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Research article

Resilient containment control of fractional-order multi-agent systems with uncertainty and time delay via non-fragile approaches

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Abstract: This paper investigated resilient containment control ($\mathcal{CC}$)-based consensus in fractional-order multi-agent systems ($\mathcal{FOMAS}s$) subject to parametric uncertainties, communication time delays, and external disturbances. A non-fragile ($\mathcal{NF}$) distributed control protocol was proposed to accommodate controller perturbations and delay variations simultaneously. By integrating fractional calculus, algebraic graph theory, and an improved Razumikhin technique, we derived concise algebraic conditions ensuring all followers asymptotically converge to the convex hull that the leaders form under worst-case uncertainties. The results cover non-delayed and delayed cases and are expressed as simple, verifiable matrix inequalities. At the end, we provide examples to demonstrate the feasibility of the proposed method, including a numerical case study, and we illustrate the applicability of the developed theoretical results through designing a controller for electronic circuits.

Keywords: Caputo fractional derivative; containment control; Razumikhin method; uncertain parameters; non-fragile; time delay; resilient control
Mathematics Subject Classification: 26A33, 34B15, 34K37

1. Introduction

Cooperative behaviors such as consensus control [1–6], formation control [7, 8], and containment control [9–12] play a central role in the deployment of large-scale systems. These systems include networks of autonomous robots, groups of sensors, and a variety of cyber-physical infrastructures. These behaviours support contemporary applications in several fields, such as logistics planning, autonomous vehicle coordination, distributed surveillance, and smart grid regulation [13]. The $\mathcal{MAS}s$ framework is at the heart of these kinds of systems, ensuring that agents act coordinately by having local interactions that follow graph-theoretic principles. Research has focused in consensus control as a basic common behaviour in the $\mathcal{MAS}s$ framework [14, 15], which has been extensively investigated in diverse contexts of dynamical systems, encompassing linear systems [16], nonlinear systems [17], and systems characterized by delays [18]. Most research has predominantly concentrated on $\mathcal{MAS}s$ with either single leadership [19] or the absence of a leader [20]. A primary goal in $\mathcal{MAS}s$ is consensus control, meaning that agents are all set to the same value, usually the average of their starting states. During this period, there are many leaders in the network, and the aim changes to containment control. This ensures that all of the follower agents move closer and closer to the convex hull produced by the leader agents [21, 22]. For situations with more than one leader, $\mathcal{CC}$ procedures are built in a way that is comparable to consensus protocols. The research into $\mathcal{CC}$ has been motivated by several practical applications, particularly scenarios where heterogeneous vehicle fleets must manoeuvre between target sites. In contrast, only specific vehicles are equipped with sensors for obstacle detection. Some sensor-equipped cars act as leaders, while others act as followers. Leaders create a mobile safe area by finding dangerous places where obstacles are placed. Therefore, as long as all of the followers remain within the dynamically constructed safe zone maintained by the leaders, the formation can safely reach its target [23–26].

Recent studies in complex network synchronization and multi-agent control have explored diverse strategies and stability criteria. Zhao et al. [27] proposed a hybrid event-triggered prescribed-time synchronization method for piecewise smooth dynamic networks, introducing an exponential-type function for fast, parameter-independent convergence and validating the approach via LMIs on Chua's circuits. In [28], an observer-based fixed-time topology identification and synchronization scheme for multi-weighted networks was presented, employing quantized pinning controllers and beta-function-based stability criteria with demonstrations on chaotic circuits and micro-grids. Other works have addressed fault-tolerant consensus, such as [29], which developed an adaptive consensus protocol for uncertain nonlinear second-order $\mathcal{MAS}s$ with actuator faults and implemented it on electronic circuits, and [30], which used neural-network-based adaptive observers to achieve resilient consensus under network faults and actuator failures. Learning-based resilience has also been explored in [31], where online estimation of unknown leader dynamics enabled distributed fault-tolerant control in heterogeneous $\mathcal{MAS}s$. Although these contributions enhance synchronization, consensus, and fault-tolerant control, they pertain to integer-order dynamics, concentrate on specific topologies, or handle discrete difficulties such as failures or topology identification.

