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FUZZY ADAPTIVE CONSENSUS OF SECOND-ORDER NONLINEAR MULTI-AGENT SYSTEMS IN THE PRESENCE OF INPUT SATURATION

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Abstract. *This paper studies the consensus problem of second-order nonlinear multi-agent systems with a leader. A fuzzy adaptive consensus method with prescribed performance is proposed for second-order nonlinear multi-agent systems with unknown dynamics in the presence of input saturation. An auxiliary system is introduced to counteract the effect of input saturation and fuzzy logic systems are used to approximate the unknown dynamics. By combining prescribed performance control and dynamic surface control technique, consensus controllers are developed to guarantee that the outputs of all followers can track that of the leader, and synchronization errors stay in the predefined bounds. The proposed consensus scheme can overcome the effect of input saturation and guarantee the steady and transient performances simultaneously. Simulation results are provided to show the effectiveness of the proposed method.*
Keywords: Consensus control, Dynamic surface control, Input saturation, Nonlinear multi-agent systems, Prescribed performance control

1. **Introduction.** Recent years, consensus as a fundamental problem has been paid much attention in cooperative control of multi-agent systems [1-3]. Consensus of multi-agent systems is to design a distributed control protocol using the local information of each agent, such that the sates or outputs of all agents reach consensus. In particular, leader-follower consensus means that in the multi-agent systems, there is a leader agent and all followers are trying to track the trajectory of the leader under the condition that the leader only gives commands to a small portion of the followers [4-7]. It has a wide engineering application, such as unmanned air vehicle plane, autonomous marine vehicle formation and robot synchronization.

Since practical control systems can be modeled by second-order systems, such as robots, aircrafts and underwater vehicles, it is more meaningful to investigate consensus of multi-agent systems with second-order nonlinear dynamics [8-11]. In [8, 9], adaptive consensus controllers are proposed using the variable structure control method for second-order nonlinear multi-agent systems. In [10], a robust adaptive consensus control is designed for integrator-type multi-agent systems with external disturbances and unmodeled dynamics. Fuzzy logic systems and neural networks are function approximationers, which are effective to deal with nonlinear systems with uncertainties [12-15]. In [11], using function approximation, adaptive neural consensus control protocol is developed for second-order nonlinear multi-agent systems with unknown dynamics. It should be pointed out that the reported consensus methods in [8-11] only guarantee that synchronization errors converge to a small residual set, whose size depends on design parameters and some unknown bounded terms. However, practical control systems often require the proposed control scheme to satisfy certain pre-specified transient and steady performances.

On the other hand, since consensus controllers are relevant to system states, the magnitude of the controllers may exceed physical limitations in the case of large initial conditions or uncertainties. To solve this problem, some consensus methods have been proposed for linear systems [16-18]. However, consensus of nonlinear systems in the presence of input saturation should be further investigated.

Motivated by the above observations, this paper considers the consensus problem of second-order nonlinear multi-agent systems in the presence of input saturation. Using fuzzy approximation and the prescribed performance control technique, a consensus control scheme is designed to guarantee that the outputs of all followers can track that of the leader. Moreover, the synchronization errors stay in the predefined bounds. Thus, both the transient and steady performances are guaranteed simultaneously.

Compared with the existing results, the main advantages of the proposed control scheme in this paper are listed as follows.

- Compared with the consensus schemes in [8-11] where the consensus controllers are proposed without considering input constraints, this paper investigates the consensus of second-order nonlinear multi-agent systems in the presence of input saturation. By introducing an auxiliary system, the effect of input saturation is counteracted.
- The consensus methods reported in [8-11] can only guarantee the asymptotic stability without considering the transient performance. By employing fuzzy control and prescribed performance control technique, consensus controllers with prescribed performance are designed to achieve that the outputs of all followers converge to that of the leader. Moreover, the synchronization errors remain in the prescribed performance bounds.

The rest of this paper is organized as follows. Section 2 introduces some preliminaries and problem statement. Section 3 provides the consensus controller design. Section 4 presents the stability analysis. Section 5 gives a simulation example to show the effectiveness of the proposed control method. Section 6 concludes this paper.

