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

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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 initial 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 the 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 $G = (\mathbb{V}, E, A)$ is composed of a vertex set $\mathbb{V} = \{v_1, v_2, \ldots, v_N\}$, an edge set $E \subseteq \mathbb{V} \times \mathbb{V}$, and an adjacency matrix A. Each edge is defined by a pair of vertices (v_i, v_j). Matrix $A = [a_{ij}] \in \mathbb{R}^{N \times N}$ shows the connections between vertices, so that $a_{ij} = 1$ if $(v_j, v_i) \in E$ and $a_{ij} = 0$. Else, if matrix 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

$$\dot{x} = f(x), \quad f(0) = 0, \quad x \in U_0 \subset \mathbb{R}^n, \tag{1}$$

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 $\hat{U}_0$, namely, there is a convergence time $T(x_0)$: $\hat{U}_0 \setminus \{0\} \to [0, \infty)$ that satisfies $\lim_{t \to T(x_0)} x(t, x_0) = 0$ and $x(t, x_0) = 0$ for $\forall t \geq T(x_0)$.
2. It should be Lyapunov stable in an open neighborhood $\hat{U}_0$ such that $\hat{U}_0 \subseteq U_0$.

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.

$$T(x_0) \leq (c(1-\alpha))^{-1} V(x_0)^{1-\alpha}. \tag{2}$$

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^1 positive function $V(x) : U_0 \to \mathbb{R}$ and real numbers $c_1, c_2 > 0$ and $0 < \alpha < 1$ such that $\dot{V}(x) + c_2 V(x) + c_1 V^{\alpha}(x) \leq 0, \forall x_0 \in U_0 \setminus \{0\}$ is satisfied. Then, the convergence time $T(x_0)$ is given by the following inequality.

$$T \leq (c_2(1-\alpha))^{-1} \left(\ln\left(c_2 V^{1-\alpha}(x(0) + c_1)\right) - \ln c_1 \right). \tag{3}$$

2.3. Finite-Time Consensus Tracking

The dynamic models of N agents are assumed to be:

$$\begin{aligned} \dot{x}_i &= v_i \\ \dot{v}_i &= u_i + d_i \end{aligned}, \quad i = 1, \cdots, N, \tag{4}$$

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 $|d_i| < l_i$, $i = 1, \cdots, N$. It is assumed that l_i is an unknown constant and the control input of each agent is subjected to saturation such that $|u_i| < \Upsilon_s$. It is worth noting that the saturation bound Υ_s is unknown.

The leader dynamic is defined as

$$\begin{aligned} \dot{x}_0 &= v_0, \\ \dot{v}_0 &= 0. \end{aligned} \tag{5}$$

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

$$\begin{cases} \lim_{t \to T} |\tilde{x}_i| \to 0, \tilde{x}_i = 0, \ \forall t > T \\ \lim_{t \to T} |\tilde{v}_i| \to 0, \ \tilde{v}_i = 0, \forall t > T \end{cases}, \quad i = 1, \cdots, N, \tag{6}$$

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

$$\begin{cases} \tilde{x}_i = x_i - x_0 \\ \tilde{v}_i = v_i - v_0 \end{cases}, i = 1, \cdots, N. \tag{7}$$

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 has defined. b_i is the i^{th} element of the matrix $B = [b_1, b_2, \cdots, b_n]$. $b_i = 1$ if the i^{th} agent have 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 TSMC is designed. The terminal sliding surfaces s_i, $i=1,\cdots,N$ are suggested as

$$s_i=\tilde{v}_i-\int_0^t \phi_i d\tau,\ i=1,\cdots,N \tag{8}$$

in which ϕ_i is defined as

$$\begin{aligned}\phi_i=&\sum_{j=1}^{N}a_{ij}\left[\tanh\left(\mathrm{sig}^{\alpha_1}\left(x_j-x_i\right)\right)+\tanh\left(\mathrm{sig}^{\alpha_2}\left(v_j-v_i\right)\right)\right]\\&-b_i\left[\tanh\left(\mathrm{sig}^{\alpha_1}\left(x_i-x_0\right)\right)+\tanh\left(\mathrm{sig}^{\alpha_2}\left(v_i-v_0\right)\right)\right].\end{aligned} \tag{9}$$

$\mathrm{sig}^{\alpha}(x)$ is defined as $\mathrm{sig}^{\alpha}(x)=|x|^{\alpha}\mathrm{sgn}(x)$. The optional parameter α_1 is taken as $\alpha_1\in(0,1)$ and the parameter α_2 is determined as $\alpha_2=\frac{2\alpha_1}{1+\alpha_1}$.

