Received: Added at production | Revised: Added at production | Accepted: Added at production

DOI: xxx/xxxx

RESEARCH ARTICLEE

Distributed finite-time adaptive fault-tolerant consensus control of second-order multi-agent systems under deception attacks

Chun Liu*[1,2] | Wanyi Wang[2] | Ziquan Yu[3] | Ron J. Patton[4]

[1]School of Mechatronic Engineering and Automation, Shanghai University, Shanghai, China
[2]Institute of Artificial Intelligence, Shanghai University, Shanghai, China
[3]College of Automation Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing, China
[4]School of Engineering and Computer Science, University of Hull, Hull, U.K.

Correspondence
*Chun Liu, School of Mechatronic Engineering and Automation, Shanghai University, Shanghai, China Email: Chun_Liu@shu.edu.cn

Funding Information
This research was supported by the National Natural Science Foundation of China (62103250, 62273223 and 62336005); Shanghai Sailing Program (21YF1414000); Project of Science and Technology Commission of Shanghai Municipality (22JC1401401).

Summary

This study addresses the issue of distributed fault-tolerant consensus control for second-order multi-agent systems subject to simultaneous actuator bias faults in the physical layer and deception attacks in the cyber layer. Cyber-physical threats (malicious state-coupled nonlinear attacks and physical deflection faults), unknown control gains, external disturbances and uncertainties force the failure of the existing graph theory-based consensus control schemes, leading to disruptions in the cooperation and coordination of multi-agent systems. Then, the power integrator-based virtual control is incorporated in the distributed fault-tolerant consensus to achieve unknown parameter estimations with the adaptive technique. The consensus-based robustness to lumped uncertainties, resilience to attacks, compensation to faults, and novel finite-time convergence of the neighborhood errors and velocity errors are also realized within a prescribed finite-time settling bound. The simulation is conducted to verify the effectiveness of the distributed finite-time adaptive fault-tolerant consensus algorithm.

KEYWORDS:
second-order multi-agent systems, finite-time fault-tolerant control, distributed consensus control, adaptive technique

1 | INTRODUCTION

Consensus control of cyber multi-agent systems (MASs) has garnered significant attention and progressed rapidly in diverse control fields, such as autonomous vehicles[1], mobile robots[2], formation control[3], etc. The key issue in addressing consensus control for MASs is designing an effective distributed cooperative protocol. A concise overview of coordination or consensus in MASs is presented in[4]. Recently, there has been a tremendous surge of interest in distributed consensus control of first-order[5], second-order[6], and high-order MASs[7], as well as in linear MASs with unknown external disturbances[8] and nonlinear MASs with mismatched uncertainties[9].

Distributed consensus and coordination in MASs require accurate and reliable information interaction of each agent through cyber topologies. The network security for MASs becomes critically desirable[10] when the essential consensus is disrupted by malicious cyber-attacks. Different from the interruption of information transmission between the sensor/actuator channel or communication channel (denial-of-service attacks), the hostile attackers with deception attacks inject certain deceptive information/false data or manipulate the original data to destroy the integrity and accuracy of the exchanged signal[11]. In addition to the communication threats posed by deception attacks in the cyber layer, the physical faults of individual agents also pose threats to the security, reliability, and robustness of MASs. Therefore, MASs are hoped to explore an effective method to maintain certain security and safety even when deception attacks and physical faults coexist. However, the existing directed or undirected balanced graph theory[12,13] cannot directly solve the cyber-physical constrained consensus control issue. Distributed fault-tolerant consensus control is one of the most powerful methods to achieve the desired cooperative anti-threat performance of MASs with adaptive approximation advantages for handling unknown parameter perturbations. Based on the adaptive approximation and bounding control techniques, a distributed adaptive fault-tolerant consensus algorithm is developed for uncertain nonlinear MASs with physical faults[14]. An adaptive fault-tolerant constrained consensus protocol through disturbance rejection law is proposed in[15], which employs an auxiliary variable-based observer. Furthermore, there are limited studies on distributed consensus control in MASs under individual deception attacks with fault compensation in the physical layer. At present, impulse control has been applied to MASs under deception attacks, with the following emphasis. Aiming at achieving synchronization and security, a brand-new impulsive controller in the communication layer and an adaptive distributed fault-tolerant controller in the physical layer are designed to tackle deception attacks in delayed and uncertain nonlinear MASs[16]. The mean-square bounded synchronization of cyber-physical MASs under deception and injection attacks is achieved using a distributed impulsive control scheme[17]. An efficient impulsive control strategy is developed for MASs with deception attacks, which occur in sensor-to-controller channels, to achieve secure synchronization[18]. However, impulse control mainly focuses on discrete-time systems with the limitation that deception attacks inevitably occur at the moment when the impulse signal activates. Furthermore, it is extremely difficult and challenging to ensure the desirable anti-attack fault-tolerant consensus property of MASs with the occurrence of timing and node-disparate physical actuator faults and deception attacks.

In general, asymptotical consensus[19] in MASs entails that each agent is capable of reaching a consensus objective through continuous adaptation and adjustment, even in the presence of physical faults or cyber-attacks. However, in some practical applications, such as the space-time-specific mission requirements of clusters in intelligent unmanned systems[20], there is an urgent need to achieve cooperative consensus within a limited amount of time durations. Thus, improving the convergence speed in the finite-time phase is relevant for the distributed consensus control problem of MASs[21,22]. Under the effective construction of distributed protocols, the finite-time consensus control strategy for stochastic MASs in[23] is proposed to enhance the convergence rate and ensure the finite-time consensus in probabilities. Additionally, for the MASs with faults in the physical layer, finite-time control techniques combined with fault-tolerant control are partially investigated to achieve the comprehensive compensation for physical faults and limited convergence of consensus[24,25]. Based on the backstepping technique and finite-time Lyapunov stability theory, an adaptive neural network fault-tolerant finite-time control scheme is developed to achieve the convergence of tracking errors in the anticipated finite-time period[25]. The consensus issue of the nonlinear discrete-time MASs with Markov jump parameters is investigated to realize the leader-following finite-time tracking objective through the fault-tolerant controller, thus simultaneously addressing the input saturation faults[26]. Deception attacks that introduce false communication data pose a challenge to adaptive control algorithms by leading to inaccurate parameter estimations. However, for MASs facing both deception attacks and actuator faults in the cyber-physical layer simultaneously, the availability of distributed fault-tolerant finite-time consensus control algorithms based on adaptive techniques remains limited. An adaptive neural network-based finite-time resilient control can guarantee finite-time stability for the time-delay nonlinear dynamics subject to unknown actuator faults and false data injection attacks[27]. Therefore, it is necessary and challenging to design distributed finite-time adaptive fault-tolerant consensus control improvements with safe and secure capabilities for MASs against actuator faults in the physical layer and miscellaneous deception attacks in the cyber layer.

The main contribution of this study is outlined as follows. (i) In contrast to fault-tolerant consensus control strategies of general MASs in resisting independent attacks in the cyber layer or compensating separated actuator faults in the physical layer, this study represents a comprehensive attempt to effectively handle cyber-physical threats, which manifest as self-dynamic deviations induced by actuator bias faults, robustness degradation caused by lumped uncertainties and unreliable communication subject to deception attacks in control channels of the second-order MASs. (ii) The commonly applied Babarlat lemma and uniformly ultimately bounded theory-based filtering technique cannot guarantee the convergence of the neighborhood errors in finite-time periods, and conventional adaptive methods cannot provide sufficient resilience against specific attacks. This paper introduces a fusion method that integrates innovative power integrator-based virtual control and adaptive techniques. This approach not only effectively handles time-varying deception attack signals but also overcomes the challenges associated with approximating unknown bounds in control gains, handling external disturbances and uncertainties, and addressing actuator bias faults. Unlike realizing an asymptotical consensus performance, the comprehensive robustness to lumped uncertainties, resilience to attacks, and tolerance to faults are generated under the convergence speed improvement during the finite-time convergence phase.

The remainder of this study is arranged as follows. In Section 2, preliminaries and problem formulation are presented. Section 3 introduces the distributed finite-time adaptive fault-tolerant consensus control strategy. To demonstrate the effectiveness of the proposed control algorithm, Section 4 showcases the simulation results. Conclusions with future investigations in Section 5 are finally provided.

2 | PRELIMINARIES AND PROBLEM FORMULATION

2.1 | Preliminaries

Lemma 1. (Reference[28]) The Laplacian matrix $\mathscr{L}$ of an undirected connected graph $\mathcal{G}$ possesses the following properties: (i) $\mathscr{L}$ is semi-definite. (ii) $\mathscr{L}$ has a simple eigenvalue 0 with an associated eigenvector 1_N. (iii) Assume that the eigenvalues of $\mathscr{L}$ are denoted as $0, \lambda_2(\mathscr{L}), \cdots, \lambda_N(\mathscr{L})$, and $0 \le \lambda_2(\mathscr{L}) \le \cdots \le \lambda_N(\mathscr{L})$ is derived. Furthermore, if $1_N^T X = 0$, $X^T \mathscr{L} X \ge \lambda_2(\mathscr{L}) X^T X$ is derived.

Lemma 2. (Reference[29]) The following dynamics of the system are considered as

$$\dot{x} = f(x,t), f(0,t) = 0, x \in \mathbb{U} \subset \mathbb{R}^N \tag{1}$$

where $f(x,t) : \mathbb{U} \times \mathbb{R}_+ \to \mathbb{R}^N$ is a continuous function on an open neighborhood $\mathbb{U}$ containing the origin $x = 0$. Assume that a continuously differentiable function $V(x,t) : \mathbb{U} \times \mathbb{R}_+ \to \mathbb{R}$, and real numbers $d > 0, 0 < \alpha < 1$ exist, then $V(x,t)$ is positive definite and $\dot{V}(x,t) + dV^\alpha(x,t) \le 0$ on $\mathbb{U}_0$, where $\mathbb{U}_0 \subset \mathbb{U}$ is an neighborhood of the origin and $\dot{V}(x,t) = \frac{\partial V(x,t)}{\partial x} f(x,t)$. Then, the origin is a finite-time-stable equilibrium of (1), and there exists a finite settling time T^* satisfying

$$T^* \le \frac{V(x(t_0))^{1-\alpha}}{d(1-\alpha)} \tag{2}$$

such that $\lim_{t\to T^*} V(x,t) = 0$ for $t \ge T^*$ is finally derived for any given $x(t_0) \in \mathbb{U}_0/0$.

Lemma 3. (Reference[30])

(i) For $0 < h = h_1/h_2 \le 1$, where $h_1, h_2 > 0$ are odd integers, then $|x-y|^h \le 2^{h-1}\left|x^h - y^h\right|$ is derived with $x \in \mathbb{R}$ and $y \in \mathbb{R}$.

(ii) For $y, z \in \mathbb{R}$ and $c, d > 0$, it follows that $|y|^c|z|^d \le \frac{c}{c+d}|y|^{c+d} + \frac{d}{c+d}|z|^{c+d}$.

(iii) For $h = h_2/h_1 \ge 1$, where $h_1, h_2 > 0$ are odd integers, then $\left|x^h - y^h\right| \le 2^{1-h}|x-y|^h$.

Lemma 4. (Reference[31]) For $x_i \in \mathbb{R}$, $i = 1, 2, \cdots, N$, $0 < h \le 1$, it follows that $\left(\sum_{i=1}^N |x_i|\right)^h \le \sum_{i=1}^N |x_i|^h \le N^{1-h}\left(\sum_{i=1}^N |x_i|\right)^h$.