2. **Preliminaries and Problem Statement.**

2.1. **Preliminaries.**

The information communication among followers is described by a directed graph $\mathcal{G} = (\mathcal{V}, \mathcal{E}, \Lambda)$, where $\mathcal{V} = \{n_1, \cdots, n_N\}$ is a node set, $\mathcal{E} = \{(n_i, n_j) \in \mathcal{V}\times\mathcal{V}\}$ is an edge set, and $\Lambda = [a_{ij}]_{N\times N}$ is an adjacency matrix. n_i denotes follower i. $(n_i, n_j) \in \mathcal{E}$ means follower i can transform its infirmation to follower j. The neighbor set of node i is denoted as $\mathcal{N}_i = \{j \,|\, (n_i, n_j) \in \mathcal{E}\}$. $a_{ij} = 1$ if $(n_i, n_j) \in \mathcal{E}$; otherwise $a_{ij} = 0$. The directed graph $\mathcal{G}$ contains a spanning tree if there exists a root agent, who has a directed path to every other node. The Laplacian matrix of the graph $\mathcal{G}$ is defined as $\mathcal{L} = [\mathcal{L}_{ij}]_{N\times N}$. $\mathcal{L}_{ij} = -a_{ij}$, if $i \neq j$; otherwise $\mathcal{L}_{ij} = \sum_{j\in\mathcal{N}_i} a_{ij}$. The degree matrix of the graph $\mathcal{G}$ is defined as $\mathcal{D} = \mathrm{diag}(d_1, \cdots, d_N)$, where $d_i = \sum_{j\in\mathcal{N}_i} a_{ij}$. The leader adjacency matrix is defined as $\Lambda_0 = \mathrm{diag}(a_{10}, \cdots, a_{N0})$, where $a_{i0} = 1$, if follower i can get the information of the leader; otherwise $a_{i0} = 0$.

Assumption 2.1. *The communication graph $\mathcal{G}$ among the followers is directed, and the root agent can get the information of the leader.*

2.2. **Problem statement.** Consider second-order nonlinear multi-agent systems consisting of N followers and a leader. The ith follower is described by

$$\begin{aligned}\dot{x}_i &= v_i,\\ \dot{v}_i &= u_i + f_i\left(x_i, v_i\right) + \varpi_i(t),\end{aligned} \tag{1}$$

where x_i is the position signal. v_i is the velocity signal. $f_i(x_i, v_i)$ is an unknown function. $\varpi_i(t)$ is a bounded external disturbance. u_i is the system input given by

$$u_i = sat(\chi_i) \begin{cases} \text{sign}(\chi_i) u_{iM}, & |\chi_i| \geq u_{iM}, \\ \chi_i, & |\chi_i| < u_{iM}, \end{cases} \tag{2}$$

where χ_i is the input of the actuator, and u_{iM} is the saturation value of the actuator.

The control objective of this paper is to design consensus controllers to guarantee that the outputs of all followers synchronize to that of the leader; i.e., $x_i \to x_r(t)$, where $x_r(t)$ is the output of the leader. Besides, synchronization errors remain in the prescribed bounds.

3. **Consensus Controller Design.**

The synchronization error is defined as

$$s_{i,1} = \sum_{j \in \mathcal{N}_i} a_{ij}\left(x_i - x_j\right) + a_{i0}\left(x_i - x_r(t)\right). \tag{3}$$

Prescribed performance is achieved by ensuring that the synchronization error $s_{i,1}$ satisfies the following inequality [19]

$$-\rho_{1i}\mu_i(t) < s_{i,1} < \rho_{2i}\mu_i(t), \quad t \geq 0, \tag{4}$$

where $0 < \rho_{1i},\ \rho_{2i} \leq 1$ are design constants. $\mu_i(t)$ is a performance function, which is chosen as:

$$\mu_i(t) = (\mu_{i0} - \mu_{i\infty})e^{-c_i t} + \mu_{i\infty}, \quad \forall t \geq 0, \tag{5}$$

where $c_i > 0$, $\mu_{i0} > 0$, $\mu_{i0} > \mu_{i\infty}$, and $-\rho_{1i}\mu_i(0) < s_{i,1}(0) < \rho_{2i}\mu_i(0)$.

