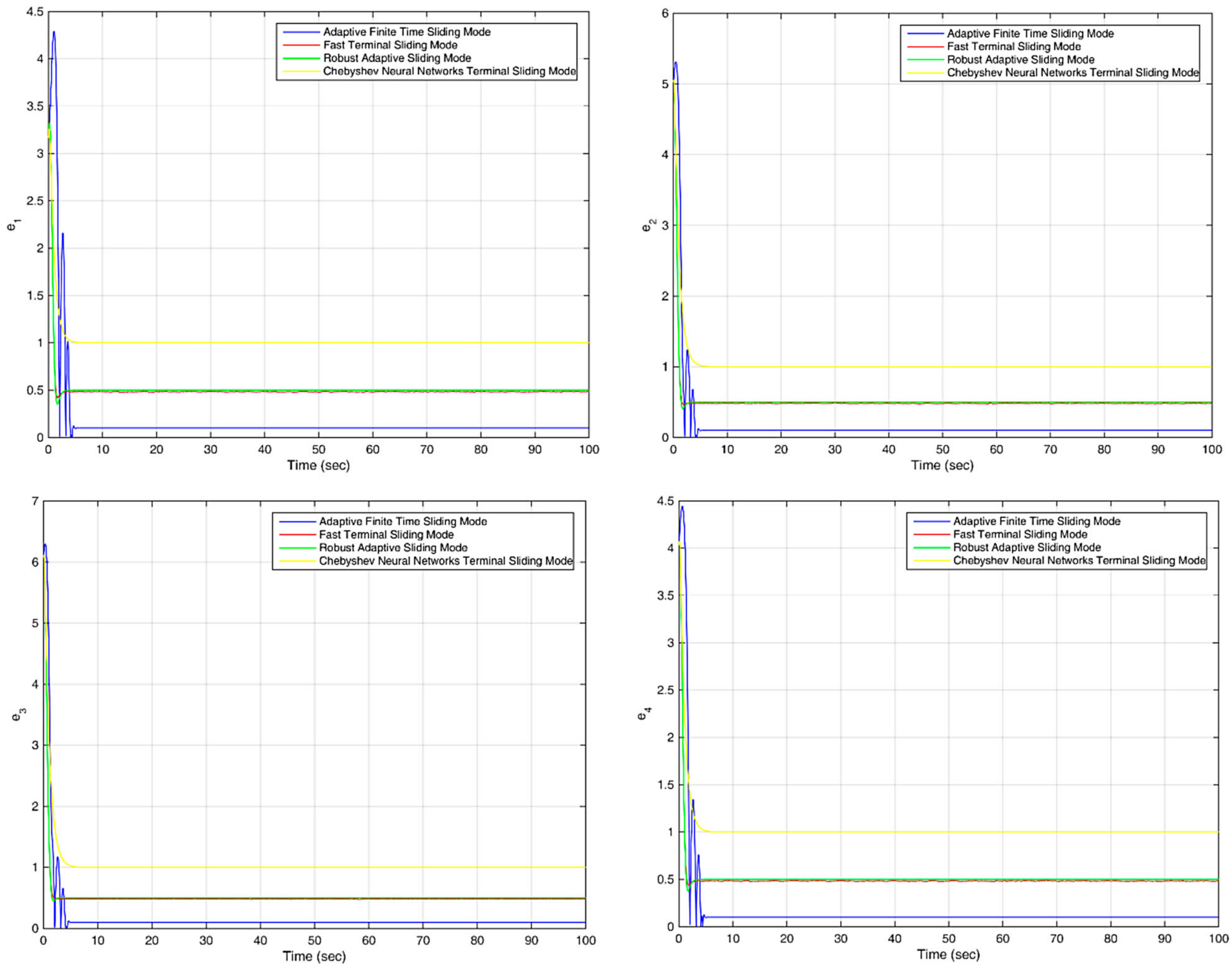

Figure 2. The error of four robots in following leader robot under different methods in scenario 1.