2.2 | Second-order MASs with deception attack and actuator fault modeling

Consider a group of N agents with scalar-described second-order systems

$$\begin{cases} \dot{x}_i &= v_i \\ \dot{v}_i &= g_i u_i + f_{di} + h_{di}, \quad i = 1, \cdots, N \end{cases} \tag{3}$$

where $u_i \in \mathbb{R}, x_i \in \mathbb{R}$ and $v_i \in \mathbb{R}$ denote the control input, position state, and velocity state, respectively. g_i is time-varying control gain and is possibly unavailable for the controller, f_{di} denotes the external disturbance on the velocity channel, and h_{di} is the uncertainty on the velocity channel.

For leaderless MASs, the distributed neighborhood error is designed as

$$e_i = \sum_{j\in N_i} a_{ij}\left(x_i - x_j\right), i = 1, \cdots, N \tag{4}$$

where a_{ij} is the element of the adjacency matrix $\mathcal{A}$ under the graph $\mathcal{G}$, N_i denotes the neighbor set of node v_i .

Assumption 1. The time-varying control gain g_i $(i = 1, \ldots, N)$ is positive, bounded, and unknown. Let $\underline{g}_i$ and $\overline{g}_i$ denote the unknown finite positive lower and upper bounds, respectively, such that $0 < \underline{g}_i \le |g_i| \le \overline{g}_i < \infty$.

The state-dependent deception attacks in the cyber layer are modeled as

$$\tilde{u}_i = u_i + \rho_i\left(r_i\right) \tag{5}$$

with the actual deception attack signal $\rho_i\left(r_i\right)$ described as

$$\rho_i\left(r_i\right) = W_i\psi_i\left(r_i\right) \tag{6}$$

where $\tilde{u}_i$ denotes the actually attacked control input, and the deception attack $\rho_i(r_i)$ is combined with the unknown time-varying weighting matrix W_i and the known state-coupled nonlinear function $\psi_i\left(r_i\right)$ with the coupled state denoted as $r_i = \bigcup_{j\in N_i \bigcup i} x_i$.

Assumption 2. The deception attacks $\rho_i\left(r_i\right)$ are indicative of certain basic structural information. There exists a known scalar function $\bar{\psi}_i\left(r_i\right)$ and a positive unknown constant $\omega_i > 0$ such that $\left|\rho_i\left(r_i\right)\right| \leq \omega_i\bar{\psi}_i\left(r_i\right)$ for $\left[t_a, \infty\right)$ with the initial attack occurring time t_a, where $\bar{\psi}_i\left(r_i\right)$ is continuously bounded for any sate x_i.

The general actuator fault in the physical layer is modeled as follows

$$\tilde{u}_i^F = \tilde{u}_i + \phi_i \tag{7}$$

where $\tilde{u}_i^F$ denotes the actual fault-induced input and ϕ_i is an unknown actuator bias fault.

Assumption 3. An unknown finite positive scalar $\bar{\phi}_i$ exists such that the actuator bias fault ϕ_i satisfies the inequality $\left|\phi_i\right| \leq \bar{\phi}_i < \infty$.

Define the lumped uncertainty m_i as $m_i = f_{di} + h_{di}$, then the velocity dynamics of second-order MASs subject to deception attacks (5) and (6) as well as actuator bias faults (7) are expressed as follows:

$$\dot{v}_i = g_i(u_i + \rho_i(r_i) + \phi_i) + m_i \tag{8}$$

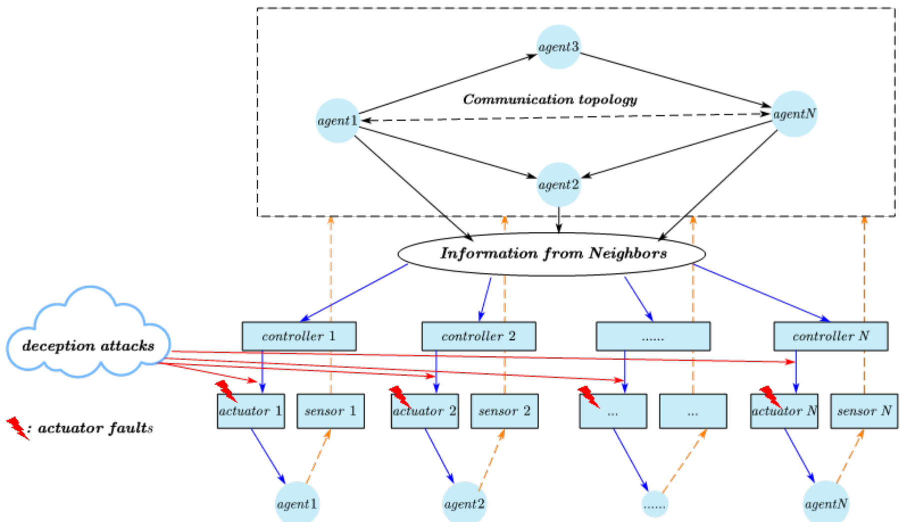

Figure 1 Configuration of second-order MASs under deception attacks in the cyber layer and actuator bias faults in the physical layer

Assumption 4. There exists an unknown finite positive constant θ_i for the lumped uncertainty such that $|m_i| \leq \theta_i$.

The objective of this study is to develop the distributed finite-time adaptive fault-tolerant consensus protocol to achieve the convergence performance of the neighborhood error e_i and velocity error $v_i - v_j, i, j = 1, \cdots, N$ with the finite settling time bound T^* of the considered second-order MASs (3) regardless of deception attacks (5), (6) and actuator bias faults (7). Figure 1 illustrates the configuration of the second-order MASs under actuator bias faults in the physical hierarchy and deception attacks in the cyber hierarchy.

Remark 1. The assumption of boundedness for the control gains g_i and external perturbations f_{di} in second-order MASs is based on energy-limited and attenuable conditions[18,27]. Furthermore, in the presence of both actuator bias faults and deception attacks, the system dynamics are prone to collapse, and the integrity and consensus performance of MASs are easily compromised. The state-dependent deception attacks considered in (6) contain certain crude structural information of the second-order MASs, which can be parameterized as $\left|\rho_i\left(r_i\right)\right| \le w_i \bar{\psi}_i\left(r_i\right)$. Here, $\bar{\psi}_i$ represents the boundary of $\Psi_i(r_i)$, making the constant ω_i a positive bound within the time-varying weight matrix W_i. Compared with the Bernoulli distribution-modeled deception attacks[16,17] with known positive attack bounds, the state-dependent deception attacks in this study involve dynamical and coupled states of the neighboring agents $r_i = \bigcup_{j \in N_i \bigcup i} x_i$.

Remark 2. In the field of practical engineering, external disturbances and uncertainties are two crucial factors that influence the safety of MASs. The variables denoted by f_{di} and h_{di} not only pertain to the behavior of the i-th agent, but are also influenced by neighboring agents[32]. Due to the resulting consensus problems arising from both uncertainties, the lumped uncertainty term m_i is adopted to collectively represent their combined effects. In order to enhance the realism of system simulations and achieve superior control performance, it is common practice to constrain the lumped uncertainty within bounded ranges, specifically ensuring $|m_i| \le \theta_i$[32,33].

3 | MAIN RESULT

To ensure the finite-time convergence of the neighborhood error e_i and velocity error $v_i - v_j, i, j = 1, \cdots, N$ of the cyber-physical second-order MASs, the virtual control v_i^* based on power integrator technique is introduced as

$$v_i^* = -c_2 e_i^q \tag{9}$$

where $0 < q = q_1/q_2 < 1$, q_1, q_2 are positive odd integers, and $c_2 > 0$ is an arbitrarily finite positive scalar. To gradually steer the behavior of each agent towards the desired state, the virtual error δ_i of the velocity state v_i is designed as

$$\delta_i = v_i^{\frac{1}{q}} - \left(v_i^*\right)^{\frac{1}{q}} \tag{10}$$

The ith distributed finite-time fault-tolerant consensus controller with the updated adaptive laws is expressed as

$$u_i = u_{0i} + u_{ci} \tag{11}$$

where $u_{0i} = -c_1 \delta_i^{2q-1}$ denotes the negative feedback control item with the constant gain c_1, and u_{ci} denotes the cyber-physical compensation control item as follows

$$u_{ci} = -\underline{g}\hat{w}_i \delta_i^{2-q} \bar{\psi}_i(r_i) \tanh(\delta_i^{2-q} \bar{\psi}_i(r_i)/\tau_i) - \underline{g}\hat{\bar{\phi}}_i \delta_i^{2-q} \tanh(\delta_i^{2-q}/\tau_i) - \hat{\theta}_i \delta_i^{2-q} \tanh(\delta_i^{2-q}/\tau_i) \tag{12}$$

where $\underline{g} = \min\{\underline{g}_1, \ldots, \underline{g}_N\}$ with each $\underline{g}_i$ denoted as the lower bound of the control gain $g_i (i = 1, \ldots, N)$. The updated adaptive laws of the parameter estimations $\hat{w}_i, \hat{\bar{\phi}}_i$ and $\hat{\theta}_i$ of the unknown parameters $w_i, \bar{\phi}_i$ and θ_i are given as

$$\dot{\hat{w}}_i = -\alpha_{1i}\beta_{1i}\hat{w}_i^q - \underline{g}\delta_i^{2-q} \bar{\psi}_i(r_i) \tanh(\delta_i^{2-q} \bar{\psi}_i(r_i)/\tau_i) \tag{13}$$

$$\dot{\hat{\bar{\phi}}}_i = -\alpha_{2i}\beta_{2i}\hat{\bar{\phi}}_i^q - \underline{g}\delta_i^{2-q} \tanh(\delta_i^{2-q}/\tau_i) \tag{14}$$

$$\dot{\hat{\theta}}_i = -\alpha_{3i}\beta_{3i}\hat{\theta}_i^q - \underline{g}\delta_i^{2-q} \tanh(\delta_i^{2-q}/\tau_i) \tag{15}$$

where $\alpha_{1i}, \alpha_{2i}, \alpha_{3i}, \beta_{1i}, \beta_{2i}, \beta_{3i}$ and τ_i are positive constant parameters, and $\bar{\psi}_i(r_i)$ is defined as the known scalar function in Assumption 2.3.

Remark 3. The virtual error in 10 serves two key functions: enabling adaptive adjustments for agents based on their current state and facilitating error convergence by incorporating velocity differences and neighborhood error, thus enhancing system stability and reducing errors efficiently. Negative feedback control focuses on regulating position and velocity changes in second-order MASs, but this method falls short of providing genuine compensation. To address the influence of physical failures with unknown boundaries and time-varying cyber-attacks, the compensation controller with an updated adaptive law is essential.