In the past few decades, there has been a growing interest in fractional calculus, since its non-local operators are ideal for modelling complex physical processes that involve memory [25, 32–35]. Additionally, the $\mathcal{CC}$ of $\mathcal{FOMAS}s$ has attracted significant interest; frequency-theoretic approaches [36] exhibit advanced evolution in the linear context, while Lyapunov-functional techniques [37] are prevalent in the examination of their nonlinear counterpart. Despite these improvements, real-world applications of $\mathcal{FOMAS}s$ still present significant problems that can seriously affect confinement performance. In networked systems, communication delays are unavoidable and can cause problems that make the system less stable and may even cause consensus failure. However, there exists a substantial body of literature on the linear delayed $\mathcal{FOMAS}s$ [38, 39], employing widely utilized methodologies such as Razumikhin algorithms [21] and Laplace transforms [40]. In addition, real-world $\mathcal{FOMAS}s$ has modelling flaws, including parameter variations, outside disturbances, and dynamics that are not modelled. These inaccuracies can have a significant impact on containment stability. The issue of controller fragility, wherein minor fluctuations in applied control gains, caused by hardware defects, constrained arithmetic precision, or external factors, can render the entire multi-agent network unstable, is of comparable significance. Although the current literature mainly emphasizes nominal system designs, it largely neglects non-fragile control methodologies capable of maintaining containment efficacy under parametric uncertainty and implementation mistakes in the controller. The simultaneous occurrence of these challenges, including time delays [17, 41], system uncertainties [19, 42, 43], and controller fragility [44], within the nonlinear $\mathcal{FOMAS}s$ framework presents a significant analytical problem that remains inadequately addressed in the theoretical literature (see Table 1). As a result, there is a strong requirement to provide unified methods that simultaneously address both strong $\mathcal{CC}$ design and non-fragile implementation attributes. The above research gap inspires the pursuit of theoretical and practical solutions to the issue of $\mathcal{CC}$ in delayed nonlinear $\mathcal{FOMAS}s$, ensuring resilient performance under actual operational settings.

Table 1. Comparative analysis of related works in $\mathcal{FOMAS}s$.

methods	leader-follower	$\mathcal{CC}$	uncertainty	time-delay	non-fragile	external disturbance
[11]	✓	✓	×	✓	×	×
[12]	✓	✓	×	×	×	×
[17]	✓	×	✓	✓	×	×
[21]	✓	✓	×	×	×	×
[23]	✓	✓	×	×	×	✓
[24]	✓	✓	×	✓	×	×
[44]	✓	×	×	×	✓	×
our model	✓	✓	✓	✓	✓	✓

This study addresses the formidable challenge of developing cohesive control frameworks for nonlinear $\mathcal{FOMAS}s$ constrained by various practical limitations. Some of the main problems are: (i) fractional-order dynamics with non-local memory effects that make it hard to analyze stability, (ii) network-induced delays that slow down performance, (iii) parametric uncertainties as well as external disturbances that affect containment, and (iv) controller fragility due to implementation errors, which is a problem that is often ignored. Most existing research addresses these challenges individually. In contrast, this work develops new analytical methods that handle all difficulties at once, resulting in straightforward stability conditions that are practical and scalable. Finally, the feasibility of the proposed method is verified through some numerical examples, and the applicability of the developed theoretical result is demonstrated by designing a controller for electronic circuits.

To address these challenges, this study presents a comprehensive framework for robust $\mathcal{CC}$ of delayed nonlinear $\mathcal{FOMAS}s$ characterized by uncertainty. We find stable conditions for containment by using an improved Razumikhin-type methodology designed for fractional dynamics, along with algebraic graph theory and matrix inequality approaches. The method works with both non-delayed and delayed protocols; therefore, it can handle a wide range of network conditions and implementation limits. Theoretical prerequisites ensure robust containment while simplifying the complex dynamics associated with fractional-order and delay effects.

Motivated by the previously mentioned problems and research shortcomings, this work investigates the $\mathcal{CC}$ problem with uncertainty for delayed nonlinear $\mathcal{NFFOMAS}$. The primary contributions of this research have been outlined as follows:

(i) This proposed study concentrates on $\mathcal{NFFOMAS}$, providing a coherent and effective methodology for handling the $\mathcal{CC}$ problem under uncertainty, while addressing the challenges associated with fractional-order operators and system delays.
(ii) The integration of classical Lyapunov theory with algebraic graph theory avoids the necessity to examine the analytical intricacies of fractional derivatives. The first-order derivative of the Lyapunov function $W(\tau)$ yields stability requirements that address time delays and disturbances without incorporating fractional calculus.
(iii) The suggested non-fragile control architecture considers controller uncertainties and residual nonlinearities, which guarantees robust containment performance in systems that are not fully characterized.
(iv) The suggested method's feasibility and effectiveness are further illustrated using a fractional-order nonlinear circuit network [45], wherein each agent is depicted by a tunnel diode circuit featuring fractional-order capacitive and inductive components. A distributed cooperative control law has been developed to assure that all follower circuits follow the leader circuit's path, even when there are nonlinearities and external disturbances.

The structure of this paper is organized as follows: Section 2 provides an overview of algebraic graph theory, offers the fundamentals of Caputo fractional derivative, and presents essential lemmas and definitions required for the analysis. Section 3 presents the investigation of the problems and provides the main theoretical results. Numerical examples are described in Section 4 to show the efficacy and validity of the stated findings, including applications to electrical systems. The paper is finally concluded by summarizing the main conclusions and their consequences in Section 5.

2. Preliminaries

This section starts with essential definitions followed by fundamental lemmas that will be utilized in subsequent sections.

