Finite-Time Consensus Using an Adaptive Terminal Sliding Mode Control Subjected to Input Saturation and Unknown Bounded Disturbance

Received 2019/07/22
Accepted after revision 2020/07/23

http://dx.doi.org/10.5755/j01.itc.49.3.23879

HOW TO CITE: Ren, M., Huang, H., Mirabdollahi, S. E. (2020). Finite-Time Consensus Using an Adaptive Terminal Sliding Mode Control Subjected to Input Saturation and Unknown Bounded Disturbance. *Information Technology and Control*, 49(3), 412-420. https://doi.org/10.5755/j01.itc.49.3.23879

Ming Ren
Department of Mathematics and Physics Education, Luoyang Institute of Science and Technology, Luoyang 471023, China

Heyan Huang*
College of Sciences, Shanghai University of Applied Technology, Shanghai 201418, China

S. E. Mirabdollahi
Department of Electrical Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran

*Corresponding author: email:shhuangheyan@163.com

In this paper, finite-time consensus control of double-integrator multi-agent systems is presented. A new adaptive-terminal sliding mode control is proposed to satisfy the goal within a finite time by considering disturbances and input saturation. The agents are subjected to disturbances with unknown upper bounds and input saturation. The control inputs are designed based on terminal sliding mode technique to achieve the consensus purpose within the finite time to reduce the settling and reaching times. Then, a fast terminal sliding mode control is applied and the control inputs are modified to reduce the high dependency of reaching times to ini-
tial speeds. To handle the disturbance with unknown upper bounds, the control laws are adopted by an adaptive-terminal sliding mode method. The upper bounds of disturbances are estimated in the finite time. In the proposed method, the maximum control efforts are always adjusted to be less than the saturation boundary by adaptive estimation method. The proposed method efficiency is verified by numerical simulation.

**KEYWORDS:** Adaptive terminal sliding mode control, finite-time consensus control, multi-agent systems, input saturation, unknown disturbance.

### 1. Introduction

In recent decades, studying multi-agent control has received more attention because of their enormous system applicability [1, 5, 18, 22, 32]. In many different articles, a variety of control objectives are specified and studied for multi-agent systems [6, 10, 11, 19, 21, 25, 37, 38, 41] that among them, the consensus approach has gained more publicity because of its applicability [40, 45]. Consensus refers to a group of agents which reach a state agreement based upon local information exchange. Satisfying the consensus goal needs each agent to produce its control input with using its neighbor’s local data. In order to achieve the mentioned agreement, consensus control purposes can be divided into asymptotic and finite time consensuses. For asymptotic consensuses [4, 36] the agreement between agents is implemented within the infinite time, whereas for finite time consensus [7, 33] the aforementioned agreement is achieved in the specified adjustable and flexible finite time. In comparison with asymptotic consensus, the finite time consensus has some outstanding benefits such as faster transient response, high-precision tracking performance and much better convergence rate [9, 17].

Conventional convenient finite-time stabilization methods to achieve nonlinear system finite time consensus are as follows: Lyapunov-like method [14], geometric homogeneity based strategy [20], and terminal sliding mode control technique [2, 29-31]. The finite time consensus can be satisfied by using the TSMC technique [16, 43-44], which is based on the typical sliding mode control approach [3, 10] and is robust versus disturbances and uncertainties [26-27].

Introducing new control methods in the presence of uncertainty and disturbance is one of the attractive study objectives [8, 15, 23, 34-35]. In respect to consensus problem, two important issue including agent disturbances and actuator saturation must be considered. If these two issues are not considered in multi-agent system consensus problems, some crucial undesirable problems such as convergence rate and tracking accuracy and even divergence/instability will appear. The finite time consensus for a typical multi-agent system with disturbance and actuator saturation agents is investigated in [20, 24]. The finite time consensus problem of disturbed multi-agent systems with agents without saturation actuators are considered in [16, 43-44]. Asymptotic consensus for multi-agent system in the presence of agents’ disturbance is discussed and solved in [13, 45]. Furthermore the finite time consensus issue of disturbed multi-agent systems with agents without saturation actuators are discussed in [16, 43-44]. As a result of the importance of these reviewed problems, including finite time consensus, agent disturbances and actuator saturation of each agent, a new robust approach is proposed and generalized in this paper to satisfy the consensus control goal.