Theorem 1. Consider the second-order MASs (3) with deception attacks (5), (6) in the cyber layer and actuator bias faults (7) in the physical layer. The second-order MASs under the distributed finite-time fault-tolerant consensus controller (11), (12) with the updated adaptive laws (13)-(15) can achieve the finite-time consensus convergence property as follows:

(1) for $\forall i, j \in 1, \cdots, N$, the distributed neighbourhood errors e_i and the velocity errors $\left|v_i - v_j\right|$ converge to the small residual set Ω as follows

$$\begin{aligned} \Omega = \Bigg\{ \left|e_i\right| &\leq \sqrt{\frac{2}{\lambda_{\min}(\Lambda)}} \left(\frac{d}{\eta_2 \tilde{c}}\right)^{\frac{1}{1+q}}, \\ \left|v_i - v_j\right| &\leq 2\left[\frac{c_2^{\frac{1}{2}(q+1)}}{q^{\frac{q}{2}} 2^{\frac{q}{2}-1}} + c_2 \left(\frac{2}{\lambda_{\min}(\Lambda)}\right)^{\frac{q}{2}}\right] \left(\frac{d}{\eta_2 \tilde{c}}\right)^{\frac{q}{1+q}} \Bigg\} \end{aligned} \tag{16}$$

with the finite-time settling bound T^* satisfying

$$T^* < \frac{V\left(t_0\right)^{\left(1-\frac{1+q}{2}\right)} k_v^{\frac{1+q}{2}}}{\left(1-\eta_2\right) \tilde{c} \left(1-\frac{1+q}{2}\right) k_d} \tag{17}$$

where Λ is a symmetric positive definite matrix, $0 < \eta_2 < 1, \tilde{c} = \frac{\eta_1 k_d}{k_v^{\frac{1+q}{2}}}, 0 < \eta_1 \leq 1, k_d = \min\{k_3, k_4, k_5, k_6, k_7\}, k_3 = -\frac{2^{1-q} q}{1+q} + \frac{c_1 \underline{g}}{2^{1-q} c_2^{1+1/q}} - \frac{2-q}{c_2}(\bar{a}+\bar{b}\bar{N})(2^{1-q} + \frac{c_2}{1+q}), k_4 = c_2 - \frac{2^{1-q}}{1+q} - \frac{2-q}{1+q}(\bar{a}+\bar{b}\bar{N})$ with $\bar{a} = \max_{\forall i \in \{1,\ldots,N\}}\{\sum_{j\in N_i} a_{ij}\}, \bar{b} = \max_{\forall i \in \{1,\ldots,N\}}\{a_{ij}\}, \bar{N}$ is the maximum out-degree number of the ith agent, $k_5 = \frac{\underline{g}\underline{\alpha}_1\left(2^{(q-1)(1-q)} - 2^{q-1}\right)}{2^{1-q} c_2^{1+1/q} \underline{g}^q (1+q)}, k_6 = \frac{\underline{g}\underline{\alpha}_2\left(2^{(q-1)(1-q)} - 2^{q-1}\right)}{2^{1-q} c_2^{1+1/q} \underline{g}^q (1+q)}, k_7 = \frac{\underline{\alpha}_3\left(2^{(q-1)(1-q)} - 2^{q-1}\right)}{2^{1-q} c_2^{1+1/q} \underline{g}^q (1+q)}$, $\underline{\alpha}_1 = \min\{\alpha_{11}, \cdots, \alpha_{1N}\}, \underline{\alpha}_2 = \min\{\alpha_{21}, \cdots, \alpha_{2N}\}, \underline{\alpha}_3 = \min\{\alpha_{31}, \cdots, \alpha_{3N}\}$ with the designed scalar constants $\alpha_{1i}, \alpha_{2i}, \alpha_{3i}, i = 1, \cdots, N, k_v = \max\{\frac{1}{2\lambda_2(\mathscr{L})}, \frac{1}{c_2^{1+1/q}}, \frac{g_i}{2^{2-q} c_2^{1+1/q} \underline{g}\beta_{1m}}, \frac{g_i}{2^{2-q} c_2^{1+1/q} \underline{g}\beta_{2m}}, \frac{1}{2^{2-q} c_2^{1+1/q} \underline{g}\beta_{3m}}\}$ with the positive designed parameters $\beta_{1m}, \beta_{2m}, \beta_{3m}$, and $V(t_0)$ is the artificial Lyapunov function.

(2) all generalized parameter estimation errors are defined as $\tilde{w}_i = w_i - \underline{g}\hat{w}_i, \tilde{\bar{\phi}}_i = \bar{\phi}_i - \underline{g}\hat{\bar{\phi}}_i, \tilde{\theta}_i = \theta_i - \underline{g}\hat{\theta}_i$, where $\tilde{w}_i$, $\tilde{\bar{\phi}}_i$ and $\tilde{\theta}_i$ converge to the following sets within the finite-time settling bound T^*,

$$|\tilde{w}_i| \leq \sqrt{\frac{2k_\gamma \underline{g}\bar{\beta}_1}{\bar{g}}} \left(\frac{d}{\eta_2 \tilde{c}}\right)^{\frac{1}{1+q}} \tag{18}$$

$$\left|\tilde{\bar{\phi}}_i\right| \leq \sqrt{\frac{2k_\gamma \underline{g}\bar{\beta}_2}{\bar{g}}} \left(\frac{d}{\eta_2 \tilde{c}}\right)^{\frac{1}{1+q}} \tag{19}$$

$$|\tilde{\theta}_i| \leq \sqrt{\frac{2k_\gamma \underline{g}\bar{\beta}_3}{\bar{g}}} \left(\frac{d}{\eta_2 \tilde{c}}\right)^{\frac{1}{1+q}} \tag{20}$$

where $k_\gamma = 2^{1-q} c_2^{\frac{1+q}{q}}, \bar{\beta}_1 = \max\{\beta_{11}, \cdots, \beta_{1N}\}, \bar{\beta}_2 = \max\{\beta_{21}, \cdots, \beta_{2N}\}$ and $\bar{\beta}_3 = \max\{\beta_{31}, \cdots, \beta_{3N}\}$ with the designed scalar constants $\beta_{1i}, \beta_{2i}, \beta_{3i}, i = 1, 2, \cdots, N, d = \sum_{i=1}^{N}[(1 - 2^{q-1} + \frac{1}{1+q} 2^{-(q-1)^2(1+q)} + \frac{q}{1+q}) \frac{(g_i \alpha_{1i} w_i^{1+q} + g_i \alpha_{2i} \bar{\phi}_i^{1+q} + \alpha_{3i} \theta_i^{1+q})}{2^{1-q} c_2^{1+1/q} \underline{g}^q (1+q)} + \frac{0.2785 \tau_i \left(g_i w_i + g_i \bar{\phi}_i + \theta_i\right)}{2^{1-q} c_2^{1+1/q}}] < \infty$, and $\bar{g} = \min\{\bar{g}_1, \ldots, \bar{g}_N\}$ with each $\bar{g}_i$ denoted as the upper bound of the control gain $g_i(\bar{i} = 1, \cdots, N)$.

Proof: Construct the first Lyapunov function as

$$V_1 = \frac{1}{2} E^T \Lambda E \tag{21}$$

with $E = \left[e_1^T, \cdots, e_N^T\right]^T$, $\tilde{\Lambda} = \operatorname{diag}\left\{a, \lambda_2, \ldots, \lambda_N\right\}$ and $\Lambda = U_N^T \tilde{\Lambda}^{-1} U_N$, where a denotes an arbitrarily positive scalar, and U_N^T denotes an orthogonal matrix satisfying $\mathscr{L} = U_N^T \operatorname{diag}\{0, \lambda_2(\mathscr{L}), \cdots, \lambda_N(\mathscr{L})\} U_N = U_N^T \Lambda_0 U_N$ with $\Lambda_0 = \operatorname{diag}\{0, \lambda_2(\mathscr{L}), \cdots, \lambda_N(\mathscr{L})\}$ provided by Lemma 1.

It is obtained that

$$V_1 = \frac{1}{2} E^T \Lambda E = \frac{1}{2} X^T \mathscr{L} X \tag{22}$$

where $X = [x_1^T, x_2^T, \cdots, x_N^T]^T$.

Then, the time derivative of V_1 in (21), (22) is derived as

$$\dot{V}_1 = E^T \dot{X} = \sum_{i=1}^{N} e_i v_i \tag{23}$$

Let $v_i^* = -c_2 e_i^q$ (9) be the virtual control of v_i, it is derived that

$$\dot{V}_1 = \sum_{i=1}^{N} e_i v_i^* + \sum_{i=1}^{N} e_i (v_i - v_i^*) = -c_2 \sum_{i=1}^{N} e_i^{1+q} + \sum_{i=1}^{N} e_i (v_i - v_i^*) \tag{24}$$

By recalling that the virtual error δ_i (10), it follows from Lemma 3 that

$$\begin{aligned}\sum_{i=1}^{N} e_i \left(v_i - v_i^*\right) \leq \sum_{i=1}^{N} \left|e_i\right| \left| \left(v_i^{\frac{1}{q}}\right)^q - \left(\left(v_i^*\right)^{\frac{1}{q}}\right)^q \right| \leq 2^{1-q} \sum_{i=1}^{N} \left|e_i\right| \left|\delta_i\right|^q \\ \leq \frac{2^{1-q}}{1+q} \sum_{i=1}^{N} \left(\left|e_i\right|^{1+q} + q\left|\delta_i\right|^{1+q}\right) = \frac{2^{1-q}}{1+q} \sum_{i=1}^{N} \left(e_i^{1+q} + q\delta_i^{1+q}\right)\end{aligned} \tag{25}$$

By substituting (25) into (24), it is obtained that

$$\dot{V}_1 \leq -c_2 \sum_{i=1}^{N} e_i^{1+q} + \frac{2^{1-q}}{1+q} \sum_{i=1}^{N} \left(e_i^{1+q} + q\delta_i^{1+q}\right) \tag{26}$$

To address the virtual control v_i^* (9), the second Lyapunov function candidate V_2 is defined by adding a power integrator[30] as follows

$$V_2 = \frac{1}{2^{1-q} c_2^{1+1/q}} \sum_{i=1}^{N} \int_{v_i^*}^{v_i} \left(s^{\frac{1}{q}} - \left(v_i^*\right)^{\frac{1}{q}}\right)^{2-q} ds \tag{27}$$

Let $f(s, v_i^*) = (s^{\frac{1}{q}} - (v_i^*)^{\frac{1}{q}})^{2-q}$, $\mathcal{W}_i = \int_{v_i^*}^{v_i} f(s, v_i^*)\, ds$, the time derivative of V_2 in (27) is obtained that

$$\begin{aligned}\dot{V}_2 &= \frac{1}{2^{1-q} c_2^{1+1/q}} \sum_{i=1}^{N} \left[\frac{d(\mathcal{W}_i)}{dv_i} \frac{d(v_i)}{dt} + \int_{v_i^*}^{v_i} \frac{d(f(s, v_i^*))}{d(s, v_i^*)} \frac{d(s, v_i^*)}{d(v_i^*)^{\frac{1}{q}}} \frac{d(v_i^*)^{\frac{1}{q}}}{dt} \right] \\ &= \frac{1}{2^{1-q} c_2^{1+1/q}} \sum_{i=1}^{N} \left[f(v_i, v_i^*)\dot{v}_i + (2-q) \int_{v_i^*}^{v_i} \left(s^{\frac{1}{q}} - \left(v_i^*\right)^{\frac{1}{q}}\right)^{1-q} (-1) ds \frac{d(v_i^*)^{\frac{1}{q}}}{dt} \right] \\ &= \frac{1}{2^{1-q} c_2^{1+1/q}} \sum_{i=1}^{N} \left[\left(v_i^{\frac{1}{q}} - \left(v_i^*\right)^{\frac{1}{q}}\right)^{2-q} \dot{v}_i + (2-q) \int_{v_i^*}^{v_i} \left(s^{\frac{1}{q}} - \left(v_i^*\right)^{\frac{1}{q}}\right)^{1-q} ds \frac{d\left(-\left(v_i^*\right)^{\frac{1}{q}}\right)}{dt} \right] \\ &= \frac{1}{2^{1-q} c_2^{1+1/q}} \sum_{i=1}^{N} \left[\delta_i^{2-q} \dot{v}_i + (2-q) \int_{v_i^*}^{v_i} \left(s^{\frac{1}{q}} - \left(v_i^*\right)^{\frac{1}{q}}\right)^{1-q} c_2^{\frac{1}{q}} \dot{e}_i ds \right] \\ &= \frac{1}{2^{1-q} c_2^{1+1/q}} \sum_{i=1}^{N} \left[\delta_i^{2-q} \dot{v}_i + (2-q) \int_{v_i^*}^{v_i} (s^{\frac{1}{q}} - (v_i^*)^{\frac{1}{q}})^{1-q} c_2^{\frac{1}{q}} \sum_{j \in N_i} a_{ij}(v_i - v_j) ds \right]\end{aligned} \tag{28}$$