Let $\mathfrak{G} = (\mathfrak{V}, \mathfrak{E})$ be a directed weighted graph, where $\mathfrak{V} = \{\iota_1, \iota_2, \ldots, \iota_N\}$ represents the set of nodes and $\mathfrak{E} \subseteq \{(\iota_p, \iota_q) \mid \iota_p, \iota_q \in \mathfrak{V}\}$ denotes the set of directed edges. Each edge $\mathfrak{E}_{pq}$ is an ordered pair (ι_p, ι_q), signifying a directed connection from node ι_q (head) to node ι_p (tail). The neighbor set of a node ι_p is defined as $N_p = \{\iota_q \mid (\iota_q, \iota_p) \in \mathfrak{E}\}$, representing all nodes ι_q that have a directed edge towards ι_p. The weighted adjacency matrix associated with $\mathfrak{G}$ is given by $\mathcal{M} = (m_{pq})_{N\times N}$, where $m_{pq} > 0$ if $(\iota_p, \iota_q) \in \mathfrak{E}$ and $m_{pq} = 0$ otherwise ([13]).

The following describes the Laplacian matrix $\mathcal{H} = \left(h_{pq}\right)_{N\times N}$ of graph $\mathfrak{G}$:

$$\begin{cases} h_{pq} = -m_{pq}, & p \neq q, \\ h_{pp} = \displaystyle\sum_{q=1, q\neq p}^{N} m_{pq}, & p = q. \end{cases}$$

Clearly, $\sum_{q=1}^{N} h_{pq} = 0$ for $p = 1, 2, \ldots, N$.

Definition 2.1. [46] The Caputo fractional derivative of order $0 < \kappa < 1$ for $y(\tau)$, where $u-1 \leq \kappa \leq u$, $u \in \mathbb{N}$, is described as

$$^{C}\mathcal{D}^{\kappa}_{0+}[y(\tau)] = \frac{1}{\Gamma(u-\kappa)} \int_0^{\tau} (\tau-\sigma)^{u-\kappa-1} y^{u}(\sigma) d\sigma.$$

Lemma 2.1. *[47] Let $y(\tau) \in \mathbb{R}^n$ be an absolutely continuous function, $U \in \mathbb{R}^{n\times n}$, and $U > 0$. Further*

$$\frac{1}{2}{}^{C}_{\tau_0}\mathcal{D}^{\kappa}_{\tau}\left(y^{\top}(\tau)Uy(\tau)\right) \leq y^{\top}(\tau)U{}^{C}_{\tau_0}\mathcal{D}^{\kappa}_{\tau}y(\tau), \ \ 0 < \kappa < 1.$$

Suppose $C = \{\phi \mid \phi : [-\sigma, 0] \to \mathbb{R}^n \text{ is continuous}\}$ denote the Banach space endowed with the supremum norm. Consider a fractional system:

$$^{C}_{\tau_0}\mathcal{D}^{\kappa}_{\tau}y(\tau) = h(\tau, y_{\tau}), \quad \tau \geq \tau_0, \tag{2.1}$$

where $0 < \kappa \leq 1$, and $y_{\tau}(\theta) = y(\tau+\theta)$ for $\theta \in [-\sigma, 0]$. The function $h : \mathbb{R}\times$ (bounded subset of C) $\to$ bounded subset of $\mathbb{R}^n$, and satisfies $h(\tau, 0) = 0$.

Lemma 2.2. *[48] Assume $\lambda_1, \lambda_2, \lambda_3$ are positive numbers and a Lyapunov function $W : \mathbb{R}^n \to \mathbb{R}$ satisfies*

$$\lambda_1(\|y\|^2) \leq W(y) \leq \lambda_2(\|y\|^2),$$

and

$$^{C}_{\tau_0}\mathcal{D}^{\kappa}_{\tau}W(y(\tau)) \leq -\lambda_3(\|y\|^2), \quad \forall \quad \tau \geq \tau_0,$$

whenever the inequality

$$W(y(\tau+\theta)) \leq \rho(W(y(\tau))), \quad \theta \in [-\sigma, 0]$$

holds for some $\rho > 1$, then the system (2.1) *is asymptotically stable.*

This work investigates the CC of a delayed nonlinear system $\mathcal{NFFOMAS}$ comprising j followers, denoted by the set $\mathcal{F}_1 = \{1, 2, \ldots, j\}$, and $i-j$ leaders, represented by the set $\mathcal{F}_2 = \{j+1, j+2, \ldots, i\}$. The state $z_p(\tau) \in \mathbb{R}^n$ of the agent p is described by

$$\begin{aligned} ^{C}_{\tau_0}\mathcal{D}^{\kappa}_{\tau}z_p(\tau) = &(\mathcal{M}+\Delta\mathcal{M})z_p(\tau) + (\mathcal{N}+\Delta\mathcal{N})z_p(\tau-\sigma) + g_1\left(\tau, z_p(\tau)\right) + g_2\left(\tau, z_p(\tau-\sigma)\right) \\ &+ u_p(\tau), \quad p = 1, 2, \ldots, i, \end{aligned} \tag{2.2}$$

where $0 < \kappa < 1$, N represents the number of nodes, and the state vector is given by

$$z_p(\tau) = \left(z_{p1}(\tau), z_{p2}(\tau), \ldots, z_{pn}(\tau)\right)^{\top} \in \mathbb{R}^n.$$

Here, $\mathcal{M} \in \mathbb{R}^{n\times n}$ and $\mathcal{N} \in \mathbb{R}^{n\times n}$ are constant system matrices; $\Delta\mathcal{M}$ and $\Delta\mathcal{N}$ denote uncertain matrices such that $\Delta\mathcal{M} = \Omega_1\Psi(\tau)\Omega_2$, $\Delta\mathcal{N} = \Omega_3\Psi(\tau)\Omega_4$, where $\Omega_1, \Omega_2, \Omega_3, \Omega_4$ are known real matrices, and $\Psi(\tau)$ is the unknown time-varying matrix satisfying $\Psi^{\top}(\tau)\Psi(\tau) \leq I$. The functions g_r, $r = 1, 2$ satisfy the subsequent constraint (H1) and $g_r(\tau, 0) = 0$. The term $u_p(\tau)$ represents the control input, which is to be designed accordingly, and $\sigma > 0$ is the time delay.