In this part we discussed the finite-time consensus control problem for a usual multi-agent system having double integrator agents and a fixed speed leader. Each system agent is subjected simultaneously to the control input saturation and disturbances. We assumed that the with control inputs saturations are unknown but constant. In addition to that, agent disturbance are supposed to be limited, while their upper bounds are unknown. A new adaptive ATSMC method is proposed in order to estimate these upper bounds in finite time and also to solve the multi-agent system finite time consensus problem. Furthermore, the global dynamic finite-time stability of tracking errors are proved in several theorems in this article.

Further, mathematical preliminaries are presented in Section 2. Section 3 evaluates the fast finite-time consensus tracking problem. Finally, numerical results and conclusions are shown in Sections 4 and 5.
2. Mathematical Preliminaries

2.1. Graph theory

A graph defined by $G = (\mathbb{V}, \mathbb{E}, \mathbb{A})$ is composed of a vertex set $\mathbb{V} = \{v_1, v_2, \ldots, v_N\}$, an edge set $\mathbb{E} \subseteq \mathbb{V} \times \mathbb{V}$, and an adjacency matrix $\mathbb{A}$. Each edge is defined by a pair of vertices $(v_i, v_j)$. Matrix $\mathbb{A} = [a_{ij}] \in \mathbb{R}^{N \times N}$ shows the connections between vertices, so that $a_{ij} = 1$ if $(v_i, v_j) \in \mathbb{E}$ and $a_{ij} = 0$. Else, if matrix $\mathbb{A}$ is symmetric, the graph $G$ is known as undirected. A path is a sequence of edges from vertex $i$ to vertex $j$. $G$ is called connected if there exist at least one path between any two arbitrary separate vertices.

2.2. Finite-Time Stability

The main finite-time stability definition and two effective lemmas are introduced in this section. These definitions are used throughout this research.

Definition 1 [42]. Suppose a nonlinear time invariant system like

$$\dot{x} = f(x), \quad f(0) = 0, \quad x \in U_0 \subseteq \mathbb{R}^n,$$

where $f: U_0 \to \mathbb{R}^n$ is a continuous vector function on an open neighborhood $U_0$ of the origin $x = 0$. The equilibrium point $x = 0$ of system (1) is called locally finite-time stable if the following conditions hold.

1. It should be finite-time convergent in $U_0$,
   namely, there is a convergence time $T(x_0): U_0 \setminus \{0\} \to [0, \infty)$ that satisfies $\lim_{t \to T(x_0)} x(t, x_0) = 0$ and $x(t, x_0) = 0$ for all $t \geq T(x_0)$.

2. It should be Lyapunov stable in an open neighborhood $U_0$ such that $U_0 \subseteq U_0$.

Lemma 1 [42]. Consider the nonlinear system (1). Assume that there exist a $C^1$ positive function $V(x): U_0 \to \mathbb{R}$, real constants $c > 0$, and $0 < \alpha < 1$ such that $\dot{V}(x) + cV^\alpha(x) \leq 0$, $\forall x \in U_0 \setminus \{0\}$ is satisfied. Then, the equilibrium point $x = 0$ of system (1) is locally finite-time stable. Furthermore, the convergence time $T(x_0)$ satisfies the following inequality.

$$T(x_0) \leq (c(1-\alpha))^{1/\alpha} V(x_0)^{1-\alpha}.$$  

Moreover, if $U_0 = \mathbb{R}^n$, then $x = 0$ is globally finite-time stable.

Lemma 2 [12]. Consider the nonlinear system (1). Suppose there exist a $C^2$ positive function $V(x): U_0 \to \mathbb{R}$ and real numbers $c_1, c_2 > 0$ and $0 < \alpha < 1$ such that $\dot{V}(x) + cV^\alpha(x) + cV^\alpha(x) \leq 0, \forall x \in U_0 \setminus \{0\}$ is satisfied. Then, the convergence time $T(x_0)$ is given by the following inequality.

$$T \leq (c_2 (1-\alpha))^{1/\alpha} \left\{ \ln (c_2 \alpha F^{1-\alpha}(x(0)+c_1)) - \ln c_1 \right\}.$$  

2.3. Finite-Time Consensus Tracking

The dynamic models of $N$ agents are assumed to be:

$$\dot{x}_i(t) = v_i(t), \quad \dot{v}_i(t) = u_i + d_i, \quad i = 1, \ldots, N,$$

where $x_i$ and $v_i$ are the $i^{th}$ agent position and velocity, respectively. $u_i$ and $d_i$ denote the control input and bounded disturbance satisfying the inequality $|d_i| < l_i$, $i = 1, \ldots, N$. It is assumed that $l_i$ is an unknown constant and the control input of each agent is subjected to saturation such that $|v_i| < Y_i$. It is worth noting that the saturation bound $Y_i$ is unknown.