the control parameters are designated as follows:

$$A = \begin{bmatrix} 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \end{bmatrix}$$

$$B = [1.1.1.0.9]^T$$

$$\begin{aligned} \tau_{imax} &= 100 \\ K &= 0.1I_4 \\ \lambda &= 0.1I_4 \\ \sigma &= 10I_4 \end{aligned} \tag{25}$$

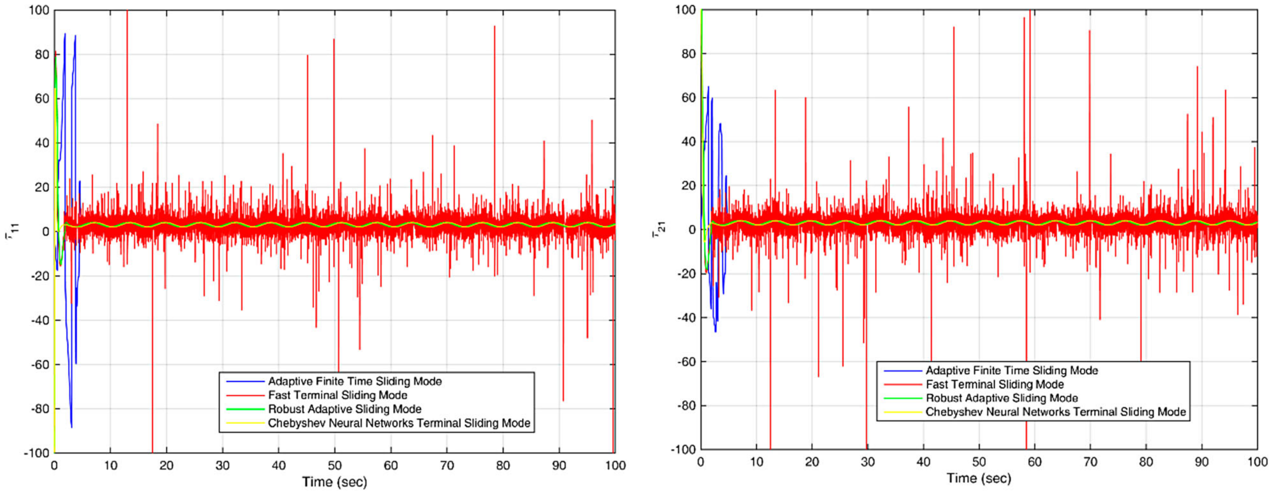

Figure 3. Control signals of robot 1 in the leader-follower case in scenario 1.

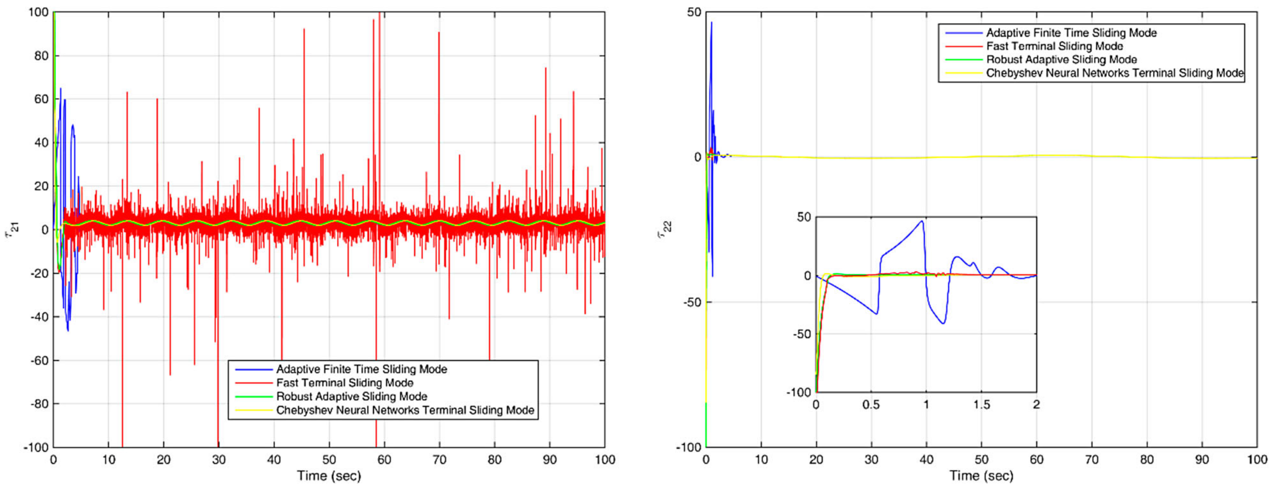

Figure 4. Control signals of robot 2 in the leader-follower case in scenario 1.