(H1) Let $d_1, d_2, \ldots, d_{i-j} \geq 0$ with $\sum_{p=1}^{i-j} d_p = 1$. Then there exist constants $\varphi_1, \varphi_2 > 0$ fulfilling the inequality for any $z, \mu_i \in \mathbb{R}^n$,

$$\left\| g_r(\tau, z) - \sum_{p=1}^{i-j} d_p g_r(\tau, \mu_p) \right\| \leq \varphi_r \left\| z - \sum_{p=1}^{i-j} d_p \mu_p \right\|, \quad r = 1, 2. \tag{2.3}$$

(H2) There exists at least one leader with a communication path to every follower, and each leader does not receive messages from any other agent. In view of (H2), $\mathcal{H}$ is of the form

$$\mathcal{H} = \begin{pmatrix} \mathcal{H}_1 & \mathcal{H}_2 \\ 0_{(i-j)\times j} & 0_{(i-j)\times(i-j)} \end{pmatrix}. \tag{2.4}$$

Lemma 2.3. *[24] If (H2) is satisfied, $\mathcal{H}_1$ in* (2.4) *qualifies as an invertible M-matrix, and the matrix $-\mathcal{H}_1^{-1}\mathcal{H}_2 = (h_{pq})_{j\times(i-j)}$ is non-negative with row sums equal to* 1.

Remark 2.1. An undirected communication topology among followers ensures that $\mathcal{H}_1$ is symmetric.

Lemma 2.4. *[17] Let $\kappa_1, \kappa_2 \in \mathbb{R}^n$ and $\kappa_3 > 0$, then inequality $2\kappa_1^\top \kappa_2 \leq \kappa_3 \kappa_1^\top \kappa_1 + \frac{1}{\kappa_3}\kappa_2^\top \kappa_2$ holds.*

Definition 2.2. A set $\mathcal{S} \subset \mathbb{R}^n$ is said to be convex if, for any $u, v \in \mathcal{S}$ and any $\nu \in [0, 1]$, the point $(1 - \nu)u + \nu v$ also belongs to $\mathcal{S}$. The convex hull of a finite set of points $z_1, z_2, \ldots, z_{i-j} \in \mathbb{R}^n$, denoted by $C_0\{z_1, z_2, \ldots, z_{i-j}\}$, is defined as the smallest convex set containing all the points, given by

$$C_0\{z_1, z_2, \ldots, z_{i-j}\} = \left\{ \sum_{p=1}^{i-j} \nu_p z_p \,\middle|\, \nu_p \geq 0, \sum_{p=1}^{i-j} \nu_p = 1 \right\}.$$

The $\mathcal{CC}$ of $\mathcal{NFFOMAS}$ in (2.2) is achieved when all followers asymptotically converge to the convex hull spanned by the leaders.

3. $\mathcal{CC}$ investigation of $\mathcal{NFFOMAS}$ (2.2)

This section presents the $\mathcal{CC}$ analysis of $\mathcal{NFFOMAS}$ (2.2) through non-delayed and delayed communication protocols. Effective algebraic criteria are developed to achieve $\mathcal{CC}$ of $\mathcal{NFFOMAS}$ (2.2) using an enhanced Razumikhin approach, algebraic graph theory, and matrix analysis methods.

In practical $\mathcal{MAS}s$, communication delays are inevitable due to network transmission, processing time, and physical constraints. However, in specific scenarios, agents may communicate instantaneously without significant delays. Therefore, we propose non-delayed and delayed communication protocols to address $\mathcal{CC}$ under different communication conditions.

3.1. $\mathcal{CC}$ investigation through non-delayed communication strategy

The non-delayed communication strategy is constructed by

$$u_p(\tau) = \begin{cases} (\mathcal{K}_1 + \Delta\mathcal{K}_1) \sum\limits_{q\in\mathcal{F}_1\cup\mathcal{F}_2} m_{pq}(z_q(\tau) - z_p(\tau)) + \Delta u_p(\tau), & p \in \mathcal{F}_1, \\ 0, \quad p \in \mathcal{F}_2, \end{cases} \tag{3.1}$$

where $\mathcal{K}_1 \in \mathbb{R}^{n\times n}$ is the gain matrix, $\Delta\mathcal{K}_1 = \Omega_5\Psi(\tau)\Omega_6$, and $\Delta u_p(\tau)$ is the disturbance term. Using (3.1) into (2.2), one has