The leader dynamic is defined as

$$\dot{x}_0(t) = v_0(t), \quad \dot{v}_0(t) = 0.$$  

Based on finite-time consensus tracking, positions and velocities of all agents should converge to the position and velocity of the leader in a specific adjustable finite time. This goal can be defined mathematically as

$$\left\{ \begin{array}{l} \lim_{t \to T} \dot{x}_i \to 0, \dot{x}_0 = 0, \forall t > T \\ \lim_{t \to T} \dot{v}_i \to 0, \dot{v}_0 = 0, \forall t > T \end{array} \right., \quad i = 1, \ldots, N,$$

where $T$ is the required finite time for achieving the defined goal. Tracking errors $\tilde{x}_i$ and $\tilde{v}_i$ are defined as,

$$\tilde{x}_i = x_i - x_0, \quad i = 1, \ldots, N,$$

$$\tilde{v}_i = v_i - v_0.$$  

Assumption 1. In the multi-agent system of (4), it is assumed that each agent is connected to the leader independently or through other agents. To clarify this assumption mathematically, matrix $\mathbb{B}$ has been defined. $b_i$ is the $i^{th}$ element of the matrix $\mathbb{B} = [b_1, b_2, \ldots, b_N]$. $b_i = 1$ if the $i^{th}$ agent has access to the leader independently, otherwise $b_i = 0$. 
Finite-Time Consensus with Unknown Bounded Disturbance and Saturation

To achieve the described consensus problem, a TS-MC is designed. The terminal sliding surfaces $s_i$, $i = 1, \cdots, N$ are suggested as

$$s_i = v_i - \frac{1}{\alpha} \theta d_t, \quad i = 1, \cdots, N \quad (8)$$

in which $\phi_i$ is defined as

$$\phi_i = \sum_{j=1}^{N} \eta_j \left[ \tanh \left( \alpha (x_j - x_i) \right) + \tanh \left( \alpha (v_j - v_i) \right) \right] - \beta \left[ \tanh \left( \alpha (x_i - x_o) \right) + \tanh \left( \alpha (v_i - v_o) \right) \right] \quad (9)$$

$\text{sgn}(x)$ is defined as $\text{sgn}(x) = |x| \text{sgn}(x)$. The optional parameter $\alpha_i$ is taken as $\alpha_i \in (0,1)$ and the parameter $\alpha_i$ is determined as $\alpha_i = \frac{2 \alpha}{1 + \alpha}$.  

**Theorem 1.** Considering the agents, leader, tracking errors, and sliding surfaces described by (4), (5), (6), and (8), respectively, the sliding mode dynamics (sliding motions) $s_i = \dot{s}_i = 0$, $i = 1, \cdots, N$ are globally finite-time stable. This means that tracking errors $\sigma_i$ and $\dot{v}_i$ on sliding motion $s_i = \dot{s}_i = 0$ will exactly converge to zero in the finite settling time, $T_r$.

**Proof.** Assume that the sliding mode dynamic $s_i = \dot{s}_i = 0$ has been achieved for the $i$th agent (input control for the $i$th agent will be designed later to guarantee sliding motion existence $s_i = \dot{s}_i = 0$). Based on (7) and (8), sliding mode dynamic $s_i = \dot{s}_i = 0$, $i = 1, \cdots, N$ can be expressed as

$$\begin{align*}
\dot{x}_i &= \dot{v}_i, \\
\dot{v}_i &= \phi_i.
\end{align*} \quad (10)$$

According to Theorem 1 [12], it can be demonstrated that there exist a $T_r$ such that $\dot{x}_i$ and $\dot{v}_i$ in (10) become zero for times larger than $T_r$. Consequently, sliding motions $s_i = \dot{s}_i = 0$, $i = 1, \cdots, N$ are globally finite-time stable. This completes the proof.

The control inputs are designed to assure the existence of $s_i = \dot{s}_i = 0$, $i = 1, \cdots, N$ in the finite reaching time, $T_r$, for all agents.