Since it can be obtained that

$$\left| \int_{v_i^*}^{v_i} (s^{\frac{1}{q}} - (v_i^*)^{\frac{1}{q}})^{1-q} ds \right| \leq \left| (v_i^{\frac{1}{q}} - (v_i^*)^{\frac{1}{q}})^{1-q} \right| \left|v_i - v_i^*\right| = \left|\delta_i\right|^{1-q} \left|v_i - v_i^*\right| \leq \left|\delta_i\right|^{1-q} 2^{1-q} \left|\delta_i\right|^q = 2^{1-q} \left|\delta_i\right| \tag{29}$$

Define $\bar{a} = \max_{\forall i \in \{1,\cdots,N\}} \{\sum_{j \in N_i} a_{ij}\}$ and $\bar{b} = \max_{\forall i \in \{1,\cdots,N\}} \{a_{ij}\}$, and $\bar{N}$ is denoted as the maximum out-degree number of the ith agent in graph $\mathcal{G}$. Based on (29), it follows that

$$\begin{aligned}\frac{2-q}{2^{1-q} c_2^{1+1/q}} \sum_{i=1}^{N} \int_{v_i^*}^{v_i} \left((s)^{\frac{1}{q}} - \left(v_i^*\right)^{\frac{1}{q}}\right)^{1-q} c_2^{\frac{1}{q}} \sum_{j \in N_i} a_{ij} \left(v_i - v_j\right) ds \leq \frac{2-q}{c_2} \sum_{i=1}^{N} \left|\delta_i\right| \left| \sum_{j \in N_i} a_{ij} \left(v_i - v_j\right) \right| \\ \leq \frac{2-q}{c_2} \sum_{i=1}^{N} \left|\delta_i\right| \left| \sum_{j \in N_i} a_{ij} v_i - \sum_{j \in N_i} a_{ij} v_j \right| \leq \frac{2-q}{c_2} \sum_{i=1}^{N} \left|\delta_i\right| \left(\bar{a} \left|v_i\right| + \bar{b} \sum_{j \in N_i} \left|v_j\right| \right) \leq \frac{2-q}{c_2} \sum_{i=1}^{N} \left|\delta_i\right| \left(\bar{a} \left|v_i\right| + \bar{b}\bar{N} \left|v_i\right|\right)\end{aligned} \tag{30}$$

Upon using Lemma 3, it is derived that

$$\begin{aligned}\left|\delta_i\right|\left|v_i\right| &\le \left|\delta_i\right|\left|v_i - v_i^*\right| + \left|\delta_i\right|\left|v_i^*\right| \le 2^{1-q}\left|\delta_i\right|\left|\delta_i\right|^q + c_2\left|\delta_i\|e_i\right|^q \\ &\le 2^{1-q}\left|\delta_i\right|^{1+q} + \frac{c_2}{1+q}\left(\left|\delta_i\right|^{1+q} + q\left|e_i\right|^{1+q}\right)\end{aligned} \tag{31}$$

The inequality (30) can be further written as follows by using (31),

$$\frac{2-q}{2^{1-q}c_2^{\frac{1}{q}}}\sum_{i=1}^{N}\int_{v_i^*}^{v_i}\left(s^{\frac{1}{q}} - \left(v_i^*\right)^{\frac{1}{q}}\right)^{1-q} ds \cdot c_2^{\frac{1}{q}}\sum_{j\in N_i} a_{ij}\left(v_i - v_j\right) \le \frac{2-q}{c_2}(\bar{a} + \bar{b}\bar{N})\sum_{i=1}^{N}\left[\left(2^{1-q} + \frac{c_2}{1+q}\right)\delta_i^{1+q} + \frac{c_2}{1+q}e_i^{1+q}\right] \tag{32}$$

By employing the updated adaptive laws $\dot{\hat{w}}_i$, $\dot{\hat{\bar{\phi}}}_i$ and $\dot{\hat{\theta}}_i$ (13)–(15) into the first item of the right hand of (28), one obtains that

$$\begin{aligned}\sum_{i=1}^{N}\delta_i^{2-q}\dot{v}_i &= \sum_{i=1}^{N}\delta_i^{2-q}\left[g_i\left(u_{0i} + u_{ci} + \rho_i\left(r_i\right) + \phi_i\right) + m_i\right] \\ &\le -\underline{g}\sum_{i=1}^{N}c_1\delta_i^{q+1} - \sum_{i=1}^{N}g_i\left[\underline{g}\hat{w}_i\delta_i^{2-q}\bar{\psi}_i(r_i)\tanh\left(\delta_i^{2-q}\bar{\psi}_i(r_i)/\tau_i\right)\right. \\ &\quad \left. + \underline{g}\delta_i^{2-1}\hat{\bar{\phi}}_i\tanh\left(\delta_i^{2-q}/\tau_i\right) + \delta_i^{2-q}\hat{\theta}_i\tanh\left(\delta_i^{2-q}/\tau_i\right)\right] \\ &\quad + \sum_{i=1}^{N}\delta_i^{2-q}\left(g_i w_i\bar{\psi}_i(r_i) + g_i\phi_i + \theta_i\right)\end{aligned} \tag{33}$$

where $\underline{g} = \min\left\{\underline{g}_1, \ldots, \underline{g}_N\right\}$ is denoted with the lower bound element $\underline{g}_i$.

Then, it is obtained that

$$\begin{aligned}\sum_{i=1}^{N}\delta_i^{2-q}\dot{v}_i \le -\underline{g}\sum_{i=1}^{N}c_1\delta_i^{q+1} &- \sum_{i=1}^{N}g_i\left[\underline{g}\hat{w}_i\delta_i^{2-q}\bar{\psi}_i(r_i)\tanh\left(\bar{\psi}_i(r_i)\delta_i^{2-q}/\tau_i\right)\right. \\ &\left. + \underline{g}\delta_i^{2-1}\hat{\bar{\phi}}_i\tanh\left(\delta_i^{2-q}/\tau_i\right) + \delta_i^{2-1}\hat{\theta}_i\tanh\left(\delta_i^{2-q}/\tau_i\right)\right] \\ &+ \sum_{i=1}^{N}\left(g_i w_i\bar{\psi}_i(r_i)\left|\delta_i^{2-q}\right| + g_i\phi_i\left|\delta_i^{2-q}\right| + \theta_i\left|\delta_i^{2-q}\right|\right)\end{aligned} \tag{34}$$

According to $0 \le |s| - s\cdot\tanh(s/k) \le 0.2785k$ [34], where $s, k \in \mathbb{R}$, it is obtained that $0 \le \left|\delta_i^{2-q}\right| \le \delta_i^{2-q}\tanh\left(\delta_i^{2-q}/\tau_i\right) + 0.2785\tau_i$.

By substituting (32) and (34) into (28), it is obtained that

$$\begin{aligned}\dot{V}_2 \le &\left[\frac{2-q}{c_2}(\bar{a} + \bar{b}\bar{N})\left(2^{1-q} + \frac{c_2}{1+q}\right) - \frac{\underline{g}c_1}{2^{1-q}c_2^{1+1/q}}\right]\sum_{i=1}^{N}\delta_i^{q+1} \\ &+ \frac{2-q}{1+q}(\bar{a} + \bar{b}\bar{N})\sum_{i=1}^{N}e_i^{1+q} + \frac{1}{2^{1-q}c_2^{1+1/q}}\sum_{i=1}^{N}[0.2785\tau_i\left(g_i w_i + g_i\bar{\phi}_i + \theta_i\right) \\ &+ g_i\left(w_i - \underline{g}\hat{w}_i\right)\delta_i^{2-q}\bar{\psi}_i(r_i)\tanh(\delta_i^{2-q}\bar{\psi}_i(r_i)/\tau_i) \\ &+ g_i\left(\bar{\phi}_i - \underline{g}\hat{\bar{\phi}}_i\right)\delta_i^{2-q}\tanh\left(\delta_i^{2-q}/\tau_i\right) + \left(\theta_i - \underline{g}\hat{\theta}_i\right)\delta_i^{2-q}\tanh\left(\delta_i^{2-q}/\tau_i\right)]\end{aligned} \tag{35}$$

Define $k_1 = \frac{2-q}{c_2}(\bar{a} + \bar{b}\bar{N})\left(2^{1-q} + \frac{c_2}{1+q}\right) - \frac{\underline{g}c_1}{2^{1-q}c_2^{1+1/q}}$ and $k_2 = \frac{2-q}{1+q}(\bar{a} + \bar{b}\bar{N})$, it is obtained that

$$\begin{aligned}\dot{V}_2 \le\ &k_1\sum_{i=1}^{N}\delta_i^{q+1} + k_2\sum_{i=1}^{N}e_i^{1+q} + \frac{1}{2^{1-q}c_2^{1+1/q}}\sum_{i=1}^{N}\left[0.2785\tau_i\left(g_i w_i + g_i\bar{\phi}_i + \theta_i\right)\right. \\ &+ g_i\left(w_i - \underline{g}\hat{w}_i\right)\delta_i^{2-q}\bar{\psi}_i(r_i)\tanh\left(\delta_i^{2-q}\bar{\psi}_i(r_i)/\tau_i\right) \\ &\left. + g_i\left(\bar{\phi}_i - \underline{g}\hat{\bar{\phi}}_i\right)\delta_i^{2-q}\tanh\left(\delta_i^{2-q}/\tau_i\right) + \left(\theta_i - \underline{g}\hat{\theta}_i\right)\delta_i^{2-q}\tanh\left(\delta_i^{2-q}/\tau_i\right)\right]\end{aligned} \tag{36}$$

To resist the deception attack $\rho_i(r_i)$ (5), (6) in the cyber layer and to compensate actuator bias fault ϕ_i (7) and lumped uncertainty m_i in the physical layer, the third Lyapunov function candidate V_3 is formulated as follows

$$\begin{aligned} V_3 &= \sum_{i=1}^{N} \frac{g_i \tilde{w}_i^2}{2k_\gamma \underline{g}\beta_{1i}} + \sum_{i=1}^{N} \frac{g_i \tilde{\bar{\phi}}_i^2}{2k_\gamma \underline{g}\beta_{2i}} + \sum_{i=1}^{N} \frac{\tilde{\theta}_i^2}{2k_\gamma \underline{g}\beta_{3i}} \\ &= \sum_{i=1}^{N} \frac{g_i}{2k_\gamma \underline{g}\beta_{1i}}(w_i - \underline{g}\hat{w}_i)^2 + \sum_{i=1}^{N} \frac{g_i}{2k_\gamma \underline{g}\beta_{2i}}(\bar{\phi}_i - \underline{g}\hat{\bar{\phi}}_i)^2 + \sum_{i=1}^{N} \frac{1}{2k_\gamma \underline{g}\beta_{3i}}(\theta_i - \underline{g}\hat{\theta}_i)^2 \end{aligned} \tag{37}$$

where $k_\gamma = 2^{1-q}c_2^{1+1/q}$ and $\beta_{1i}, \beta_{2i}, \beta_{3i}$ are designed positive parameters.