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 $\tilde{x}_i$ and $\tilde{v}_i$ on sliding motion $s_i=\dot{s}_i=0$ will exactly converge to zero in the finite settling time, T_s.

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

$$\begin{cases}\dot{\tilde{x}}_i=\tilde{v}_i,\\ \dot{\tilde{v}}_i=\phi_i.\end{cases} \tag{10}$$

According to the definition of ϕ_i and by referring to Theorem 1 [12], it can be demonstrated that there exist a T_s such that $\tilde{x}_i$ and $\tilde{v}_i$ in (10) become zero for times larger than T_s. 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

$$u_i=\phi_i-k_i\mathrm{sgn}(s_i)-\hat{l}_i\mathrm{sgn}(s_i)-\hat{\delta}_i,\ i=1,\cdots,N, \tag{11}$$

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

$$\begin{cases}\dot{\hat{\delta}}_i=\gamma_i|s_i|,\ \ \hat{\delta}_i(0)>0,\ i=1,\cdots,N.\\ \dot{\hat{l}}_i=\lambda_i|s_i|,\ \ \hat{l}_i(0)>0,\ i=1,\cdots,N.\end{cases} \tag{12}$$

λ_i and γ_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 $0\le\hat{l}_i\le l_i^*,0\le\hat{\gamma}_i\le\gamma_i^*$, in which the constants l_i^* and γ_i^* are not necessarily equal to the nominal value of l_i and γ_i. Therefore, l_i^* and γ_i^* can be assumed to be $l_i^*=l_i+\eta_{1i},\gamma_i^*=\gamma_i+\eta_{2i}$ in which $\eta_{1i}>0$ and $\eta_{2i}>0$ are an arbitrary number.

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 $t\ge T_r$ 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 $t\ge T_r$ where T_r is determined by

$$T_r\le\frac{\sqrt{\sum_{i=1}^{N}s_i^2(0)+\sum_{i=1}^{N}\left(\hat{l}_i(0)-l_i^*(0)\right)^2+\sum_{i=1}^{N}\left(\hat{\delta}_i(0)-\delta_i^*(0)\right)^2}}{\min\left(\min_i\left((1-\lambda_i)|s_i|\right)),\min_i\left((1-\gamma_i)|s_i|\right)),\ \min_i(k_i)\right)} \tag{13}$$

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

$$\dot{s}_i=-k_i\mathrm{sgn}(s_i)-\hat{l}_i\mathrm{sgn}(s_i)+d_i+\delta_i. \tag{14}$$

By substituting (12) and (14) in

$\dot{V}=\sum_{i=1}^{N}s_i\dot{s}_i+\sum_{i=1}^{N}\tilde{l}_i\dot{\tilde{l}}_i+\sum_{i=1}^{N}\tilde{\delta}_i\dot{\tilde{\delta}}_i$, the following relation is obtained.

$$\dot{V}=-\sum_{i=1}^{N}k_i|s_i|-\sum_{i=1}^{N}\hat{l}_i|s_i|+\sum_{i=1}^{N}d_is_i+\sum_{i=1}^{N}\tilde{l}_i\lambda_i|s_i| -\sum_{i=1}^{N}\hat{\delta}_i|s_i|+\sum_{i=1}^{N}\delta_is_i+\sum_{i=1}^{N}\tilde{\delta}_i\gamma_i|s_i| . \quad (15)$$

By considering $k_m=\min_i(k_i)$ and $\sum_{i=1}^{N}d_is_i\le\sum_{i=1}^{N}l_i^*|s_i|$, $\sum_{i=1}^{N}\delta_is_i\le\sum_{i=1}^{N}\delta_i^*|s_i|$, $\dot{V}$ becomes

$$\dot{V}\le-k_m\sum_{i=1}^{N}|s_i|-\sum_{i=1}^{N}(\lambda_i-1)|\tilde{l}_i||s_i|-\sum_{i=1}^{N}(\gamma_i-1)|\tilde{\delta}_i||s_i| . \quad (16)$$