Here, it is assumed that the upper disturbance bounds $l_i$, $i = 1, \cdots, N$, are constant but unknown. The control law for the $i$th agent is proposed as

$$u_i = \phi_i - k_i \text{sgn} (s_i) - \dot{l}_i \text{sgn} (s_i) - \tilde{\delta}_i, \quad i = 1, \cdots, N, \quad (11)$$

where $k_i$, $i = 1, \cdots, N$, are optional constants. $\tilde{l}_i$, $\tilde{l}_i$, and $\delta_i$, $\delta_i$ are the unknown upper bound estimations $l_i$ and $\delta_i$ are the unknown upper bound estimations $\delta_i$ that is the error caused by input saturation

$$\begin{align*}
\dot{l}_i &= \gamma_i |v_i|, \\
\delta_i &= 0, \quad i = 1, \cdots, N.
\end{align*} \quad (12)$$

$\lambda_i$ and $\gamma_i$, $i = 1, \cdots, N$, are arbitrary parameters that satisfy $\lambda_i > 1, \gamma_i > 1$. By considering Lemma 1 in [28], it can be shown that $0 \leq \tilde{l}_i \leq l_i$, $0 \leq \tilde{l}_i \leq l_i$, in which the constants $l_i$ and $l_i$ are not necessarily equal to the nominal value $l_i$ and $l_i$. Therefore, $l_i$ and $l_i$ can be assumed to be $l_i = l_i + \eta_i$, $l_i = l_i + \eta_i$, where $\eta_i > 0$ and $\eta_i > 0$ are arbitrary numbers.

The finite time stability proof of $s_i = \dot{s}_i = 0$, $i = 1, \cdots, N$ are similar to that in Theorem 1. In Theorem 4, the existence of $s_i = \dot{s}_i = 0$, $i = 1, \cdots, N$ for $t \geq T_r$, will be shown by applying (11) and (12).

**Theorem 2.** Consider (4) with unknown bounded disturbances. By employing (11) and (12), $s_i = \dot{s}_i = 0$, $i = 1, \cdots, N$ are achieved for $t \geq T_r$, where $T_r$ is determined by

$$T_r \leq \min \left( \min \left( \left( \frac{1}{(1-\lambda_i)} \right) \left( \frac{|v_i|}{|v_i|} \right)^2 \right), \min \left( \left( (1-\gamma_i) \right) \left( \frac{|v-i|}{|v_i|} \right)^2 \right) \right) \quad (13)$$

**Proof.** By considering the candidate Lyapunov function $V = 0.5 \sum_{i=1}^{N} s_i^2 + 0.5 \sum_{i=1}^{N} \dot{l}_i^2 + 0.5 \sum_{i=1}^{N} \delta_i^2$ where $\dot{l}_i = \tilde{l}_i - l_i$ and $\delta_i = \tilde{\delta}_i - \delta_i < 0$. The sliding surface time derivative is $\dot{s}_i = \dot{v}_i - \phi_i$. Now, by replacing $\dot{v}_i$ from (7) and $u_i$ from (11), $\dot{s}_i$ is obtained as

$$\dot{s}_i = -k_i \text{sgn} (s_i) - \dot{l}_i \text{sgn} (s_i) + d_i + \tilde{\delta}_i. \quad (14)$$

By substituting (12) and (14) in
\[ V' = \sum_i y_i \dot{s}_i + \sum_i \sum_j \ddot{\delta}_j \dot{s}_i + \sum_i \sum_j \dddot{\delta}_j \dot{s}_i, \] the following relation is obtained.

\[ V' = -\sum_i N_j |s_i| + \sum_i \sum_j \ddot{\delta}_j |s_i| + \sum_j \sum_i \dddot{\delta}_j |s_i| + \sum_j \sum_i \dddot{\delta}_j |s_i|. \]

By considering \( k_w = \min(k_i) \) and \( \sum_i d_i s_i \leq \sum_i f_i |s_i| \), \( \sum_i \ddot{\delta}_i s_i \leq \sum_i \dddot{\delta}_i |s_i| \), \( \sum_i s_i |s_i| \), \( \sum_i \ddot{\delta}_i |s_i| \), \( \sum_i \dddot{\delta}_i |s_i| \).

\[ V \leq -k_w \sum_i |s_i| - \sum_i (\lambda_i - 1) |\dot{s}_i| - \sum_i (\gamma_i - 1) |\ddot{s}_i| - \sum_i (\gamma_i - 1) |\dddot{s}_i|. \]