Meanwhile, by using the updated adaptive laws of $\hat{w}_i$, $\hat{\bar{\phi}}_i$ and $\hat{\theta}_i$ (13)-(15), the derivative of V_3 in (37) is derived as

$$\begin{aligned} \dot{V}_3 &= \sum_{i=1}^{N} \frac{g_i \tilde{w}_i}{k_\gamma}\left(-\frac{\dot{\hat{w}}_i}{\beta_{1i}}\right) + \sum_{i=1}^{N} \frac{g_i \tilde{\bar{\phi}}_i}{k_\gamma}\left(-\frac{\dot{\hat{\bar{\phi}}}_i}{\beta_{2i}}\right) + \sum_{i=1}^{N} \frac{\tilde{\theta}_i}{k_\gamma}\left(-\frac{\dot{\hat{\theta}}_i}{\beta_{3i}}\right) \\ &= \sum_{i=1}^{N} \frac{g_i\alpha_{1i}}{k_\gamma}\tilde{w}_i\hat{w}_i^q + \sum_{i=1}^{N} \frac{g_i\alpha_{2i}}{k_\gamma}\tilde{\bar{\phi}}\hat{\bar{\phi}}_i^q + \sum_{i=1}^{N} \frac{\alpha_{3i}}{k_\gamma}\tilde{\theta}_i\hat{\theta}_i^q \\ &- \sum_{i=1}^{N} \frac{g_i}{k_\gamma}(w_i - g\hat{w}_i)\delta_i^{2-q}\bar{\Psi}_i(r_i)\tanh(\delta_i^{2-q}\bar{\Psi}_i(r_i)/\tau_i) \\ &- \sum_{i=1}^{N} \frac{g_i}{k_\gamma}(\bar{\phi}_i - \underline{g}\hat{\bar{\phi}}_i)\delta_i^{2-q}\tanh(\delta_i^{2-q}/\tau_i) - \sum_{i=1}^{N} \frac{1}{k_\gamma}(\theta_i - \underline{g}\hat{\theta}_i)\delta_i^{2-q}\tanh(\delta_i^{2-q}/\tau_i) \end{aligned} \tag{38}$$

Finally, define the total Lyapunov candidate as $V = V_1 + V_2 + V_3$, and it follows that

$$\begin{aligned} \dot{V} \le& -c_2\sum_{i=1}^{N} e_i^{1+q} + \frac{2^{1-q}}{1+q}\sum_{i=1}^{N}\left(e_i^{1+q} + q\delta_i^{1+q}\right) + k_1\sum_{i=1}^{N}\delta_i^{q+1} + k_2\sum_{i=1}^{N} e_i^{1+q} \\ &+ \frac{1}{2^{1-q}c_2^{\frac{1}{q}}}\sum_{i=1}^{N}\left[\frac{0.2785\tau_i}{k_\gamma}\left(g_iw_i + g_i\bar{\phi}_i + \theta_i\right) + \frac{g_i}{k_\gamma}\left(w_i - \underline{g}\hat{w}_i\right)\delta_i^{2-q}\bar{\Psi}_i(r_i)\tanh\left(\delta_i^{2-q}\bar{\Psi}_i(r_i)/\tau_i\right)\right. \\ &\left.+ \frac{g_i}{k_\gamma}\left(\bar{\phi}_i - \underline{g}\hat{\bar{\phi}}_i\right)\delta_i^{2-q}\tanh\left(\delta_i^{2-q}/\tau_i\right) + \frac{1}{k_\gamma}\left(\theta_i - \underline{g}\hat{\theta}_i\right)\delta_i^{2-q}\tanh\left(\delta_i^{2-q}/\tau_i\right)\right] \\ &+ \sum_{i=1}^{N} \frac{g_i\alpha_{1i}}{k_\gamma}\tilde{w}_i\hat{w}_i^q + \sum_{i=1}^{N} \frac{g_i\alpha_{2i}}{k_\gamma}\tilde{\bar{\phi}}\hat{\bar{\phi}}_i^q + \sum_{i=1}^{N} \frac{\alpha_{3i}}{k_\gamma}\tilde{\theta}_i\hat{\theta}_i^q \\ &- \sum_{i=1}^{N} \frac{g_i}{k_\gamma}\left(w_i - \underline{g}\hat{w}_i\right)\delta_i^{2-q}\bar{\Psi}_i(r_i)\tanh\left(\delta_i^{2-q}\bar{\Psi}_i(r_i)/\tau_i\right) \\ &- \sum_{i=1}^{N} \frac{g_i}{k_\gamma}\left(\bar{\phi}_i - \underline{g}\hat{\bar{\phi}}_i\right)\delta_i^{2-q}\tanh\left(\delta_i^{2-q}/\tau_i\right) - \sum_{i=1}^{N} \frac{1}{k_\gamma}\left(\theta_i - \underline{g}\hat{\theta}_i\right)\delta_i^{2-q}\tanh\left(\delta_i^{2-q}/\tau_i\right) \end{aligned} \tag{39}$$

Then, it follows that

$$\begin{aligned} \dot{V}(t) \le& k_3\sum_{i=1}^{N}\delta_i^{1+q} - k_4\sum_{i=1}^{N} e_i^{1+q} + \sum_{i=1}^{N}\frac{0.2785\tau_i}{k_\gamma}\left(g_iw_i + g_i\bar{\phi}_i + \theta_i\right) \\ &+ \sum_{i=1}^{N} \frac{g_i\alpha_{1i}}{k_\gamma}\tilde{w}_i\hat{w}_i^q + \sum_{i=1}^{N} \frac{g_i\alpha_{2i}}{k_\gamma}\tilde{\bar{\phi}}\hat{\bar{\phi}}_i^q + \sum_{i=1}^{N} \frac{\alpha_{3i}}{k_\gamma}\tilde{\theta}_i\hat{\theta}_i^q \end{aligned} \tag{40}$$

where $k_3 = -\frac{2^{1-q}q}{1+q} + \frac{c_1\underline{g}}{2^{1-q}c_2^{1+1/q}} - \frac{2-q}{c_2}(\bar{a}+\bar{b}\bar{N})(2^{1-q}+\frac{c_2}{1+q}) > 0$ and $k_4 = c_2 - \frac{2^{1-q}}{1+q} - \frac{2-q}{1+q}(\bar{a}+\bar{b}\bar{N}) > 0$ with $c_1 > 2^{1-q}c_2^{1+1/q}\underline{g}^{-1}[\frac{2^{1-q}q}{1+q} + \frac{2-q}{c_2}(\bar{a}+\bar{b}\bar{N})(2^{1-q}+\frac{c_2}{1+q})]$ and $c_2 > \frac{1}{1+q}\left[2^{1-q} + (2-q)(\bar{a}+\bar{b}\bar{N})\right]$.

One obtains that

$$\begin{aligned} \tilde{w}_i\hat{w}_i^q \le& \frac{1}{\underline{g}^q(1+q)}\left[\left(2^{(q-1)(1-q)} - 2^{q-1}\right)\tilde{w}_i^{1+q}\right. \\ &\left.+\left(1 - 2^{q-1} + \frac{q}{1+q} + \frac{1}{1+q}2^{-(q-1)^2(1+q)}\right)w_i^{1+q}\right] \end{aligned} \tag{41}$$

$$
\begin{aligned}
\tilde{\bar{\phi}}_i \hat{\bar{\phi}}_i^q \leq & \frac{1}{\underline{g}^q(1+q)} \Big[\left(2^{(q-1)(1-q)} - 2^{q-1}\right) \tilde{\bar{\phi}}_i^{1+q} \\
& + \left(1 - 2^{q-1} + \frac{q}{1+q} + \frac{1}{1+q} 2^{-(q-1)^2(1+q)}\right) \bar{\phi}_i^{1+q} \Big]
\end{aligned} \tag{42}
$$

$$
\begin{aligned}
\tilde{\theta}_i \hat{\theta}_i^q \leq & \frac{1}{\underline{g}^q(1+q)} \Big[\left(2^{(q-1)(1-q)} - 2^{q-1}\right) \tilde{\theta}_i^{1+q} \\
& + \left(1 - 2^{q-1} + \frac{q}{1+q} + \frac{1}{1+q} 2^{-(q-1)^2(1+q)}\right) \theta_i^{1+q} \Big]
\end{aligned} \tag{43}
$$

By substituting (41), (42) and (43) into (40), one gets

$$
\dot{V} \leq k_3 \sum_{i=1}^N \delta_i^{1+q} - k_4 \sum_{i=1}^N e_i^{1+q} - k_5 \sum_{i=1}^N \tilde{w}_i^{1+q} - k_6 \sum_{i=1}^N \tilde{\bar{\phi}}_i^{1+q} - k_7 \sum_{i=1}^N \tilde{\theta}_i^{1+q} + d \tag{44}
$$

where $k_5 = \frac{g_i \underline{\alpha}_1 (2^{(q-1)(1-q)} - 2^{q-1})}{2^{1-q} c_2^{1+1/q} \underline{g}^q (1+q)}$, $k_6 = \frac{g_i \underline{\alpha}_2 (2^{(q-1)(1-q)} - 2^{q-1})}{2^{1-q} c_2^{1+1/q} \underline{g}^q (1+q)}$, $k_7 = \frac{\underline{\alpha}_3 (2^{(q-1)(1-q)} - 2^{q-1})}{2^{1-q} c_2^{1+1/q} \underline{g}^q (1+q)}$, $d = \sum_{i=1}^N [(1 - 2^{q-1} + \frac{1}{1+q} 2^{-(q-1)^2(1+q)} + \frac{q}{1+q}) \frac{(g_i \alpha_{1i} w_i^{1+q} + g_i \alpha_{2i} \bar{\phi}_i^{1+q} + \alpha_{3i} \theta_i^{1+q})}{2^{1-q} c_2^{1+1/q} \underline{g}^q (1+q)} + \frac{0.2785 \tau_i (g_i w_i + g_i \bar{\phi}_i + \theta_i)}{2^{1-q} c_2^{1+1/q}}] < \infty$, $\underline{\alpha}_1 = \min\{\alpha_{11}, \ldots, \alpha_{1N}\}$, $\underline{\alpha}_2 = \min\{\alpha_{21}, \ldots, \alpha_{2N}\}$, and $\underline{\alpha}_3 = \min\{\alpha_{31}, \ldots, \alpha_{3N}\}$.

Note that $2^{(q-1)(1-q)} - 2^{q-1} = 2^{q-1}\left(2^{1-q} - 1\right) > 0$, $k_5 > 0$, it follows that $k_6 > 0$ and $k_7 > 0$. It thus follows that

$$
\dot{V} \leq -k_d \sum_{i=1}^N \left(\delta_i^{1+q} + e_i^{1+q} + \tilde{w}_i^{1+q} + \tilde{\bar{\phi}}_i^{1+q} + \tilde{\theta}_i^{1+q}\right) + d \tag{45}
$$

where $k_d = \min\{k_3, k_4, k_5, k_6, k_7\}$.