Transform the synchronization error $s_{i,1}$ as follows:

$$\xi_{i,1}(t) = \Phi_i\left(\frac{s_{i,1}}{\mu_i(t)}\right) = \frac{1}{2}\ln\frac{\rho_{1i} + \frac{s_{i,1}}{\mu_i(t)}}{\rho_{2i} - \frac{s_{i,1}}{\mu_i(t)}}. \tag{6}$$

Lemma 3.1. [20] *Consider error surface $s_{i,1}$ and transformed error $\xi_{i,1}(t)$ defined in (6) where $i = 1, \cdots, N$. If $\xi_{i,1}(t)$ is bounded, prescribed performance of $s_{i,1}$ is satisfied for all $t \geq 0$, that is, (5) is satisfied.*

The consensus control design contains two steps. Each step is based on an error surface. To stabilize the error surface, the virtual control law and actual control law will be designed.

Step 1: The first error surface is chosen as $\xi_{i,1}(t)$. The derivative of (6) along with (1) and (3) is given by

$$\begin{aligned}\dot{\xi}_{i,1}(t) &= p_i\left(\dot{s}_{i,1} - \frac{\dot{\mu}(t)}{\mu(t)}s_{i,1}\right)\\ &= p_i\left(\left(d_i + a_{i0}\right)\left(s_{i,2} + \alpha_{i,2}\right) - \sum_{j \in \mathcal{N}_i} a_{ij}v_j - a_{i0}\dot{x}_r(t) - \frac{\dot{\mu}(t)}{\mu(t)}s_{i,1}\right),\end{aligned} \tag{7}$$

where $p_i = \left(\frac{1}{\Phi_i^{-1}\left(\frac{s_{i,1}}{\mu_i(t)}\right) + \rho_{1i}} - \frac{1}{\Phi_i^{-1}\left(\frac{s_{i,1}}{\mu_i(t)}\right) - \rho_{2i}}\right)$.

To stabilize the first error surface $\xi_{i,1}(t)$, the first virtual control law is designed as

$$\alpha_{i,2} = -k_{i,1}\xi_{i,1}(t) + \frac{1}{d_i + a_{i0}}\left(\sum_{j\in\mathcal{N}_i} a_{ij}v_j + a_{i0}\dot{x}_r(t) + \frac{\dot{\mu}_i(t)}{\mu_i(t)}s_{i,1}\right), \tag{8}$$

where $k_{i,1} > 0$ is a design constant. Then, the closed-loop dynamics of $\xi_{i,1}(t)$ is

$$\dot{\xi}_{i,1}(t) = p_i\left(d_i + a_{i0}\right)\left(s_{i,2} - k_{i,1}\xi_{i,1}(t)\right). \tag{9}$$

To avoid the differentiating of $\alpha_{i,2}$, let $\alpha_{i,2}$ pass through a second-order tracking differentiator (TD) to obtain the estimate of $\alpha_{i,2}$ as follows:

$$\begin{aligned} \dot{v}_{1d} &= v_{2d}, \\ \dot{v}_{2d} &= -\gamma \mathrm{sign}\left(v_{1d} - \alpha_{i,2} + \frac{v_{2d}|v_{2d}|}{2\gamma}\right), \end{aligned} \tag{10}$$

with $\gamma > 0$.