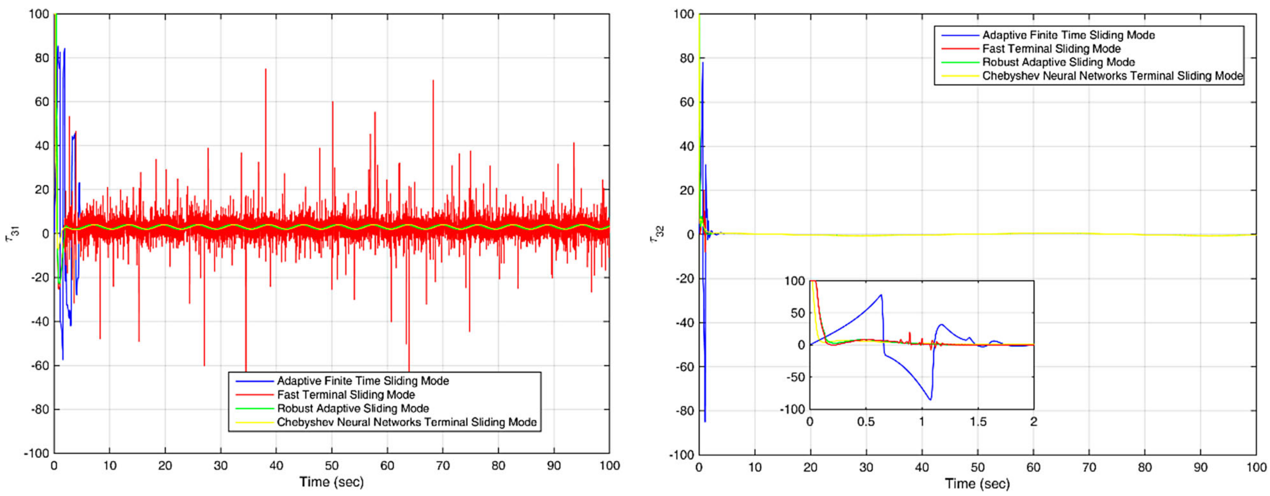

Figure 5. Control signals of robot 3 in the leader-follower case in scenario 1.