By defining $\Omega_1=\min_i((\lambda_i-1)|s_i|)$, $\Omega_2=\min_i((\gamma_i-1)|s_i|)$ and $\theta=\min(\Omega_1,\Omega_2,k_m)$, (16) is simplified as

$$\dot{V}\le-\theta\left(\sum_{i=1}^{N}|s_i|+\sum_{i=1}^{N}|\tilde{l}_i|+\sum_{i=1}^{N}|\tilde{\delta}_i|\right). \quad (17)$$

By adopting the well-known inequality $\sqrt{\left(\sum_i|y_i|\right)}<\sum_i\sqrt{|y_i|}$, (17) is converted to $\dot{V}\le-\sqrt{2}\theta V^{\frac{1}{2}}$. Finally, by setting $c=\sqrt{2}\theta$, $a=0.5$, and applying Lemma 1, it is proven that $s_i=\dot{s}_i=0$, $i=1,\cdots,N$ are always fulfilled for $t\ge T_r$ where T_r 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 part of the article and the related results are discussed respectively. Notice that matrices A and B are supposed as follows;

$$A=\begin{bmatrix}0&1&1&1&0\\1&0&0&0&0\\1&0&0&1&1\\1&0&1&0&1\\0&0&1&1&0\end{bmatrix},\quad B=\begin{bmatrix}1&0&1&0&1\end{bmatrix}. \quad (18)$$

The initial agent positions and velocities are chosen arbitrarily as $x(0)=[-200\ -50\ 50\ 150\ 200]^T$ and $v(0)=[-200\ 120\ 180\ -160\ 200]^T$, respectively. The initial leader position and velocity are assumed to be $x_0(0)=150$ and $v_0(0)=5$, respectively. Disturbances are selected as $d_1=\cos(0.2t)$, $d_2=0.7\sin(0.4t+\pi/5)$, $d_3=0.5\sin(2t)$, $d_4=0.6\cos(3t+\pi/4)$. The fifth disturbance d_5, (30), is assumed to be time variant [39].

$$d_5=\begin{cases}0.3\cos\left(3\pi\left(\frac{5.9}{60}t+0.1\right)t\right)-0.3 & t<30\\ 0.3\cos\left(3\pi\left(-\frac{5.9}{60}t+6\right)t\right)+0.3) & t\ge30\end{cases}. \quad (19)$$

In terms of selected disturbances, the upper bound disturbance vectors are calculated as $l=[1\ \ 0.7\ \ 0.5\ \ 0.6\ \ 0.3]^T$. In all calculations, the optional fractional power α_1, applied in ϕ_i (9), is chosen as $\alpha_1=0.5$. Further, the control inputs are assumed ±27. Hence, Υ_s is determined as $\Upsilon_s=27$. Also, $\lambda_i=1.1$ and $\hat{\gamma}_i(0)=0.2$, $i=1,\cdots,5$ are assumed, respectively. The tuning parameters are selected as $k_i=20$ and $\lambda_i=1.01$ for $i=1,\cdots,5$. The upper bound estimation initial values are chosen as $\hat{l}_i(0)=0.2$ for $i=1,\cdots,5$. 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)

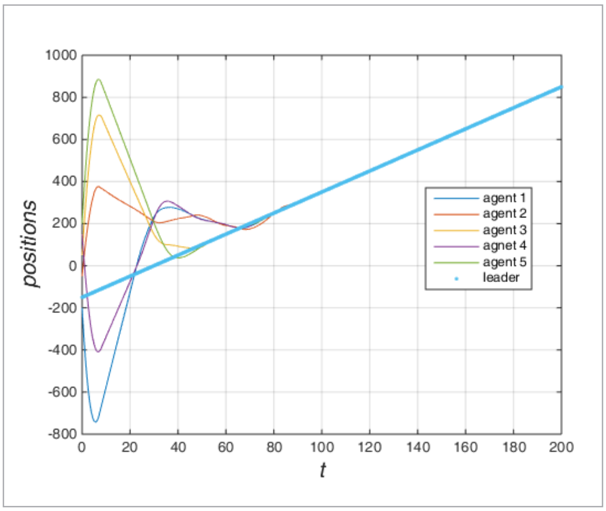


Figure 2

Agent position error by applying (11)