It is proved that a bounded constant $0 < \zeta < \infty$ and a finite-time settling bound $T^* > 0$ exist such that $V(t) < \zeta$ when $t \geq T^*$. Under Lemma 1, it follows that

$$
V_1 = \frac{1}{2} X^T \mathscr{L} X \leq \frac{1}{2\lambda_2(\mathscr{L})} E^T E = \frac{1}{2\lambda_2(\mathscr{L})} \sum_{i=1}^N e_i^2 \tag{46}
$$

Upon using Lemma 4, it follows that

$$
\begin{aligned}
V_2 &= \frac{1}{2^{1-q} c_2^{1+1/q}} \sum_{i=1}^N \int_{v_i^*}^{v_i} \left(s^{\frac{1}{q}} - (v_i^*)^{\frac{1}{q}}\right)^{2-q} ds \\
&\leq \frac{1}{2^{1-q} c_2^{1+1/q}} \sum_{i=1}^N \left| \left(v_i^{\frac{1}{q}} - (v_i^*)^{\frac{1}{q}}\right)^{2-q} \right| |v_i - v_i^*| \\
&\leq \frac{1}{2^{1-q} c_2^{1+1/q}} \sum_{i=1}^N |\delta_i|^{2-q} \cdot 2^{1-q} |\delta_i|^q = \frac{1}{c_2^{1+1/q}} \sum_{i=1}^N \delta_i^2
\end{aligned} \tag{47}
$$

From the definition of V_3 given in (37), one obtains that

$$
\begin{aligned}
V_3 \leq & \frac{1}{2^{2-q} c_2^{1+1/q} \underline{g} \beta_{1m}} \sum_{i=1}^N g_i \tilde{w}_i^2 + \frac{1}{2^{2-q} c_2^{1+1/q} \underline{g} \beta_{2m}} \sum_{i=1}^N g_i \tilde{\bar{\phi}}_i^2 \\
& + \frac{1}{2^{2-q} c_2^{1+1/q} \underline{g} \beta_{3m}} \sum_{i=1}^N \tilde{\theta}_i^2
\end{aligned} \tag{48}
$$

with $\beta_{1m} = \min\{\beta_{11}, \cdots, \beta_{1N}\}$, $\beta_{2m} = \min\{\beta_{21}, \cdots, \beta_{2N}\}$, and $\beta_{3m} = \min\{\beta_{31}, \cdots, \beta_{3N}\}$.

Subsequently, it follows that

$$
V \leq k_v \sum_{i=1}^N \left(\delta_i^2 + e_i^2 + \tilde{w}_i^2 + \tilde{\bar{\phi}}_i^2 + \tilde{\theta}_i^2\right) \tag{49}
$$

where $k_v = \max\{\frac{1}{2\lambda_2(\mathscr{L})}, \frac{1}{c_2^{1+1/q}}, \frac{g_i}{2^{2-q} c_2^{1+1/q} \underline{g} \beta_{1m}}, \frac{g_i}{2^{2-q} c_2^{1+1/q} \underline{g} \beta_{2m}}, \frac{1}{2^{2-q} c_2^{1+1/q} \underline{g} \beta_{3m}}\}$.

Upon using Lemma 3, $V^{\frac{1+q}{2}} \leq k_v^{\frac{1+q}{2}} \sum_{i=1}^{N}(e_i^{1+q} + \delta_i^{1+q} + \tilde{w}_i^{1+q} + \tilde{\tilde{\phi}}_i^{1+q} + \tilde{\theta}_i^{1+q})$ is derived. Denote $\tilde{c} = \frac{\eta_1 k_d}{k_v^{\frac{1+q}{2}}}, 0 < \eta_1 \leq 1$, it is obtained that

$$\dot{V}(t) \leq -\tilde{c}V(t)^{\frac{1+q}{2}} + d \leq -\tilde{c}V(t)^{\frac{1+q}{2}} + \eta_2\tilde{c}V(t)^{\frac{1+q}{2}} = -\left(1-\eta_2\right)\tilde{c}V(t)^{\frac{1+q}{2}} \tag{50}$$

Thus, it is obtained that

$$V(t) < \left(\frac{d}{\eta_2\tilde{c}}\right)^{\frac{2}{1+q}} = \zeta \tag{51}$$

Furthermore, according to Lemma 2 and (50), it expresses the finite settling time T^* as follows:

$$T^* < \frac{V\left(t_0\right)^{\left(1-\frac{1+q}{2}\right)} k_v^{\frac{1+q}{2}}}{\left(1-\eta_2\right)\tilde{c}\left(1-\frac{1+q}{2}\right)k_d} \tag{52}$$

Then, the estimation of the neighborhood errors e_i is derived as

$$\left|e_i\right| = \sqrt{e_i^2} \leq \sqrt{\sum_{i=1}^{N} e_i^2} \leq \sqrt{\frac{2V_1(t)}{\lambda_{\min}(\Lambda)}} \leq \sqrt{\frac{2V(t)}{\lambda_{\min}(\Lambda)}} \leq \sqrt{\frac{2}{\lambda_{\min}(\Lambda)}}\left(\frac{d}{\eta_2\tilde{c}}\right)^{\frac{1}{1+q}} \tag{53}$$

According to Lemma 3, $|\zeta^{1/q} - (v_i^*)^{1/q}| \geq 2^{1-1/q}|\zeta - v_i^*|^{1/q}$ is obtained.
If $v_i \geq v_i^*$, it holds that

$$\begin{aligned} V_2(t) &\geq \frac{1}{2^{1-q}c_2^{1+1/q}} \sum_{i=1}^{N} \int_{v_i^*}^{v_i} \left[2^{1-1/q}\left(s-v_i^*\right)^{1/q}\right]^{2-q} ds \\ &= \frac{1}{2^{1-q}c_2^{1+1/q}} \sum_{i=1}^{N} \int_{v_i^*}^{v_i} 2^{(1-1/q)(2-q)}\left(s-v_i^*\right)^{\frac{2}{q}-1} ds \\ &= \frac{1}{2/q-1+1} \frac{2^{(1-1/q)(2-q)}}{2^{1-q}c_2^{1+1/q}} \sum_{i=1}^{N} \left(s-v_i^*\right)^{\frac{2}{q}-1+1}\Bigg|_{v_i^*}^{v_i} = \frac{q2^{1-\frac{2}{q}}}{c_2^{1+1/q}} \sum_{i=1}^{N}\left(v_i-v_i^*\right)^{\frac{2}{q}} \end{aligned} \tag{54}$$

When $v_i < v_i^*$ holds, the proof of (54) is also obtained. Then, one gets that

$$\begin{aligned} \left|v_i - v_i^*\right| &= \left[\left(v_i-v_i^*\right)^{\frac{2}{q}}\right]^{\frac{q}{2}} \leq \left[\sum_{i=1}^{N}\left(v_i-v_i^*\right)^{\frac{2}{q}}\right]^{\frac{q}{2}} \\ &\leq \left[\frac{c_2^{1+1/q}}{q2^{1-2/q}}V_2(t)\right]^{\frac{q}{2}} = \frac{c_2^{\frac{1}{2}(q+1)}}{q^{\frac{q}{2}}2^{\frac{q}{2}-1}}V_2(t)^{\frac{q}{2}} \leq \frac{c_2^{\frac{1}{2}(q+1)}}{q^{\frac{q}{2}}2^{\frac{q}{2}-1}}\left(\frac{d}{\eta_2\tilde{c}}\right)^{\frac{q}{1+q}} \end{aligned} \tag{55}$$

It follows from (9) and (53) that

$$\left|v_i^*\right| = \left|-c_2e_i^q\right| \leq c_2\left(\frac{2}{\lambda_{\min}(\Lambda)}\right)^{\frac{q}{2}}\left(\frac{d}{\eta_2\tilde{c}}\right)^{\frac{q}{1+q}} \tag{56}$$

and it also indicates for $\forall i, j \in \{1, \ldots, N\}$ that

$$\left|v_i - v_j\right| \leq \left|v_i\right| + \left|v_j\right| \leq 2\left[\frac{c_2^{\frac{1}{2}(q+1)}}{q^{\frac{q}{2}}2^{\frac{q}{2}-1}} + c_2\left(\frac{2}{\lambda_{\min}(\Lambda)}\right)^{\frac{q}{2}}\right]\left(\frac{d}{\eta_2\tilde{c}}\right)^{\frac{q}{1+q}} \tag{57}$$

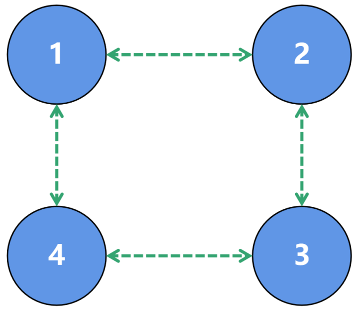

Figure 2 Communication graph topology among four agents

Moreover, for $\forall i \in \{1, \ldots, N\}$, it finally follows that

$$\begin{aligned} |\tilde{\omega}_i| &= \sqrt{\tilde{\omega}_i^2} \leq \sqrt{\sum_{i=1}^{N} \tilde{\omega}_i^2} \leq \sqrt{\frac{2k_\gamma \underline{g} \bar{\beta}_1 V_3(t)}{\bar{g}}} \leq \sqrt{\frac{2k_\gamma \underline{g} \bar{\beta}_1 V(t)}{\bar{g}}} \leq \sqrt{\frac{2k_\gamma \underline{g} \bar{\beta}_1}{\bar{g}}} \left(\frac{d}{\eta_2 \tilde{c}}\right)^{\frac{1}{1+q}} \\ \left|\tilde{\bar{\phi}}_i\right| &= \sqrt{\tilde{\bar{\phi}}_i^2} \leq \sqrt{\sum_{i=1}^{N} \tilde{\bar{\phi}}_i^2} \leq \sqrt{\frac{2k_\gamma \underline{g} \bar{\beta}_2 V_3(t)}{\bar{g}}} \leq \sqrt{\frac{2k_\gamma \underline{g} \bar{\beta}_2 V(t)}{\bar{g}}} \leq \sqrt{\frac{2k_\gamma \underline{g} \bar{\beta}_2}{\bar{g}}} \left(\frac{d}{\eta_2 \tilde{c}}\right)^{\frac{1}{1+q}} \\ |\tilde{\theta}_i| &= \sqrt{\tilde{\theta}_i^2} \leq \sqrt{\sum_{i=1}^{N} \tilde{\theta}_i^2} \leq \sqrt{\frac{2k_\gamma \underline{g} \bar{\beta}_3 V_3(t)}{\bar{g}}} \leq \sqrt{\frac{2k_\gamma \underline{g} \bar{\beta}_3 V(t)}{\bar{g}}} \leq \sqrt{2k_\gamma \underline{g} \bar{\beta}_3} \left(\frac{d}{\eta_2 \tilde{c}}\right)^{\frac{1}{1+q}} \end{aligned} \tag{58}$$

with $\bar{\beta}_1 = \max\{\beta_{11}, \cdots, \beta_{1N}\}, \bar{\beta}_2 = \max\{\beta_{21}, \cdots, \beta_{2N}\}, \bar{\beta}_3 = \max\{\beta_{31}, \cdots, \beta_{3N}\}, \bar{g} = \min\left\{\bar{g}_1, \ldots, \bar{g}_N\right\}$.

4 | NUMERICAL SIMULATION

This section provides a numerical simulation of the second-order MASs consisting of four agents to validate the efficiency and feasibility of the proposed distributed finite-time adaptive fault-tolerant consensus protocol. The dynamic behavior of the MASs is represented as follows[35]:

$$\begin{bmatrix} \dot{v}_1 \\ \dot{v}_2 \\ \dot{v}_3 \\ \dot{v}_4 \end{bmatrix} = \begin{bmatrix} g_1 & 0 & 0 & 0 \\ 0 & g_2 & 0 & 0 \\ 0 & 0 & g_3 & 0 \\ 0 & 0 & 0 & g_4 \end{bmatrix} \left(\begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{bmatrix} + \begin{bmatrix} \rho_1 \\ \rho_2 \\ \rho_3 \\ \rho_4 \end{bmatrix} + \begin{bmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \\ \phi_4 \end{bmatrix} \right) + \begin{bmatrix} f_{d1} \\ f_{d2} \\ f_{d3} \\ f_{d4} \end{bmatrix} \tag{59}$$

where $g_i = 5 + 0.01e^{-|v_i|} (i = 1, 2, 3, 4)$ denotes the control gain matrix, the state-independent deception attacks ρ_1, ρ_2, ρ_3 and ρ_4 are set as $\rho_1 = 0.1e^{-x_1-x_2}x_1, \rho_2 = 0.1e^{-x_1-x_2^2}x_2^2, \rho_3 = 0.1e^{-x_2-x_3^2}x_3^2, and\, \rho_4 = 0.1e^{-x_3-x_4-x_1}x_4$, the actuator bias faults ϕ_1, ϕ_2, ϕ_3, and ϕ_4 are given by $\phi_1 = 0.4|\sin(10t)|$, $\phi_2 = 0.3|\cos(10t)|$, $\phi_3 = 0.1|\cos(10t)|$ and $\phi_4 = 0.15|\sin(10t)|$, the external disturbances f_{d1}, f_{d2}, f_{d3} and f_{d4} are described as $f_{d1} = 0.48\sin(0.6t)$, $f_{d2} = 0.49\cos(0.5t)$, $f_{d3} = 0.58\cos(0.5t)$ and $f_{d4} = 0.58\sin(0.4t)$, and the uncertainty $h_{d1}(t)$, h_{d2}, h_{d3} and h_{d4} are set as $h_{d1} = 0.52\cos(0.6t)$, $h_{d2} = 0.51\sin(0.5t)$, $h_{d3} = 0.42\sin(0.5t)$, $h_{d4} = 0.42\cos(0.4t)$. The topology graph of MASs with four individual agents is illustrated in Figure 2, where the topology is undirected and each edge is assigned the weighting coefficient of 1.