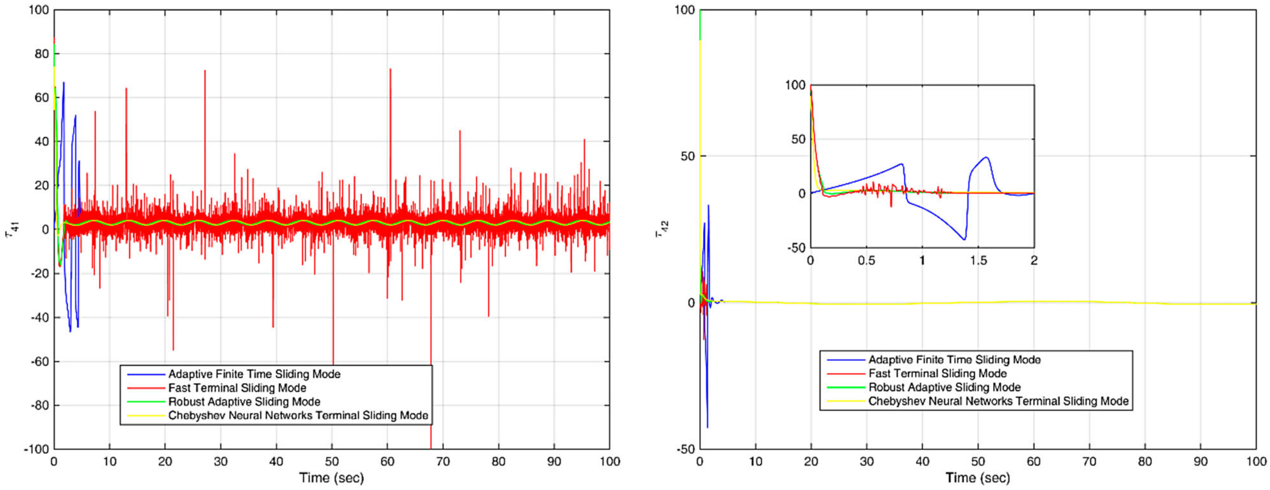

Figure 6. Control signals of robot 4 in the leader-follower case in scenario 1.

Scenario 1: MAS in leader-follower case without disturbance

In this scenario, the MAS does not experience any disturbance and the robots follow the leader robot state. The results of this scenario are shown in Figures 1–6. As Figure 1 shows, the robots follow the leader robot state well. Figure 2 shows the errors of four robots in tracking the leader robot under different control methods. Figures 3–6 show the control signals obtained using the proposed finite time adaptive sliding mode and the fast terminal sliding mode, robust adaptive sliding mode and Chebyshev neural network terminal sliding mode techniques, respectively.

The results obtained in Figures 1–6 show the optimal tracking of the leader robot by the following robots, while the lowest tracking error is related to the proposed method, and of course, the finite time convergence and saturation limit are well observed.

To better evaluate the efficiency of the proposed control method, the error values of each of the following robots in tracking the leader robot are given in Tables 1–4 under different definitions of integral square error (ISE) and integral absolute error (IAE). Table 1 shows the error value of the follower robot 1 in tracking the leader robot using different control methods under the two ISE and IAE criteria and Tables 2–4 show the same error rate for robots 2–4 in scenario 1. It is clear from Tables 1–4 that the lowest error value for the following robots under the two error criteria is obtained using the proposed finite time adaptive sliding mode scheme.

Table 1. The error value of the follower robot 1 (e_1) in tracking the leader robot using different control methods in scenario 1.

Controllers	ISE	IAE
Adaptive finite time sliding mode	29.6017	18.6383
Fast terminal sliding mode	30.0875	50.3203
Robust adaptive sliding mode	31.7172	51.9782
Chebyshev neural networks terminal sliding mode	108.6496	102.5337

Table 2. The error value of the follower robot 2 (e_2) in tracking the leader robot using different control methods in scenario 1.

Controllers	ISE	IAE
Adaptive finite time sliding mode	34.9384	18.1738
Fast terminal sliding mode	36.7268	51.3597
Robust adaptive sliding mode	38.3970	53.0219
Chebyshev neural networks terminal sliding mode	119.7553	104.4962

Table 3. The error value of the follower robot 3 (e_3) in tracking the leader robot using different control methods in scenario 1.

Controllers	ISE	IAE
Adaptive finite time sliding mode	41.8594	18.6843
Fast terminal sliding mode	43.5463	52.2269
Robust adaptive sliding mode	45.2003	53.9027
Chebyshev neural networks terminal sliding mode	128.6681	105.7230

Table 4. The error value of the follower robot 4 (e_4) in tracking the leader robot using different control methods in scenario 1.

Controllers	ISE	IAE
Adaptive finite time sliding mode	29.5485	18.0198
Fast terminal sliding mode	32.6899	50.7477
Robust adaptive sliding mode	34.3779	52.4369
Chebyshev neural networks terminal sliding mode	113.3604	103.4558

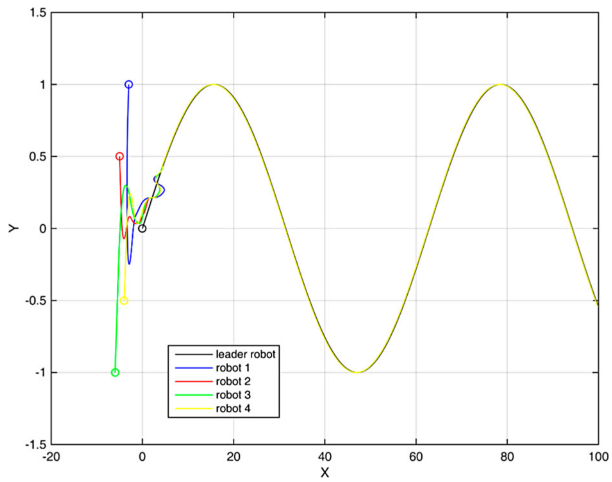

Figure 7. States of four mechanical robots in the leader-follower case in scenario 2.