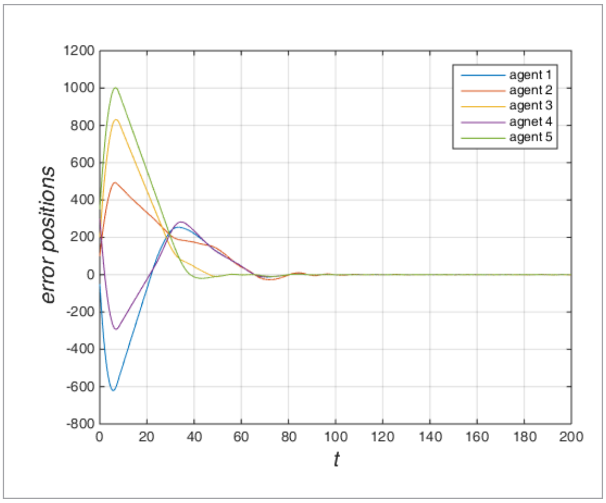


Figure 3

Agent velocity by applying (11)

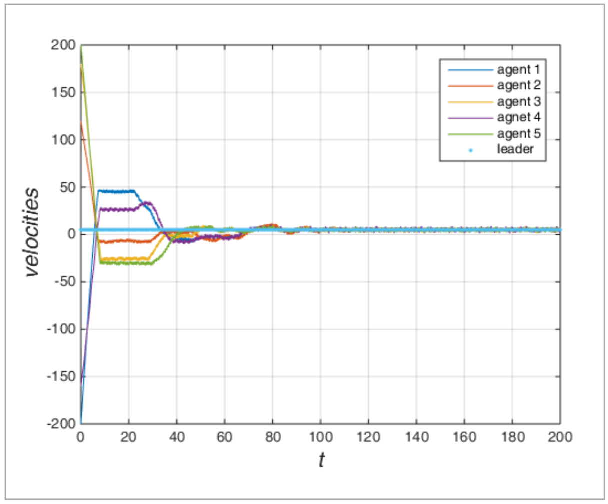


Figure 4

Agent velocity error by applying (11)

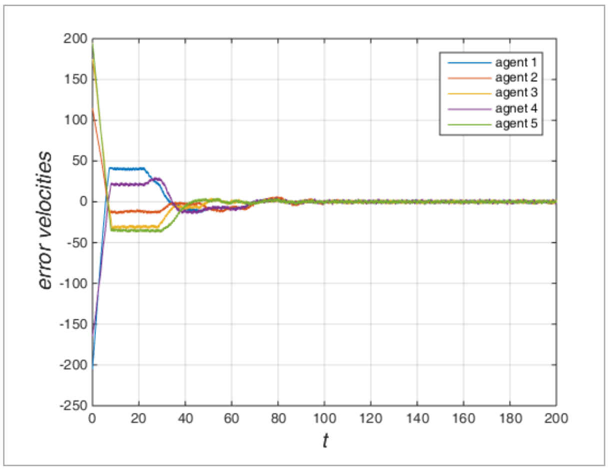
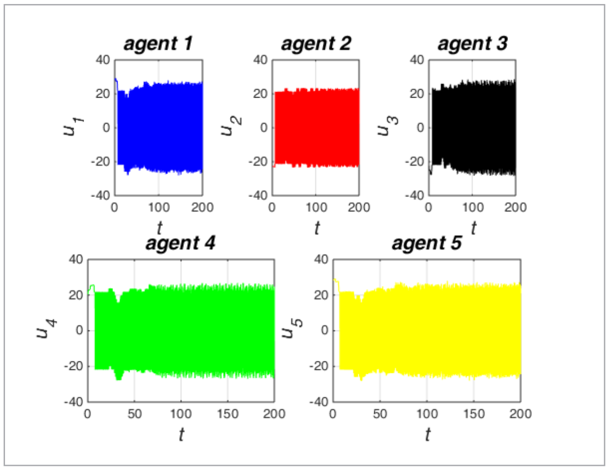


Figure 5

Agent Control Signals



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.

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