Remark 3.1. *Compared with the first-order filters introduced in conventional dynamic surface control design, the TD provides the fastest tracking of $\alpha_{i,2}$; i.e., TD assures that the state arrives at the steady state in minimal and finite time T. The finite-time convergence means that there exists a constant τ^* such that $|v_{1d} - \alpha_{i,2}| \le \tau^*$. Moreover, the parameter γ can be selected regarding to the physical limitations of the vehicle and in turn to obtain an optimized transient profile.*

Step 2: The second error surface is defined as

$$s_{i,2} = v_i - v_{1d}. \tag{11}$$

The derivative of (11) along (1) is given by

$$\dot{s}_{i,2} = u_i + f_i(x_i, v_i) + \varpi_i(t) - \dot{v}_{1d}. \tag{12}$$

By universal approximation theorem [12], fuzzy logic systems can approximate an unknown function $f_i(x_i, v_i)$ as

$$f_i\left(x_i, v_i\right) = \theta_i^{*T}\varphi_i\left(x_i, v_i\right) + \varepsilon_i, \tag{13}$$

where θ_i^* is the optimal parameter vector, $\varphi_i(x_i, v_i)$ is the fuzzy basis function vector, and ε_i is the corresponding minimal fuzzy approximation error. Then

$$\dot{s}_{i,2} = u_i + \theta_i^{*T}\varphi_i\left(x_i, v_i\right) - \dot{v}_{1d} + \varepsilon_i + \varpi_i(t). \tag{14}$$

To compensate the input saturation of the actuator, an auxiliary system is introduced as [21]

$$\dot{\Gamma}_i = \begin{cases} -\eta_i\Gamma_i - \frac{|s_{i,2}(u_i-\chi_i)| + 0.5(u_i-\chi_i)^2}{\Gamma_i} + (u_i - \chi_i), & |\Gamma_i| \ge \vartheta_i \\ 0, & |\Gamma_i| < \vartheta_i \end{cases} \tag{15}$$

where Γ_i is the state of the auxiliary system. $\eta_i > 0$, $\vartheta_i > 0$ are design constants.

To stabilize the second error surface $s_{i,2}$, the input of the actuator χ_i and parameter adaptive law for θ_i are designed as

$$\chi_i = -k_{i,2}\left(s_{i,2} - \Gamma_i\right) - \theta_i^T\varphi_i\left(x_i, v_i\right) + \dot{v}_{1d} \tag{16}$$

$$\dot{\theta}_i = \lambda_i\left(s_{i,2}\varphi_i\left(x_i, v_i\right) - \sigma_i\theta_i\right), \tag{17}$$

where $k_{i,2} > 0$, $\sigma_i > 0$, $\lambda_i > 0$ are design constants.

4. **Stability Analysis.** The main result of this paper is summarized in the following theorem.

Theorem 4.1. *Consider the closed-loop multi-agent systems consisting of the follower dynamics (1), the actuator input (16), the virtual control law (8) and the adaptive law (17) in the presence of input saturation. If Assumption 2.1 is satisfied, then the outputs of all followers can track that of the leader, and the synchronization errors satisfy the prescribed performance (4).*

Proof: Consider the following Lyapunov function

$$V = \sum_{i=1}^{N} \left(\frac{1}{2}\xi_{i,1}^2 + \frac{1}{2}s_{i,2}^2 + \frac{1}{2}\Gamma_i^2 + \frac{1}{2\lambda_i}\tilde{\theta}_i^T\tilde{\theta}_i \right), \tag{18}$$

where $\tilde{\theta}_i = \theta_i^* - \theta_i$.

The derivative of (18) along with (9), (14)-(17) is given by

$$\begin{aligned} \dot{V} = \sum_{i=1}^{N} \Bigg(& p_i\left(d_i + a_{i0}\right)\xi_{i,1}\left(s_{i,2} - k_{i,1}\xi_{i,1}\right) + s_{i,2}\left(u_i - \chi_i - k_{i,2}(s_{i,2} - \Gamma_i) + \varepsilon_i + \varpi_i(t)\right) \\ & + \Gamma_i\left(-\eta_i\Gamma_i - \frac{|s_{i,2}(u_i - \chi_i)| + 0.5(u_i - \chi_i)^2}{\Gamma_i} + (u_i - \chi_i)\right) + \sigma_i\tilde{\theta}_i^T\theta_i \Bigg). \end{aligned} \tag{19}$$

Note the fact that

$$s_{i,2}\left(u_i - \chi_i\right) - \left|s_{i,2}\left(u_i - \chi_i\right)\right| \le 0. \tag{20}$$