Scenario 2: MAS in the leader-follower case with disturbance

In this scenario, the MAS experiences the following disturbance.

$$\begin{aligned} d_1 &= 0.7\sin(0.2t) \\ d_2 &= 0.8cos(0.3t) \end{aligned} \tag{26}$$

The simulation results are shown in Figures 7–12. Figure 7 shows the states of four mechanical robots in the leader following case, Figure 8 shows the errors of four robots in tracking the leader robot under different control methods and Figures 9–12 represent the control signals.

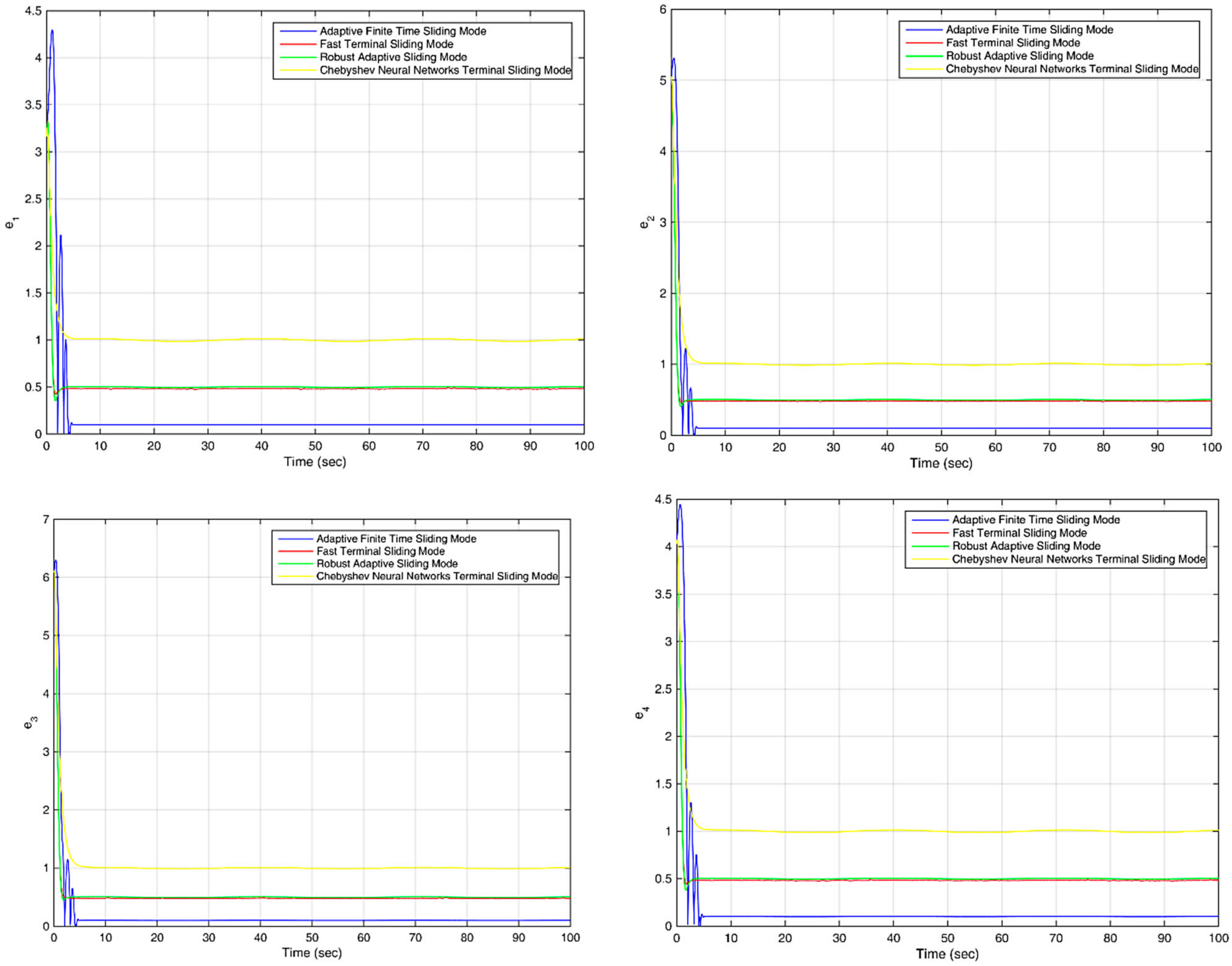

Figure 8. The error of four robots in following leader robot under different methods in scenario 2.

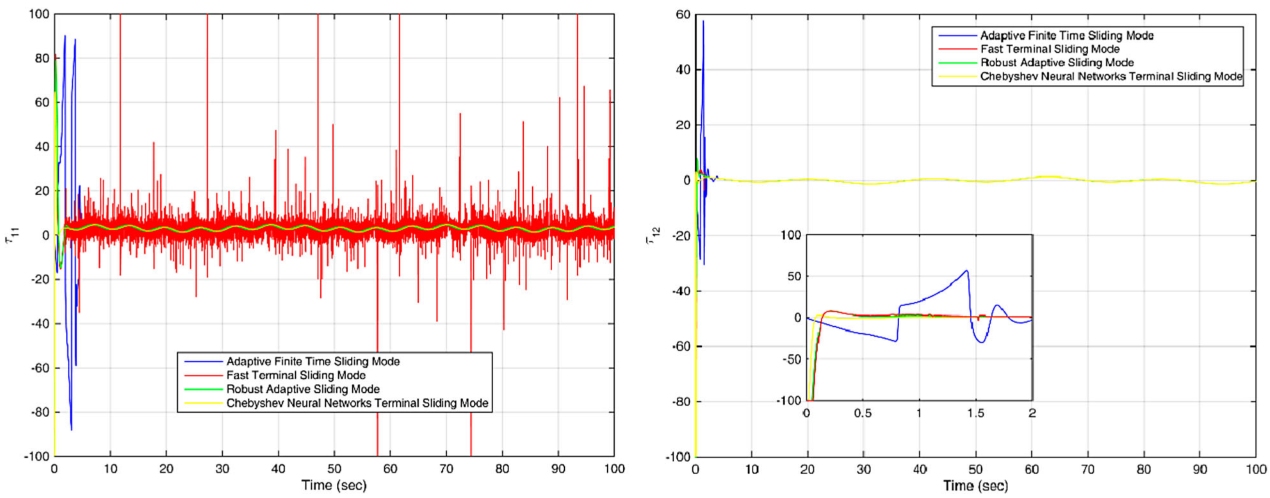

Figure 9. Control signals of robot 1 in the leader-follower case in scenario 2.