$$\begin{cases} {}^{C}_{\tau_0}\mathcal{D}^{\kappa}_{\tau} Z_{\mathcal{F}_1}(\tau) &= (\mathcal{I}_j \otimes (\mathcal{M}+\Delta\mathcal{M}))Z_{\mathcal{F}_1}(\tau) + (\mathcal{I}_j \otimes (\mathcal{N}+\Delta\mathcal{N}))Z_{\mathcal{F}_1}(\tau-\sigma) + \mathcal{G}_1\left(\tau, Z_{\mathcal{F}_1}(\tau)\right) \\ &\quad +\mathcal{G}_2\left(\tau, Z_{\mathcal{F}_1}(\tau-\sigma)\right) - (\mathcal{H}_1 \otimes (\mathcal{K}_1 + \Omega_5\Psi\Omega_6))Z_{\mathcal{F}_1}(\tau) \\ &\quad -(\mathcal{H}_2 \otimes (\mathcal{K}_1 + \Omega_5\Psi\Omega_6))Z_{\mathcal{F}_2}(\tau) + \Delta u(\tau), \\ {}^{C}_{\tau_0}\mathcal{D}^{\kappa}_{\tau} Z_{\mathcal{F}_2}(\tau) &= (\mathcal{I}_{i-j} \otimes (\mathcal{M}+\Delta\mathcal{M}))Z_{\mathcal{F}_2}(\tau) + (\mathcal{I}_{i-j} \otimes (\mathcal{N}+\Delta\mathcal{N}))Z_{\mathcal{F}_2}(\tau-\sigma) + \mathcal{G}_1\left(\tau, Z_{\mathcal{F}_2}(\tau)\right) \\ &\quad +\mathcal{G}_2\left(\tau, Z_{\mathcal{F}_2}(\tau-\sigma)\right), \end{cases} \tag{3.2}$$

where $Z_{\mathcal{F}_1} = (z_1^\top(\tau), z_2^\top(\tau), \ldots, z_j^\top(\tau))^\top$, $Z_{\mathcal{F}_2} = (z_{j+1}^\top(\tau), z_{j+2}^\top(\tau), \ldots, z_i^\top(\tau))^\top$, $\mathcal{G}_1(\tau, Z_{\mathcal{F}_1}) = (g_1^\top(\tau, z_1), g_1^\top(\tau, z_2), \ldots, g_1^\top(\tau, z_j))$, $\mathcal{G}_1(\tau, Z_{\mathcal{F}_2}) = (g_1^\top(\tau, z_{j+1}), g_1^\top(\tau, z_{j+2}), \ldots, g_1^\top(\tau, z_i))$, $\mathcal{G}_2(\tau, Z_{\mathcal{F}_1}(\tau-\sigma))$, $\mathcal{G}_2(\tau, Z_{\mathcal{F}_2}(\tau-\sigma))$ signifies the column stack vector of $g_2(\tau, z_p(\tau-\sigma))(p \in F_1)$, $g_2(\tau, z_q(\tau-\sigma))(q \in \mathcal{F}_2)$, respectively.

Let the containment error be defined as $\Xi(\tau) = Z_{\mathcal{F}_1} - (-\mathcal{H}_1^{-1}\mathcal{H}_2 \otimes \mathcal{I}_n)Z_{\mathcal{F}_2}$. According to Lemma 2.3, the matrix $-\mathcal{H}_1^{-1}\mathcal{H}_2 \otimes \mathcal{I}_n$ is non-negative, whose row sums equal unity. Consequently, convergence of all followers to the convex hull spanned by the leaders occurs when $\lim_{\tau\to\infty} \|\Xi(\tau)\| = 0$, thereby establishing CC for $\mathcal{NFFOMAS}$ (2.2). The corresponding error dynamics are described by:

$$\begin{aligned} {}^{C}_{\tau_0}\mathcal{D}^{\kappa}_{\tau}\Xi(\tau) = {} & (\mathcal{I}_j \otimes (\mathcal{M}+\Delta\mathcal{M}))\Xi(\tau) + (\mathcal{I}_j \otimes (\mathcal{N}+\Delta\mathcal{N}))\Xi(\tau-\sigma) - (\mathcal{H}_1 \otimes (\mathcal{K}_1 + \Omega_5\Psi\Omega_6))\Xi(\tau) \\ & + \Delta u(\tau) + \mathcal{G}_1(\tau, Z_{\mathcal{F}_1}) + (\mathcal{H}_1^{-1}\mathcal{H}_2 \otimes \mathcal{I}_n)\mathcal{G}_1(\tau, Z_{\mathcal{F}_2}) + \mathcal{G}_2(\tau, Z_{\mathcal{F}_2}(\tau-\sigma)) \\ & + (\mathcal{H}_1^{-1}\mathcal{H}_2 \otimes \mathcal{I}_n)\mathcal{G}_2(\tau, Z_{\mathcal{F}_2}(\tau-\sigma)). \end{aligned} \tag{3.3}$$