By defining \( \Omega = \min((\lambda_i - 1)|s_i|, \Omega_2, k_w) \) and \( \theta = \min(\Omega_1, \Omega_2, k_w) \), (16) is simplified as

\[ V \leq -\theta (\sum_i |s_i| + \sum_i |\dot{s}_i| + \sum_i |\dddot{s}_i|). \]

By adopting the well-known inequality

\[ \sqrt{\sum_i |y_i|^2} \leq \sqrt{\sum_i |y_i|^2}, \]

(17) is converted to \( V \leq -\theta \|
\) \( \sqrt{\sum_i |y_i|^2} \)

Finally, by setting \( c = \sqrt{2\theta} \), \( a = 0.5 \), and applying Lemma 1, it is proven that \( s_i = \dot{s}_i = \dddot{s}_i = 0 \), \( i = 1, \ldots, N \) are always fulfilled for \( t \geq T \), where \( T \) is estimated by (13). This ends the proof.

3. Numerical Simulations

A multi-agent system consists of five agents and one leader is simulated in this article and the related results are discussed respectively. Notice that matrices \( A \) and \( B \) are supposed as follows;

\[
A = \begin{bmatrix}
0 & 1 & 1 & 1 & 0 \\
1 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 1 & 1 \\
1 & 0 & 1 & 0 & 1 \\
0 & 0 & 1 & 1 & 0 \\
\end{bmatrix}, \quad B = [1 0 1 0 1].
\]

The initial agent positions and velocities are chosen arbitrarily as \( \dot{x}_0 = [-200 50 150 200] \) and \( v(0) = [-200 120 180 -160 200] \), respectively. The initial leader position and velocity are assumed to be \( x_0 = 150 \) and \( v_0 = 5 \), respectively. Disturbances are selected as \( d_i = \cos(0.2t), d_i = 0.7 \sin(0.4t + \pi/5), d_i = 0.5 \sin(2t), d_i = 0.6 \cos(3t + \pi/4) \). The fifth disturbance \( d_i \), (30), is assumed to be time variant [39].

\[
d_i = \begin{cases}
0.3 \cos \left(3\pi \left(\frac{5.9}{60} + 0.1\right)t\right) - 0.3 & t < 30 \\
0.3 \cos \left(3\pi \left(\frac{5.9}{60} + 0.3\right)t\right) + 0.3 & t \geq 30
\end{cases}
\]

In terms of selected disturbances, the upper bound disturbance vectors are calculated as \( d = [1 0.7 0.5 0.6 0.3]^T \). In all calculations, the optional fractional power \( \alpha \), applied in \( \phi \), is chosen as \( \alpha = 1.5 \). Further, the control inputs are assumed \( \pm 27 \). Hence, \( \hat{Y}_i \) is determined as \( Y_0 = 27 \). Also, \( \lambda_i = 1.1 \) and \( \gamma_i = 0.2 \), \( i = 1, \ldots, 5 \) are assumed, respectively. The tuning parameters are selected as \( k_i = 20 \) and \( \lambda_i = 1.01 \) for \( i = 1, \ldots, 5 \). The upper bound estimation initial values are chosen as \( \dot{\hat{Y}}(0) = 0.2 \), \( i = 1, \ldots, 5 \). Agent Positions, velocities and errors in the presence of unknown bounded disturbances by applying (11) are shown in Figures 1-4. Agent control signals is shown in Figure 5.

Figure 1
Agent position by applying (11)
4. Conclusion

In this research we discussed finite-time consensus problem for multi-agent systems with leader in the presence of bounded disturbances and saturation constraints on control inputs. In order to handle the problem, control inputs were designed by considering disturbance with unknown upper bounds. For satisfying the finite-time consensus aim, the control inputs and the finite-time estimation laws were designed by applying adaptive TSMC method. Mathematical analysis clearly shows that all proposed control inputs could satisfy the finite-time consensus goal within the total adjustable finite-time. Finally in order to validate the theoretical results, numerical simulations were depicted.
References