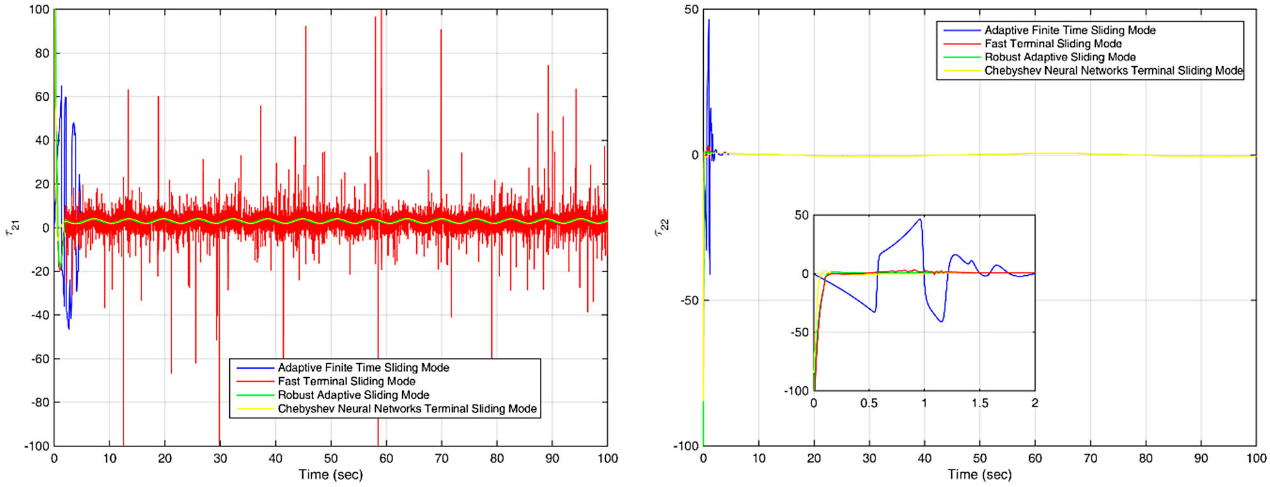

Figure 10. Control signals of robot 2 in the leader-follower case in scenario 2.

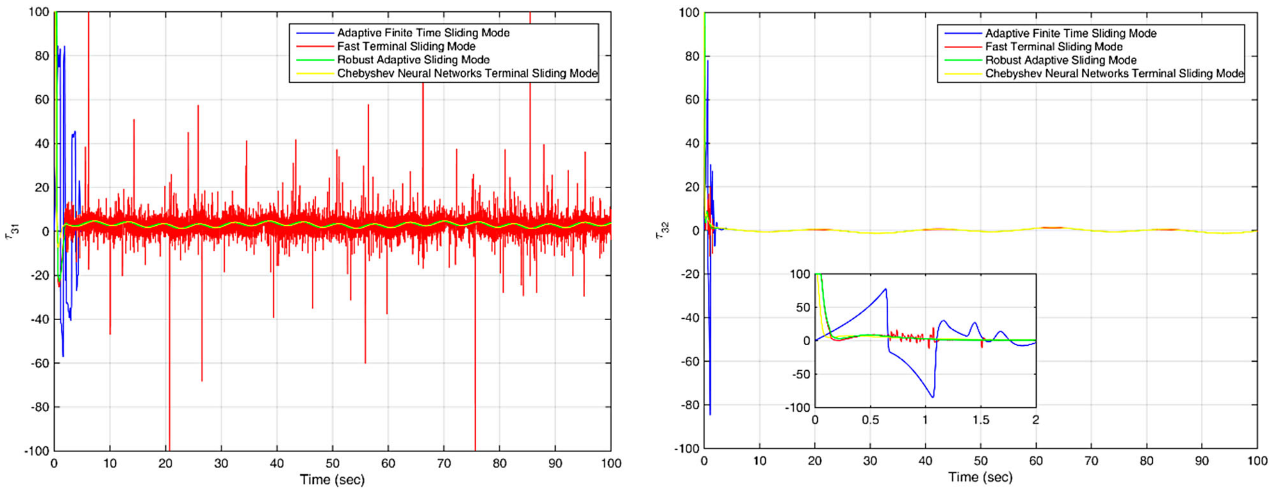

Figure 11. Control signals of robot 3 in the leader-follower case in scenario 2.