Then

$$\begin{aligned} \dot{V} \le \sum_{i=1}^{N} \Big(& p_i\left(d_i + a_{i0}\right)\xi_{i,1}\left(s_{i,2} - k_{i,1}\xi_{i,1}\right) + s_{i,2}\big(- k_{i,2}(s_{i,2} - \Gamma_i) + \varepsilon_i + \varpi_i(t)\big) \\ & - \eta_i\Gamma_i^2 - 0.5(u_i - \chi_i)^2 + \Gamma_i\left(u_i - \chi_i\right) + \sigma_i\tilde{\theta}_i^T\theta_i \Big). \end{aligned} \tag{21}$$

Use the Young inequality

$$\begin{aligned} \xi_{i,1}s_{i,2} &\le \frac{1}{2}\xi_{i,1}^2 + \frac{1}{2}s_{i,2}^2, \\ s_{i,2}\Gamma_i &\le \frac{1}{2}s_{i,2}^2 + \frac{1}{2}\Gamma_i^2, \\ s_{i,2}\left(\varepsilon_i + \varpi_i(t)\right) &\le \frac{1}{2}s_{i,2}^2 + \frac{1}{2}\varepsilon_M^2, \\ \Gamma_i\left(u_i - \chi_i\right) &\le \frac{1}{2}\Gamma_i + \frac{1}{2}(u_i - \chi_i)^2, \\ \tilde{\theta}_i^T\theta_i &\le \frac{1}{2}||\theta_i^*||^2 - \frac{1}{2}||\tilde{\theta}_i||^2, \end{aligned}$$

where $|\varepsilon_i + \varpi_i(t)| \le \varepsilon_M$. Then, we have

$$\begin{aligned} \dot{V} \le \sum_{i=1}^{N} \Bigg(& - p_i\left(d_i + a_{i0}\right)\left(k_{i,1} - \frac{1}{2}\right)\xi_{i,1}^2 - \left(k_{i,2} - \frac{1}{2}p_i\left(d_i + a_{i0}\right) - 1\right)s_{i,2}^2 \\ & - \left(\eta_i - 1\right)\Gamma_i^2 - \frac{\sigma_i}{2}||\tilde{\theta}_i||^2 + \frac{1}{2}\varepsilon_M^2 + \frac{\sigma_i}{2}||\theta_i^*||^2 \Bigg). \end{aligned} \tag{22}$$

The design parameters are designed as

$$k_{i,1} - \frac{1}{2} = k_{i,1}^* > 0,\ k_{i,2} - \frac{1}{2}p_i(d_i + a_{i0}) - 1 = k_{i,2}^* > 0,\ \eta_i - 1 = \eta_i^* > 0. \tag{23}$$

Let

$$\varrho = \min\left(2p_i(d_i + a_{i0})k_{i,1}, 2k_{i,2}^*, 2\eta_i^*, \sigma_i\lambda_i\right),$$
$$\delta = \frac{N}{2}\varepsilon_M^2 + \sum_{i=1}^{N}\frac{\sigma_i}{2}||\theta_i^*||^2.$$

Then

$$\dot{V} \le -\varrho V + \delta, \tag{24}$$

which implies that signals $\xi_{i,1}(t)$, $s_{i,2}$, $\tilde{\theta}_i$ are uniformly ultimately bounded. Then, by Lemma 3.1, $s_{i,1}$ satisfies the prescribed performance (4).

Let $s_{*1} = [s_{1,1}, \cdots, s_{N,1}]^T$. Then

$$s_{*1} = (\mathcal{L} + \Lambda_0)\left(x - \bar{1}x_r(t)\right), \tag{25}$$

where $x = [x_1, \cdots, x_N]^T$, $\bar{1} = [1, \cdots, 1]^T \in R^N$. Then, the tracking error satisfies

$$||x - \bar{1}x_r(t)|| \le \frac{1}{\underline{\sigma}(\mathcal{L} + \Lambda_0)}||s_{*1}||. \tag{26}$$

Therefore, by choosing appropriate parameters ρ_{1i}, ρ_{2i}, $\mu_{i\infty}$, the tracking error can converge to a small neighborhood of the origin; i.e., the outputs of all followers can track that of the leader. Thus, both the transient and steady performances are guaranteed in the presence of input saturation.