Theorem 3.1. *Assume that conditions (H1) and (H2) are satisfied. Then, the CC of $\mathcal{NFFOMAS}$ (2.2) under protocol (3.1) will be achieved if there exist three positive scalars θ_r for $r = 1, 2, 3$, along with a symmetric matrix $\mathbb{Y} > 0$, such that:*

$$\begin{pmatrix} \Lambda_{11} & \mathcal{I}_j \otimes \mathbb{Y}(\mathcal{N} + \Omega_3\Psi\Omega_4) \\ \mathcal{I}_j \otimes (\mathcal{N} + \Omega_3\Psi\Omega_4)^\top\mathbb{Y} & \mathcal{I}_j \otimes \left(\frac{\varphi_2^2}{\theta_2}\mathcal{I}_n - \theta_3\mathbb{Y}\right) \end{pmatrix} < 0, \tag{3.4}$$

where $\Lambda_{11} = \mathcal{I}_j \otimes \left(\mathbb{Y}\mathcal{M} + \mathcal{M}^\top\mathbb{Y} + 2\mathbb{Y}\Omega_1\Psi\Omega_2 + \frac{\varphi_1^2}{\theta_1}\mathcal{I}_n + (\theta_1+\theta_2)\mathbb{Y}^2 + \theta_3\mathbb{Y} + (\mathbb{Y}+\mathbb{Y}^\top)\frac{\Delta u(\tau)}{\beta}\right) - \mathcal{H}_1 \otimes (\mathbb{Y}(\mathcal{K}_1 + \Omega_5\Psi\Omega_6) + (\mathcal{K}_1 + \Omega_5\Psi\Omega_6)^\top\mathbb{Y})$.

Proof. Choose the Lyapunov function

$$W(\tau) = \Xi^\top(\tau)(\mathcal{I}_j \otimes \mathbb{Y})\Xi(\tau).$$

By differentiating $W(\tau)$ along the solution trajectories of system (3.3) and applying Lemma 2.1, we obtain:

$$\begin{aligned} {}^{C}_{\tau_0}\mathcal{D}^{\kappa}_{\tau}W(\tau) &\le 2\Xi^\top(\tau)(\mathcal{I}_j \otimes \mathbb{Y}){}^{C}_{\tau_0}\mathcal{D}^{\kappa}_{\tau}\Xi(\tau) \\ &= 2\Xi^\top(\tau)(\mathcal{I}_j \otimes \mathbb{Y})\Big[(\mathcal{I}_j \otimes (\mathcal{M}+\Delta\mathcal{M}))\Xi(\tau) + (\mathcal{I}_j \otimes (\mathcal{N}+\Delta\mathcal{N}))\Xi(\tau-\sigma) \\ &\quad - (\mathcal{H}_1 \otimes (\mathcal{K}_1 + \Delta\mathcal{K}_1))\Xi(\tau) + \Delta u(\tau) + \mathcal{G}_1(\tau, Z_{\mathcal{F}_1}) + (\mathcal{H}_1^{-1}\mathcal{H}_2 \otimes \mathcal{I}_n)\mathcal{G}_1(\tau, Z_{\mathcal{F}_2}) \\ &\quad + \mathcal{G}_2(\tau, Z_{\mathcal{F}_2}(\tau-\sigma)) + (\mathcal{H}_1^{-1}\mathcal{H}_2 \otimes \mathcal{I}_n)\mathcal{G}_2(\tau, Z_{\mathcal{F}_2}(\tau-\sigma))\Big]. \end{aligned} \tag{3.5}$$

For any $\theta_1, \theta_2 > 0$, one has

$$\begin{aligned}
&2\Xi^\top(\tau)(\mathcal{I}_j \otimes \mathbb{Y})\left[\mathcal{G}_1(\tau, Z_{\mathcal{F}_1}) + (\mathcal{H}_1^{-1}\mathcal{H}_2 \otimes \mathcal{I}_n)\mathcal{G}_1(\tau, Z_{\mathcal{F}_2})\right] \\
&\leq \frac{1}{\theta_1}\left[\mathcal{G}_1(\tau, Z_{\mathcal{F}_1}) + (\mathcal{H}_1^{-1}\mathcal{H}_2 \otimes \mathcal{I}_n)\mathcal{G}_1(\tau, Z_{\mathcal{F}_2})\right]^\top \left[\mathcal{G}_1(\tau, Z_{\mathcal{F}_1}) + (\mathcal{H}_1^{-1}\mathcal{H}_2 \otimes \mathcal{I}_n)\mathcal{G}_1(\tau, Z_{\mathcal{F}_2})\right] \\
&\quad + \theta_1\Xi^\top(\tau)(\mathcal{I}_j \otimes \mathbb{Y}^2)\Xi(\tau),
\end{aligned} \tag{3.6}$$