The simulation aims to validate whether the MASs of four agents can achieve consensus convergence within the finite time by applying the designed distributed finite-time adaptive fault-tolerant consensus control protocol. The simulation involves the following parameter settings: control parameters $c_1 = 20$, and $c_2 = 4$. The parameters α_i, β_i, q and τ_i in the updated adaptive law are set to $\alpha_i = \beta_i = 0.01$. $q = 0.9$ and $\tau_i = 0.5$ $(i = 1, 2, 3, 4)$. The state-coupled nonlinear function $\bar{\psi}_i$ $(i = 1, 2, 3, 4)$ is limited as $\bar{\psi}_1 = |x_1|, \bar{\psi}_2 = |x_2^2|, \bar{\psi}_3 = |x_3^2|$, and $\bar{\psi}_4 = |x_4|$, respectively.

Fig. 3 depicts the changing trends in external disturbances, uncertainties, and lumped uncertainties within the second-order MASs over the time interval of 0 to 6s. Fig. 4 and Fig. 5 respectively depict the position trajectories and velocity trajectories of four agents from their initial states to the final states. Obviously, it is derived that under the proposed finite-time adaptive fault-tolerant consensus control protocol, the position states and velocity states of the four agents can achieve consensus convergence in the finite time (around 0.64s). It indicates that despite the existence of external disturbances, uncertainties and actuator bias faults in the physical layer and deception attacks in the cyber layer, the MASs can still achieve stability and finite-time consensus within the limited time bound. Fig. 6 depicts the distributed neighborhood error of four agents, with the error converging to zero in about 0.64 seconds. It suggests that all agents can achieve distributed coordination, thus validating the feasibility of the proposed adaptive fault-tolerant consensus control algorithm.

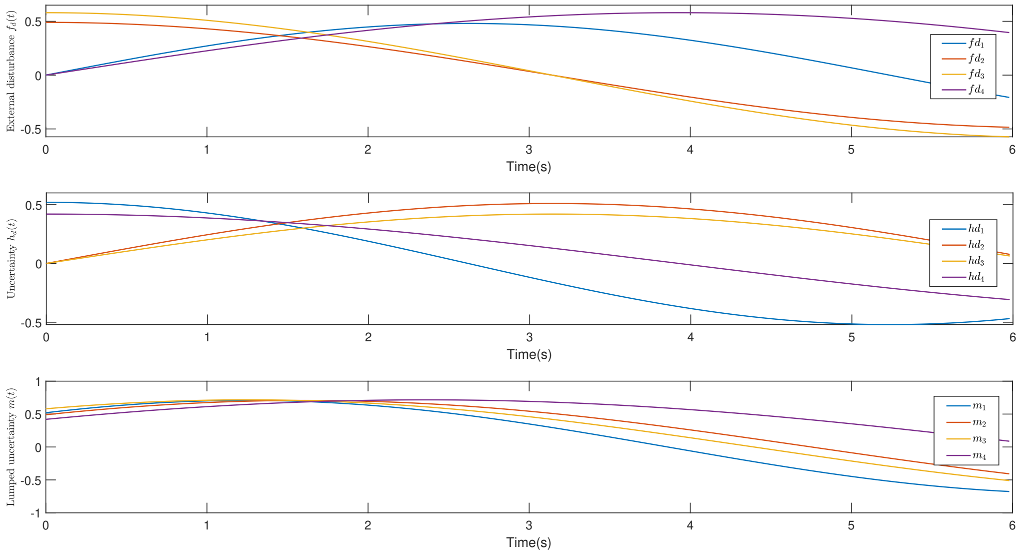

Figure 3 The changing trends of the external disturbance f_{di}, the uncertainty h_{di} and the lumped uncertainty m_i

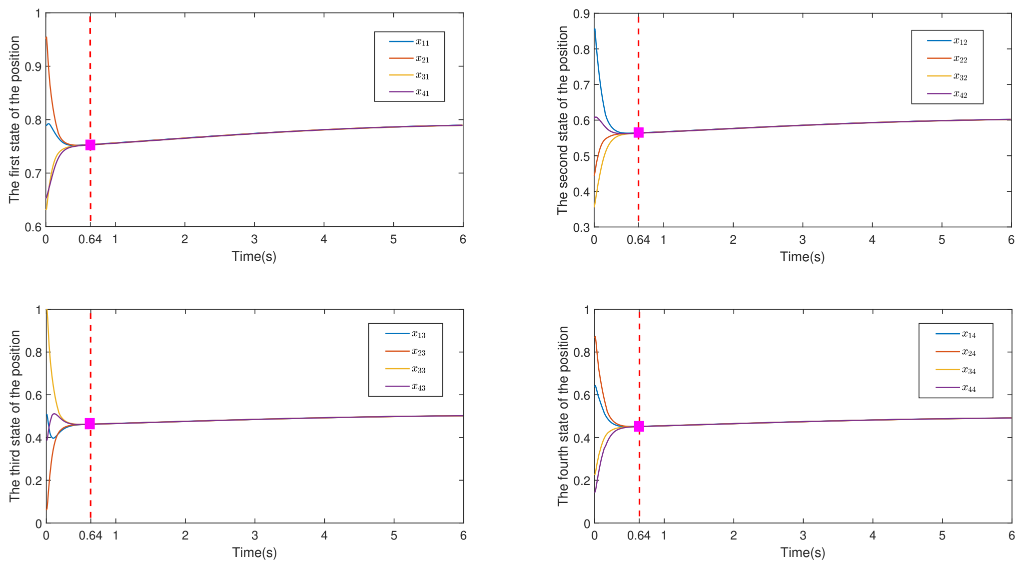

Figure 4 The finite-time position trajectories of four agents x_i, $i = 1, 2, 3, 4$

Fig. 7 displays the parameter estimation of the adaptive parameters ω_i, $\bar{\phi}_i$ and θ_i $(i = 1, 2, 3, 4)$, respectively. These three sub-figures all show the estimated parameters $\hat{\omega}_i$, $\hat{\bar{\phi}}_i$ and $\hat{\theta}_i$ finally grow to certain constant bounds. The adaptive parameter $\hat{\omega}_i$ is

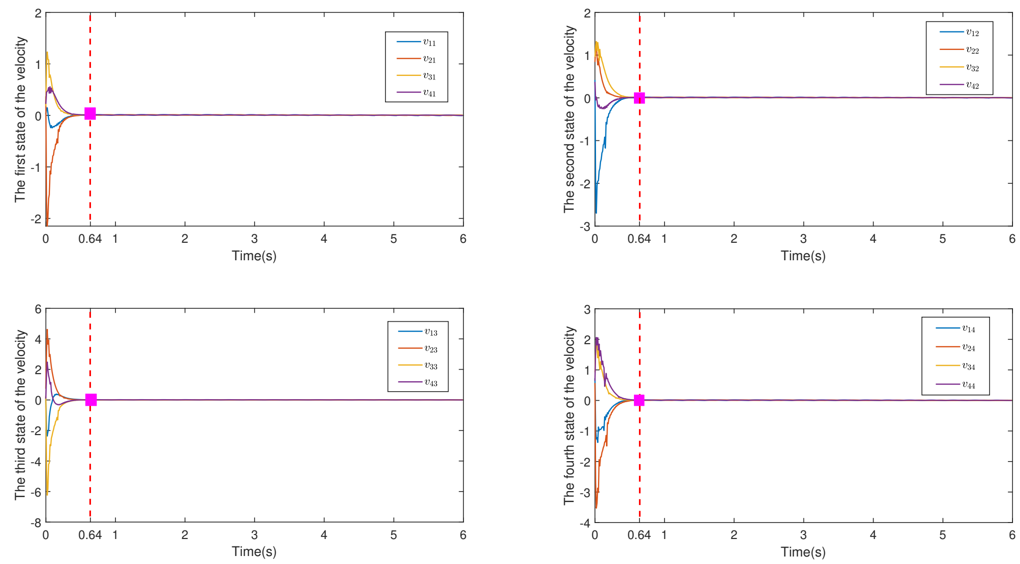

Figure 5 The finite-time velocity trajectories of four agents υ_i, $i = 1, 2, 3, 4$

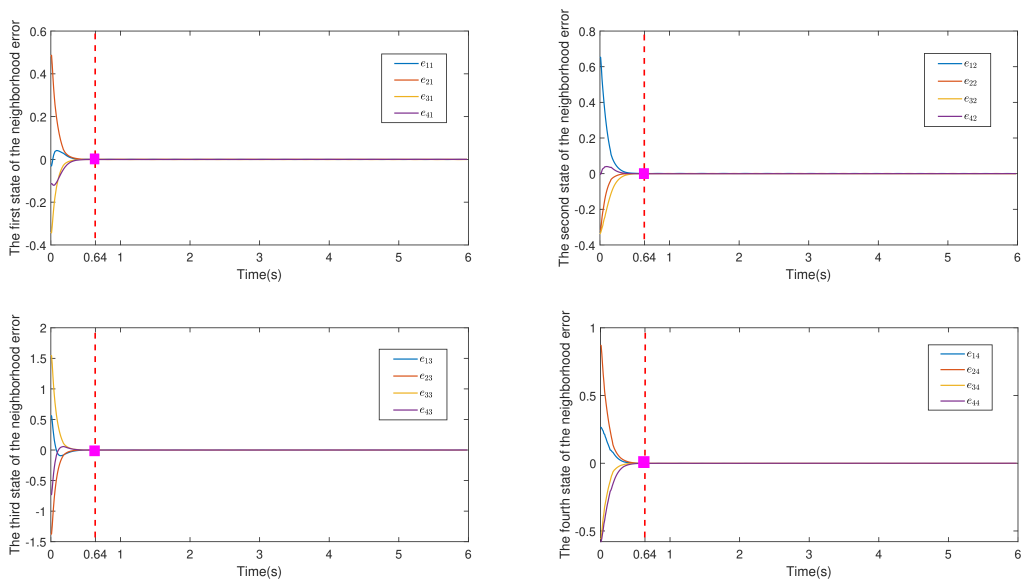

Figure 6 The finite-time neighbor error of four agents e_i, $i = 1, 2, 3, 4$

employed to mitigate the adverse effects of deception attacks, and its bounded nature elucidates the proposed anti-attack fault-tolerant consensus protocol against bounded deception attacks in MASs. The adaptive parameters $\hat{\bar{\phi}}_i$ and $\hat{\theta}_i$ are applied to adjust the consensus deviation arising from actuator bias faults and the lumped uncertainty, and the boundness of these parameters also suggests that bounded unknown actuator faults and lumped uncertainty within a finite time can be effectively managed. All of these charts showcase the limitation of the estimated parameters $\hat{\omega}_i$, $\hat{\bar{\phi}}_i$, and $\hat{\theta}_i$. This not only implies that the general parameter estimation errors ultimately converge within the finite time to certain bounds but also underscores the capability of adaptive techniques to overcome challenges in approximating unknown bounds associated with control gains, external disturbances, uncertainties, actuator bias faults, and time-varying weighted attack coefficients.