Remark 4.1. *In the presence of input saturation,* $u_i \neq \chi_i$, $|\Gamma_i| \ge \vartheta_i$. *The state of the auxiliary system* Γ_i *is introduced in the control design (16), which can guarantee the stability of the systems in the presence of input saturation. Moreover, the actuator can be out of input saturation in the case of* $|\Gamma_i| < \vartheta_i$.

5. **Numerical Example.** A simulation example is provided to show the effectiveness of the proposed consensus controllers. Consider multi-agent systems consisting of 4 one-link manipulators, which is described by

$$M\ddot{q}_i + \frac{1}{2}mgl\sin(q_i) = \tau_i, \tag{27}$$

where q_i is the angular position. $\dot{q}_i$ and $\ddot{q}_i$ denote the angular velocity and the angular acceleration, respectively. τ_i is the control input. The parameters are given as $M = 0.5\text{kg}\cdot\text{m}^2$, $m = 1\text{kg}$, $l = 1\text{m}$, and $g = 9.8\text{m/s}^2$.

Let $x_i = q_i$, $v_i = \dot{q}_i$, $u_i = \tau_i$. Then,

$$\dot{x}_i = v_i,$$
$$\dot{v}_i = -\frac{1}{2M}mgl\sin(x_i) + \frac{1}{M}\tau_i. \tag{28}$$

The output of the leader is $q_d(t) = \sin(t)$.

The information communication among the agents is described by Figure 1, where nodes 1-4 are followers, and the node 0 is the leader.

In simulation, $\varpi_i(t) = \text{square}(t)$. The initial conditions are chosen as: $[x_1(0), v_1(0)] = [0.5, 1]^T$, $[x_2(0), v_2(0)] = [x_3(0), v_3(0)] = [x_4(0), v_4(0)] = [0.6, 1]^T$, $\theta_i(0) = [0; 0; 0; 0; 0; 0]$. The performance function is chosen as $\mu_i = 4.75\exp(-t) + 0.25$, $\rho_{1i} = 0.3$, $\rho_{2i} = 0.25$. The