1. Baranauskas, R., Janaviciute, A., Jasinevicius, R., Jukavicius, V., Kazanavicius, E., Petrauskas, V., Vrubliauskas, A. On Multi Agent Systems Intellectics. Information Technology and Control, 2015, 44(1), 112-124. https://doi.org/10.5755/j01.itc.44.1.8768
2. Bayat, F., Mobayen, S., Javadi, S. Finite-Time Tracking Control of Nth-Order Chained-Form Non-Holonomic Systems in the Presence of Disturbances. ISA Transactions, 2016, 63, 78-83. https://doi.org/10.1016/j.isatra.2016.02.023
3. Chang, J. L. Dynamic Sliding Mode Controller Design for Reducing Chattering. Journal of the Chinese Institute of Engineers, 2014, 37(1), 71-78. https://doi.org/10.1049/iet-tra.2015.0627
4. Cui, G., Xu, S., Lewis, F. L., Zhang, B., Ma, Q. Distributed Consensus Tracking for Non-Linear Multi-Agent Systems with Input Saturation: A Command Filtered Backstepping Approach. IET Control Theory & Applications, 2016, 10(5), 509-516. https://doi.org/10.1049/iet-ccta.2015.0600
5. Deng, C., Yang, G. H. Distributed Adaptive Fault-Tolerant Control Approach to Cooperative Output Regulation for Linear Multi-Agent Systems. Automatica, 2019, 103, 62-68. https://doi.org/10.1016/j.automatica.2019.01.013
6. Dong, J. G. Finite-Time Connectivity Preservation Rendezvous with Disturbance Rejection. Automatica, 2016, 71, 57-61. https://doi.org/10.1016/j.automatica.2016.04.032
7. Du, H., Cheng, Y., He, Y., Jia, R. Second-Order Consensus for Nonlinear Leader-Following Multi-Agent Systems via Dynamic Output Feedback Control. International Journal of Robust and Nonlinear Control, 2016, 26(2), 329-344. https://doi.org/10.1002/rnc.3317
8. Fazeli, S., Abdollahi, N., Imani Marrani, H., Malekizade, H., Hosseinizadeh, H. A New Robust Adaptive Decentralized Tube Model Predictive Control of Continuous Time Uncertain Nonlinear Large-Scale Systems. Cogent Engineering, 2019, 6(1), 1680093. https://doi.org/10.1080/23311916.2019.1680093
9. Fu, J., Wang, J. Fixed-Time Coordinated Tracking for Second-Order Multi-Agent Systems with Bounded Input Uncertainties. Systems & Control Letters, 2016, 93, 1-12. https://doi.org/10.1016/j.sysconle.2016.03.006
10. Fu, J., Wang, J. Robust Finite-Time Containment Control for High-Order Multi-Agent Systems with Matched Uncertainties Under Directed Communication Graphs. International Journal of Control, 2016, 89(6), 1137-1151. https://doi.org/10.1080/00207179.2015.1122840
11. Ge, M. F., Guan, Z. H., Yang, C., Li, T., Wang, Y. W. Time-Varying Formation Tracking of Multiple Manipulators via Distributed Finite-Time Control. Neurocomputing, 2016, 202, 20-26. https://doi.org/10.1016/j.neucom.2016.03.008
12. Guan, Z. H., Sun, F. L., Wang, Y. W., Li, T. Finite-Time Consensus for Leader-Following Second-Order Multi-Agent Networks. IEEE Transactions on Circuits and Systems I: Regular Papers, 2012, 59(11), 2646-2654. https://doi.org/10.1109/TCSI.2012.2190676
13. Hu, H., Yu, L., Chen, G., Xie, G. Second-Order Consensus of Multi-Agent Systems with Unknown but Bounded Disturbance. International Journal of Control, Automation and Systems, 2013, 11(2), 258-267. https://doi.org/10.1007/s12555-011-0151-1
14. Huang, J., Wen, C., Wang, W., Song, Y. D. Design of Adaptive Finite-Time Controllers for Nonlinear Uncertain Systems Based on Given Transient Specifications. Automatica, 2016, 69, 395-404. https://doi.org/10.1016/j.automatica.2015.08.013
15. Imani, H., Jahed-Motlagh, M. R., Salahshoor, K., Ramezani, A., Moarefianpur, A. Robust Decentralized Model Predictive Control Approach for a Multi-Compressor System Surge Instability Including Piping Acoustic. Cogent Engineering, 2018, 5(1), 1483811. https://doi.org/10.1080/23311916.2018.1483811
16. Li, H., Liao, X., Chen, G. Leader-Following Finite-Time Consensus in Second-Order Multi-Agent Networks with Nonlinear Dynamics. International Journal of Control, Automation and Systems, 2013, 11(2), 422-426. https://doi.org/10.1007/s12555-012-0100-7
17. Li, X., Chen, M.Z., Su, H. Finite-Time Consensus of Second-Order Multi-Agent Systems via a Structural Approach. Journal of the Franklin Institute, 2016, 353(15), 3876-3896. https://doi.org/10.1016/j.jfranklin.2016.07.010
18. Li, Z., Duan, Z. Cooperative Control of Multi-Agent Systems: A Consensus Region Approach. CRC Press, 2017. https://doi.org/10.1201/b17571
19. Liu, Y., Geng, Z. Finite-Time Formation Control for Linear Multi-Agent Systems: A Motion Planning Approach. Systems & Control Letters, 2015, 85, 54-60. https://doi.org/10.1016/j.sysconle.2015.08.009
20. Lyu, J., Qin, J., Gao, D., Liu, Q. Consensus for Constrained Multi-Agent Systems with Input Saturation.
20. Rahmani, M., Rahman, M. H. An Upper-Limb Exoskeleton Robot Control Using a Novel Fast Fuzzy Sliding Mode Control. Journal of Intelligent & Fuzzy Systems, 2019, 36(3), 2581-2592. https://doi.org/10.3233/JIFS-181558