Moreover, a finite-time setting bound, denoted as T^*, is introduced as a performance metric to further assess the efficacy of the proposed adaptive fault-tolerant consensus control protocol, as illustrated in Table 1. Analysis of the data in Table 1 reveals

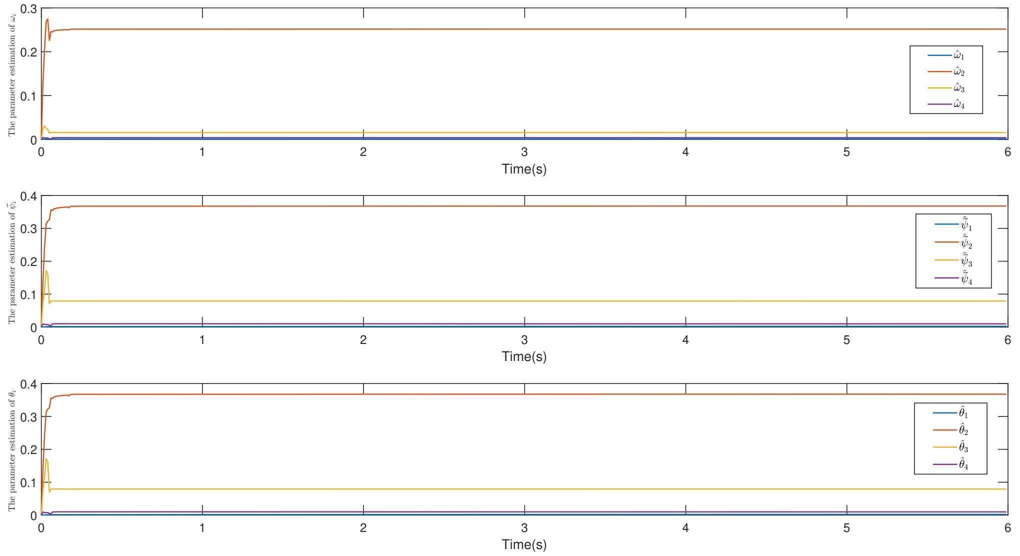

Figure 7 The estimations of three adaptive parameters. Top: $\hat{\omega}_i$, middle: $\hat{\hat{\phi}}_i$, and bottom $\hat{\theta}_i$, $i = 1, 2, 3, 4$

that the presence of uncertainty, along with the magnitudes of parameters τ and q, can impact the magnitude of the finite-time setting bound T^*. Specifically, the introduction of uncertainty typically adds complexity to the MASs, potentially resulting in extended convergence time. The influence of control parameters on convergence time is evident: under the constant parameter q conditions, an increase in parameter τ leads to shorter convergence time. Similarly, with the constant parameter τ, appropriately reducing the numerical value of parameter q also results in shorter convergence time.

Table 1 The variation of finite-time setting bound T^*.

With or without uncertainty	q	τ	T^*
without	0.9	0.5	0.58
with	0.9	0.5	0.64
with	0.9	5	0.56
with	0.85	5	0.45

5 | CONCLUSION

This study proposes the distributed finite-time adaptive fault-tolerant consensus control strategy to ensure the finite-time consensus of the second-order MASs in the presence of deceptive attacks in the cyber hierarchy, as well as actuator bias faults and lumped uncertainties in the physical hierarchy. To guarantee the convergence of the velocity errors and neighborhood errors within the finite time period, the novel power iterator-based virtual control with an adaptive technique is employed. Then, the comprehensive robustness to lumped uncertainties, resilience to attacks, and tolerance to faults are achieved during the finite-time convergence phase, and the convergence speed is improved with the generalized and bounded parameter estimation errors. Finally, the numerical simulation example demonstrates the feasibility and effectiveness of the proposed finite-time adaptive fault-tolerant consensus algorithm in a distributed fashion. In future research, deep investigations delve into the improved finite-time convergence of the homogeneous/heterogeneous MASs with both the effective tolerance and resistance to simultaneous actuator/sensor faults and random/deception attacks.

ORCID

Chun Liu https://orcid.org/0000-0002-9294-6519

References

1. Kada B, Khalid M, Shaikh M. Distributed cooperative control of autonomous multi-agent UAV systems using smooth control. *J Syst Eng Electron* 2020;31(6):1297–1307.

2. Zong C, Ji Z, Tian L, Zhang Y. Distributed multi-robot formation control based on bipartite consensus with time-varying delays. *IEEE Access* 2019;7:144790-144798.

3. Liang S, Wang F, Chen Z, Liu Z. Formation control for discrete-time heterogeneous multi-agent systems. *Int J Robust Nonlinear Control* 2022;32(10):5848-5865.

4. Amirkhani A, Barshooi A. Consensus in multi-agent systems: a review. *Artif Intell Rev* 2022;55(5):3897-3935.

5. Zheng, K, Fan H, Liu L, Cheng Z. Triggered finite-time consensus of first-order multi-agent systems with input saturation. *IET Contr Theory Appl* 2022;16(4):464-474.

6. Zhu J, Wen G, Li B. Decentralized adaptive formation control based on sliding mode strategy for a class of second-order nonlinear unknown dynamic multi-agent systems. *Int J Adapt Control Signal Process* 2022;36(4) :1045-1058.

7. Sun J, Wang Z. Event-triggered consensus control of high-order multi-agent systems with arbitrary switching topologies via model partitioning approach. *Neurocomputing* 2020;413:14-22.

8. Yu L, Liu Y. Asymptotic consensus via switching adaptive for nonlinear multi-agent systems subject to atypical disturbances. *Int J Adapt Control Signal Process* 2021;35:877–891.

9. Wang G, Wang C, Ding Z, Ji Y. Distributed consensus of nonlinear multi-agent systems with mismatched uncertainties and unknown high-frequency gains. *IEEE Trans Circuits Syst II-Express Briefs* 2021;68(3):938-942.

10. Ali MS, Tajudeen MM, Rajchakit G, Priya B, Thakur GK. Adaptive event-triggered pinning synchronization control for complex networks with random saturation subject to hybrid cyber-attacks. *Int J Adapt Control Signal Process* 2023:1-22.

11. He W, Xu W, Ge X, Han Q, Du W, Qian F. Secure control of multiagent systems against malicious attacks: A brief survey. *IEEE Trans Ind Inform* 2022;18(6):3595-3608.

12. Zhang Z, Wang C, Cai X. Consensus control of higher-order nonlinear multi-agent systems with unknown control directions. *Neurocomputing* 2019;359:122-129.

13. Gu X, Zhou W, Wu Y, Wu W, Yang G. Distributed bipartite consensus control for multi-agent systems with actuator faults under undirected topology. *Proceedings of 2021 Chinese Intelligent Systems Conference: Volume II* 2022;359-367.

14. Khalili M, Zhang X, Polycarpou M, Parisini T, Cao Y. Distributed adaptive fault-tolerant control of uncertain multi-agent systems. *Automatica* 2018;87:142-151.

15. Zhao L, Yang G. Cooperative adaptive fault-tolerant control for multi-agent systems with deception attacks. *J. Franklin Inst.* 2020;357 (6):3419–3433.

16. He W, Mo Z, Han Q, Qian F. Secure impulsive synchronization in Lipschitz-type multi-agent systems subject to deception attacks. *IEEE-CAA J Automatica Sin* 2020;7(5):1326–1334.

17. Wen G, Zhai X, Peng Z, Rahmani A. Fault-tolerant secure consensus tracking of delayed nonlinear multi-agent systems with deception attacks and uncertain parameters via impulsive control. *Commun Nonlinear Sci Numer Simul* 2020;82:105043.

18. He W, Gao X, Zhong W, Qian F. Secure impulsive synchronization control of multi-agent systems under deception attacks. *Inf Sci* 2018;459:354-368.

19. Yu L, Liu Y. Asymptotic consensus via switching adaptive for nonlinear multi-agent systems subject to atypical disturbances. *IET Control Theory Appl* 2021;35:877–891.

20. Yu Y, Guo C, Yu H. Finite-time plos-based integral sliding-mode adaptive neural path following for unmanned surface vessels with unknown dynamics and disturbances. *IEEE Trans Autom Sci Eng* 2019;16(4):1500-1511.

21. Liao R, Han L, Dong X, Li Q, Ren Z. Finite-time formation-containment tracking for second-order multi-agent systems with a virtual leader of fully unknown input. *Neurocomputing* 2020;415:234-246.

22. Guan S, Pang H, Li Y. Finite-time adaptive fuzzy consensus control for nonlinear multi-agent systems under switching-directed topologies. *IET Control Theory Appl* 2022;36(12):3105-3123.

23. Wang F, Zhang Y, Zhang L, Zhang L, Huang Y. Finite-time consensus of stochastic nonlinear multi-agent systems. *Int J Fuzzy Syst* 2020;22(1): 77-88.

24. Wang Y, Song Y, Krstic M, Wen C. Fault-tolerant finite time consensus for multiple uncertain nonlinear mechanical systems under single-way directed communication interactions and actuation failures *Automatica* 2016;63:374–383.

25. Sakthivel R, Parivallal A, Kaviarasan B, Lee H, Lim Y. Finite-time consensus of Markov jumping multi-agent systems with time-varying actuator faults and input saturation. *ISA Trans* 2018;83:89–99.

26. Dong G, Li H, Ma H, Lu R. Finite-time consensus tracking neural network ftc of multi-agent systems. *IEEE Trans Neural Netw Learn Syst* 2021;32(2):653–662.

27. Song S, Park J, Zhang B, Song X. Adaptive NN finite-time resilient control for nonlinear time-delay systems with unknown false data injection and actuator faults. *IEEE Trans Neural Netw Learn Syst* 2021;32(10):5416-5428.

28. Olfati-Saber R, Murray R. Consensus problems in networks of agents with switching topology and time-delays. *IEEE Trans Autom Control* 2004;49(9):1520–1533.

29. Bhat S, Bernstein D. Continuous finite-time stabilization of the translational and rotational double integrators. *IEEE Trans Autom Control* 1998;43(5):678-682.

30. Qian C, Lin W. Non-lipschitz continuous stabilizers for nonlinear systems with uncontrollable unstable linearization. *Syst Control Lett* 2001;42(3):185–200.

31. Hardy G, Littlewood J, Polya G. Inequalities. *World Publishing Corporation.* 2004.

32. Wang Y, Song Y, and Lewis F L. Robust adaptive fault-tolerant control of multiagent systems with uncertain nonidentical dynamics and undetectable actuation failures. *IEEE Transactions on Industrial Electronics* 2015;62(6):3978–3988.

33. u J and Wang J. Fixed-time coordinated tracking for second-order multi-agent systems with bounded input uncertainties. *Systems & Control Letters* 2016;93:1–12.

34. Polycarpou M, Ioannou P. A robust adaptive nonlinear control design. *Automatica* 1996;32(3):423-427.

35. Li T, Liu C, Wang X. Cooperative adaptive fault-tolerant control for multi-agent systems with deception attacks. *2021 40th Chinese Control Conference* 2021; 4516-4521.