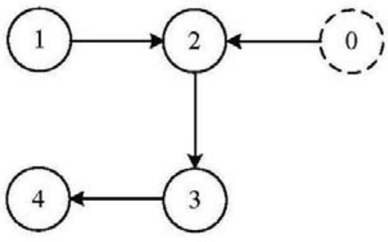

FIGURE 1. Communication graph

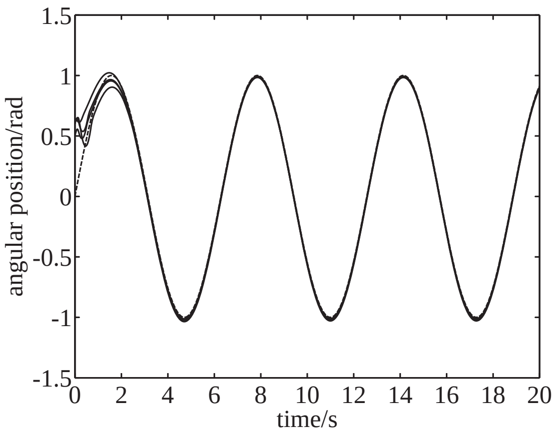

FIGURE 2. The trajectories of the angular positions

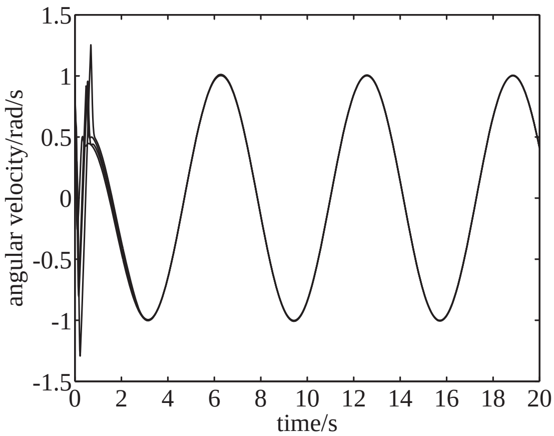

FIGURE 3. The trajectories of the angular velocities

design parameters are chosen as $k_{i,1} = 0.3$, $k_{i,2} = 30$, $\tau_i = 0.01$, $\gamma_i = 10$, $\sigma_i = 0.1$, $\eta_i = 10$, $\vartheta_i = 0.5$, $u_M = 10$. The simulation results are shown in Figures 2-6. The system states are shown in Figures 2 and 3. It can be observed that the outputs of all followers can track that of the leader with tracking errors converging to a small neighborhood of the origin. Figure 4 shows the trajectories of the synchronization errors, from which it can be observed that the synchronization errors remain in the predefined bounds. Thus, the prescribed performance is satisfied. Figures 5 and 6 show the actuator inputs and system

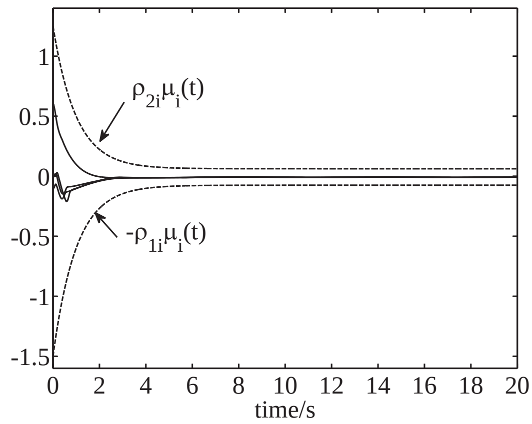

FIGURE 4. The trajectories of the synchronization errors

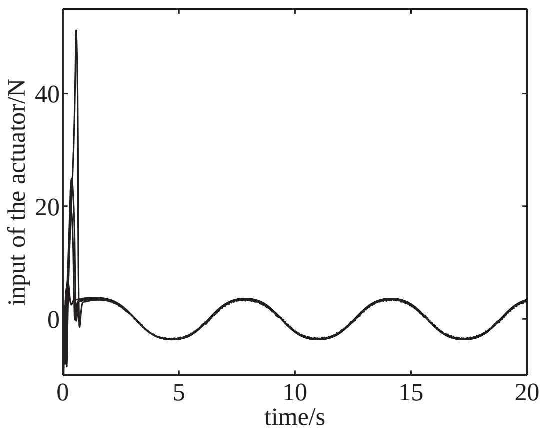

FIGURE 5. The trajectories of actuator inputs

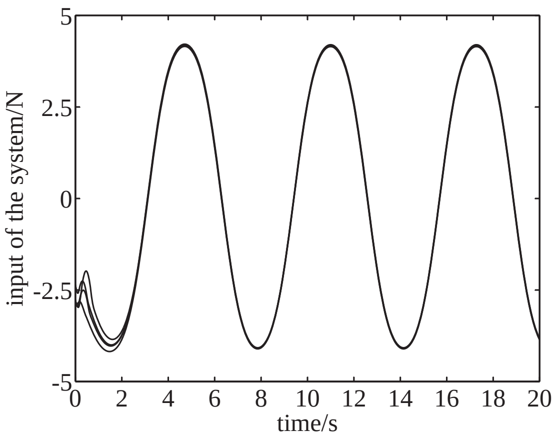

FIGURE 6. The trajectories of system inputs

inputs, respectively. It is clearly shown that the proposed control method can achieve output consensus of multi-agent systems with unknown dynamics in the presence of input saturation. Furthermore, the synchronization errors satisfy the prescribed performance (4).

6. **Conclusions.** This paper proposes a leader-follower consensus scheme for second-order nonlinear multi-agent systems in the presence of input saturation, which can achieve synchronization errors in the predefined bounds. The designed consensus controllers can compensate the input saturation of the actuator by introducing an auxiliary system. Moreover, the outputs of all followers can track that of the leader with prescribed performance. Simulation results are provided to show the effectiveness of the proposed consensus method.

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