21. Ma, Z., Liu, Z., Chen, Z. Leader-Following Consensus of Multi-Agent System with a Smart Leader. Neurocomputing, 2016, 214, 401-408. https://doi.org/10.1016/j.neucom.2016.06.042

22. Maoudj, A., Bouzouia, B., Hentout, A., Kouider, A., Toumi, R. Distributed Multi-Agent Scheduling and Control System for Robotic Flexible Assembly Cells. Journal of Intelligent Manufacturing, 2019, 30(4), 1629-1644. https://doi.org/10.1007/s10845-017-1345-z

23. Mardani, M.M., Vafamand, N., Shokrian Zeini, M., Shasadeghi, M., Khayatian, A. Sum-of-Squares-Based Finite-Time Adaptive Sliding Mode Control of Uncertain Polynomial Systems with Input Nonlinearities. Asian Journal of Control, 2018, 20(4), 1658-1662. https://doi.org/10.1002/asjc.1625

24. Mirabdollahi, S.E., Haeri, M. Multi-Agent System Finite-Time Consensus Control in the Presence of Disturbance and Input Saturation by Using of Adaptive Terminal Sliding Mode Method. Cogent Engineering, 2019, 6(1), 1698689. https://doi.org/10.1080/23311916.2019.1698689

25. Mondal, S., Su, R. Finite Time Tracking Control of Higher Order Nonlinear Multi-Agent Systems with Actuator Saturation. IFAC-PapersOnLine, 2016, 49(3), 165-170. https://doi.org/10.1016/j.ifacol.2016.07.028

26. Pai, M. C. Discrete-Time Variable Structure Control for Robust Tracking and Model Following. Journal of the Chinese Institute of Engineers, 2008, 31(1), 167-172. https://doi.org/10.1080/02533839.2008.9671370

27. Phan, V. D., Huynh, V. V., Tsai, Y. W. Adaptive Output Feedback Sliding Mode Control for Time-Delay Systems with Extended Disturbance. Journal of the Chinese Institute of Engineers, 2016, 39(3), 265-273. https://doi.org/10.1080/02533839.2015.1101614

28. Plestan, F., Shtessel, Y., Bregeault, V., Poznyak, A. New Methodologies for Adaptive Sliding Mode Control. International Journal of Control, 2010, 83(9), 1907-1919. https://doi.org/10.1080/00207179.2010.501385

29. Rahmani, M., Rahman, M. H. An Upper-Limb Exoskeleton Robot Control Using a Novel Fast Fuzzy Sliding Mode Control. Journal of Intelligent & Fuzzy Systems, 2019, 36(3), 2581-2592. https://doi.org/10.3233/JIFS-181558

30. Rahmani, M. MEMS Gyroscope Control Using a Novel Compound Robust Control. ISA Transactions, 2018, 72, 37-43. https://doi.org/10.1016/j.isatra.2017.11.009