and

$$\begin{aligned}
&2\Xi^\top(\tau)(\mathcal{I}_j \otimes \mathbb{Y})\left[\mathcal{G}_2(\tau, Z_{\mathcal{F}_1}(\tau-\sigma)) + (\mathcal{H}_1^{-1}\mathcal{H}_2 \otimes \mathcal{I}_n)\mathcal{G}_2(\tau, Z_{\mathcal{F}_2}(\tau-\sigma))\right] \\
&\leq \frac{1}{\theta_2}\left[\mathcal{G}_2(\tau, Z_{\mathcal{F}_1}(\tau-\sigma)) + (\mathcal{H}_1^{-1}\mathcal{H}_2 \otimes \mathcal{I}_n)\mathcal{G}_2(\tau, Z_{\mathcal{F}_2}(\tau-\sigma))\right]^\top [\mathcal{G}_2(\tau, Z_{\mathcal{F}_1}(\tau-\sigma)) \\
&\quad + (\mathcal{H}_1^{-1}\mathcal{H}_2 \otimes \mathcal{I}_n)\mathcal{G}_2(\tau, Z_{\mathcal{F}_2}(\tau-\sigma))] + \theta_2\Xi^\top(\tau)(\mathcal{I}_j \otimes \mathbb{Y}^2)\Xi(\tau).
\end{aligned} \tag{3.7}$$

In view of (2.3), we have

$$\begin{aligned}
&\left[\mathcal{G}_r(\tau, Z_{\mathcal{F}_1}) - (-\mathcal{H}_1^{-1}\mathcal{H}_2 \otimes \mathcal{I}_n)\mathcal{G}_r(\tau, Z_{\mathcal{F}_2})\right]^\top \left[\mathcal{G}_r(\tau, Z_{\mathcal{F}_1}) - (-\mathcal{H}_1^{-1}\mathcal{H}_2 \otimes \mathcal{I}_n)\mathcal{G}_r(\tau, Z_{\mathcal{F}_2})\right] \\
&= \left(\left[g_r(\tau, z_1) - \sum_{\mu=1}^{i-j} h_{1\mu} g_r(\tau, z_{j+\mu})\right]^\top, \ldots, \left[g_r(\tau, z_j) - \sum_{\mu=1}^{i-j} h_{j\mu} g_r(\tau, z_{j+\mu})\right]^\top\right) \\
&\quad (\times)\left(\left[g_r(\tau, z_1) - \sum_{\mu=1}^{i-j} h_{1\mu} g_r(\tau, z_{j+\mu})\right]^\top, \ldots, \left[g_r(\tau, z_j) - \sum_{\mu=1}^{i-j} h_{j\mu} g_r(\tau, z_{j+\mu})\right]^\top\right)^\top \\
&\leq \varphi_r^2 (Z_{\mathcal{F}_1} - (-\mathcal{H}_1^{-1}\mathcal{H}_2 \otimes \mathcal{I}_n)Z_{\mathcal{F}_2})^\top (Z_{\mathcal{F}_1} - (-\mathcal{H}_1^{-1}\mathcal{H}_2 \otimes \mathcal{I}_n)Z_{\mathcal{F}_2}) \\
&= \varphi_r^2 \Xi^\top(\tau)\Xi(\tau), \ r = 1, 2.
\end{aligned} \tag{3.8}$$

From (3.5)–(3.8) and Lemma 2.4, one has

$$\begin{aligned}
{}_{\tau_0}^{C}\mathcal{D}_\tau^\kappa W(\tau) \leq\ & \Xi^\top\left[\mathcal{I}_j \otimes (\mathbb{Y}\mathcal{M} + \mathcal{M}^\top\mathbb{Y} + 2\mathbb{Y}\Omega_1\Psi\Omega_2)\right]\Xi(\tau) + \Xi^\top(\tau)[\mathcal{I}_j \otimes \mathbb{Y}(\mathcal{N} + \Omega_3\Psi\Omega_4)]\Xi(\tau-\sigma) \\
&+ \Xi^\top(\tau-\sigma)[\mathcal{I}_j \otimes \mathbb{Y}(\mathcal{N} + \Omega_3\Psi\Omega_4)]\Xi(\tau) + 2\Xi^\top(\tau)(\mathcal{I}_j \otimes \mathbb{Y})\frac{\Delta u(\tau)}{\beta}\Xi(\tau) \\
&- \Xi^\top(\tau)\left[\mathcal{H}_1 \otimes (\mathbb{Y}(\mathcal{K}_1 + \Omega_5\Psi\Omega_6) + (\mathcal{K}_1 + \Omega_5\Psi\Omega_6)^\top\mathbb{Y})\right]\Xi(\tau) \\
&+ \frac{\varphi_1^2}{\theta_1}\Xi^\top(\tau)(\mathcal{I}_j \otimes \mathcal{I}_n)\Xi(\tau) + \theta_1\Xi^\top(\tau)(\mathcal{I}_j \otimes \mathbb{Y}^2)\Xi(\tau) + \theta_2\Xi^\top(\tau)(\mathcal{I}_j \otimes \mathbb{Y}^2)\Xi(\tau) \\
&+ \frac{\varphi_2^2}{\theta_2}\Xi^\top(\tau-\sigma)(\mathcal{I}_j \otimes \mathcal{I}_n)\Xi(\tau-\sigma).
\end{aligned}$$

By using the Lemma 2.2, we have

$$0 \leq \rho\Xi^\top(\tau)(\mathcal{I}_j \otimes \mathbb{Y})\Xi(\tau) - \Xi^\top(\tau-\sigma)(\mathcal{I}_j \otimes \mathbb{Y})\Xi(\tau-\sigma). \tag{3.9}$$