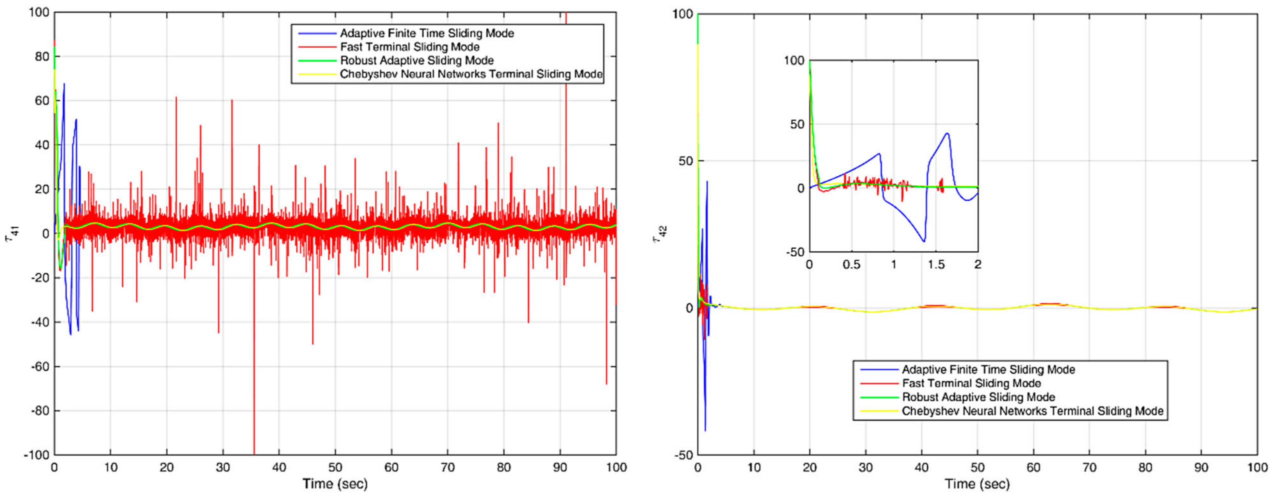

Figure 12. Control signals of robot 4 in the leader-follower case in scenario 2.

The results obtained in scenario 1 are valid here as well. It is obvious that the suggested control scheme can realize the convergence of the tracking errors to zero in finite time, and despite the saturation limitation and disturbance unrest, the follower robots track the leader robot well under the proposed scheme.

The error values obtained in scenario 2 in Tables 5–8 also confirm the superiority of the proposed adaptive sliding mode scheme. Table 5 indicates the error value of the follower robot 1 in tracking the leader robot using different control methods under four ISE and IAE criteria and Tables 6–8 show the same error rate for robots

Table 5. The error value of the follower robot 1 (e_1) in tracking the leader robot using different control methods in scenario 2.

Controllers	ISE	IAE
Adaptive finite time sliding mode	29.5454	18.5990
Fast terminal sliding mode	30.0490	50.2809
Robust adaptive sliding mode	31.7257	51.9906
Chebyshev neural networks terminal sliding mode	108.7215	102.5655

Table 6. The error value of the follower robot 2 (e_2) in tracking the leader robot using different control methods in scenario 2.

Controllers	ISE	IAE
Adaptive finite time sliding mode	34.9537	18.1595
Fast terminal sliding mode	36.6919	51.3231
Robust adaptive sliding mode	38.4102	53.0359
Chebyshev neural networks terminal sliding mode	119.8394	104.5304

Table 7. The error value of the follower robot 3 (e_3) in tracking the leader robot using different control methods in scenario 2.

Controllers	ISE	IAE
Adaptive finite time sliding mode	41.8583	18.6653
Fast terminal sliding mode	43.5250	52.2017
Robust adaptive sliding mode	45.2183	53.9183
Chebyshev neural networks terminal sliding mode	128.7752	105.7617

Table 8. The error value of the follower robot 4 (e_4) in tracking the leader robot using different control methods in scenario 2.

Controllers	ISE	IAE
Adaptive finite time sliding mode	29.5169	17.9833
Fast terminal sliding mode	32.6857	50.7404
Robust adaptive sliding mode	34.3962	52.4526
Chebyshev neural networks terminal sliding mode	113.4558	103.4935

2–4 in scenario 2. As in the first scenario, the lowest error values under different criteria are obtained by the proposed scheme. These two scenarios prove the theoretical results and it is obvious that disturbance does not have a considerable influence on the effectiveness of the proposed control method.

4. Conclusion

This paper examines the issue of finite-time leader-follower consensus control for a nonlinear MAS in the presence of external disturbances. It also takes into account actuator saturation in stability proven by the Lyapunov method. The modified terminal sliding mode control method in this paper is able to cover the effects of nonlinear terms, actuator saturation and external disturbances, and at the same time achieves leader-follower finite-time tracking objectives of the MAS. The simulation results on the 4-robots system show well the efficiency of the proposed method. Consideration of parametric uncertainty as well as actuator delay can be the path of further studies in this field.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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