31. Rahmani, M., Ghanbari, A., Ettefaghi, M. M. Hybrid Neural Network Fraction Integral Terminal Sliding Mode Control of an Inchworm Robot Manipulator. Mechanical Systems and Signal Processing, 2016, 80, 117-136. https://doi.org/10.1016/j.ymssp.2016.04.004

32. Singh, V.P., Kishor, N., Samuel, P. Distributed Multi-Agent System-Based Load Frequency Control for Multi-Area Power System in Smart Grid. IEEE Transactions on Industrial Electronics, 2017, 64(6), 5151-5160. https://doi.org/10.1109/TIE.2017.2668983

33. Sun, C., Hu, G., Xie, L. Robust Consensus Tracking for a Class of High-Order Multi-Agent Systems. International Journal of Robust and Nonlinear Control, 2016, 26(3), 578-598. https://doi.org/10.1002/rnc.3326

34. Vafamand, N., Asemani, M. H., Khayatian, A. Robust L1 Observer-Based Non-PDC Controller Design for Persistent Bounded Disturbed TS Fuzzy Systems. IEEE Transactions on Fuzzy Systems, 2017, 26(3), 1401-1413. https://doi.org/10.1109/TFUZZ.2017.2724018

35. Vafamand, N., Asemani, M.H., Khayatiyan, A. A Robust L1 Controller Design for Continuous-Time TS Systems with Persistent Bounded Disturbance and Actuator Saturation. Engineering Applications of Artificial Intelligence, 2016, 56, 212-221. https://doi.org/10.1016/j.engappai.2016.09.002

36. Wang, C., Wang, X., Ji, H. Leader-Following Consensus for a Class of Second-Order Nonlinear Multi-Agent Systems. Systems & Control Letters, 2016, 89, 61-65. https://doi.org/10.1016/j.sysconle.2015.12.007

37. Wang, H., Wang, C., Xie, G. Finite-Time Containment Control of Multi-Agent Systems with Static or Dynamic Leaders. Neurocomputing, 2017, 226, 1-6. https://doi.org/10.1016/j.neucom.2016.11.020

38. Yang, T., Zhang, P., Yu, S. Consensus of Linear Multi-Agent Systems via Reduced-Order Observer. Neurocomputing, 2017, 240, 200-208. https://doi.org/10.1016/j.neucom.2017.01.087

39. Yu, S., Long, X. Finite-Time Consensus for Second-Order Multi-Agent Systems with Disturbances by Integral Sliding Mode. Automatica, 2015, 54, 158-165. https://doi.org/10.1016/j.automatica.2015.02.001

40. Zhang, L., Hua, C., Guan, X. Distributed Output Feedback Consensus Tracking Prescribed Performance Control for a Class of Non-Linear Multi-Agent Systems with Unknown Disturbances. IET Control Theory & Applications, 2016, 10(8), 877-883. https://doi.org/10.1049/iet-cta.2015.1120
41. Zhang, Q., Hao, Y., Yang, Z., Chen, Z. Adaptive Flocking of Heterogeneous Multi-Agents Systems with Nonlinear Dynamics. Neurocomputing, 2016, 216, 72-77. https://doi.org/10.1016/j.neucom.2016.06.064

42. Zhang, Y., Yang, Y. Finite-Time Consensus of Second-Order Leader-Following Multi-Agent Systems Without Velocity Measurements. Physics Letters A, 2013, 377(3-4), 243-249. https://doi.org/10.1016/j.physleta.2012.10.055

43. Zhao, L.W., Hua, C.C. Finite-Time Consensus Tracking of Second-Order Multi-Agent Systems via Nonsingular TSM. Nonlinear Dynamics, 2014, 75(1-2), 311-318. https://doi.org/10.1007/s11071-013-1067-5

44. Zhou, N., Xia, Y., Wang, M., Fu, M. Finite-Time Attitude Control of Multiple Rigid Spacecraft Using Terminal Sliding Mode. International Journal of Robust and Nonlinear Control, 2015, 25(12), 1862-1876. https://doi.org/10.1002/rnc.3182

45. Zhu, B., Meng, C., Hu, G. Robust Consensus Tracking of Double-Integrator Dynamics by Bounded Distributed Control. International Journal of Robust and Nonlinear Control, 2016, 26(7), 1489-1511. https://doi.org/10.1002/rnc.3361

This article is an Open Access article distributed under the terms and conditions of the Creative Commons Attribution 4.0 (CC BY 4.0) License (http://creativecommons.org/licenses/by/4.0/).