For any $\theta_3 > 0$, one has

$${}_{\tau_0}^{C}\mathcal{D}_\tau^\kappa W(\tau)$$

$$
\begin{aligned}
&\leq \Xi^{\top}\left[\mathcal{I}_j \otimes (\mathbb{Y}\mathcal{M} + \mathcal{M}^{\top}\mathbb{Y} + 2\mathbb{Y}\Omega_1\Psi\Omega_2)\right]\Xi(\tau) + \Xi^{\top}(\tau)[\mathcal{I}_j \otimes \mathbb{Y}(\mathcal{N} + \Omega_3\Psi\Omega_4)]\Xi(\tau-\sigma) \\
&\quad + \Xi^{\top}(\tau-\sigma)[\mathcal{I}_j \otimes \mathbb{Y}(\mathcal{N} + \Omega_3\Psi\Omega_4)]\Xi(\tau) + \Xi^{\top}(\tau)(\mathcal{I}_j \otimes (\mathbb{Y} + \mathbb{Y}^{\top}))\frac{\Delta u(\tau)}{\beta}\Xi(\tau) \\
&\quad - \Xi^{\top}(\tau)\left[\mathcal{H}_1 \otimes (\mathbb{Y}(\mathcal{K}_1 + \Omega_5\Psi\Omega_6) + (\mathcal{K}_1 + \Omega_5\Psi\Omega_6)^{\top}\mathbb{Y})\right]\Xi(\tau) \\
&\quad + \frac{\varphi_1^2}{\theta_1}\Xi^{\top}(\tau)(\mathcal{I}_j \otimes \mathcal{I}_n)\Xi(\tau) + \theta_1\Xi^{\top}(\tau)(\mathcal{I}_j \otimes \mathbb{Y}^2)\Xi(\tau) + \theta_2\Xi^{\top}(\tau)(\mathcal{I}_j \otimes \mathbb{Y}^2)\Xi(\tau) \\
&\quad + \frac{\varphi_2^2}{\theta_2}\Xi^{\top}(\tau-\sigma)(\mathcal{I}_j \otimes \mathcal{I}_n)\Xi(\tau-\sigma) + \theta_3\left[\rho\Xi^{\top}(\tau)(\mathcal{I}_j \otimes \mathbb{Y})\Xi(\tau) - \Xi^{\top}(\tau-\sigma)(\mathcal{I}_j \otimes \mathbb{Y})\Xi(\tau-\sigma)\right] \\
&= \xi^{\top}(\tau)\begin{pmatrix} \Lambda_{11}^{*} & \mathcal{I}_j \otimes \mathbb{Y}(\mathcal{N} + \Omega_3\Psi\Omega_4) \\ \mathcal{I}_j \otimes (\mathcal{N} + \Omega_3\Psi\Omega_4)^{\top}\mathbb{Y} & \mathcal{I}_j \otimes \left(\frac{\varphi_2^2}{\theta_2}\mathcal{I}_n - \theta_3\mathbb{Y}\right) \end{pmatrix}\xi(\tau),
\end{aligned}
$$

where $\xi(\tau) = (\Xi^{\top}(\tau), \Xi^{\top}(\tau-\sigma))^{\top}$, $\Lambda_{11}^{*} = \mathcal{I}_j \otimes \left(\mathbb{Y}\mathcal{M} + \mathcal{M}^{\top}\mathbb{Y} + 2\mathbb{Y}\Omega_1\Psi\Omega_2 + \frac{\varphi_1^2}{\theta_1}\mathcal{I}_n + (\theta_1 + \theta_2)\mathbb{Y}^2 + \theta_3\rho\mathbb{Y} + (\mathbb{Y} + \mathbb{Y}^{\top})\frac{\Delta u(\tau)}{\beta}\right) - \mathcal{H}_1 \otimes (\mathbb{Y}(\mathcal{K}_1 + \Omega_5\Psi\Omega_6) + (\mathcal{K}_1 + \Omega_5\Psi\Omega_6)^{\top}\mathbb{Y})$, and $\beta = \Xi(\tau)$.

Inequality (3.4) shows that when $\lambda > 0$, is sufficiently small, and $\rho = \lambda + 1$, one has

$$
\begin{pmatrix} \Lambda_{11}^{*} & \mathcal{I}_j \otimes \mathbb{Y}(\mathcal{N} + \Omega_3\Psi\Omega_4) \\ \mathcal{I}_j \otimes (\mathcal{N} + \Omega_3\Psi\Omega_4)^{\top}\mathbb{Y} & \mathcal{I}_j \otimes \left(\frac{\varphi_2^2}{\theta_2}\mathcal{I}_n - \theta_3\mathbb{Y}\right) \end{pmatrix} < 0.
$$

Therefore, based on Lemma 2.2, the error system (3.3) is asymptotically stable, implying that

$$
\|Z_{\mathcal{F}_1}(\tau) - (-\mathcal{H}_1^{-1}\mathcal{H}_2 \otimes \mathcal{I}_n)Z_{\mathcal{F}_2}(\tau)\| \to 0 \quad \text{as} \quad \tau \to \infty,
$$

which confirms that the $\mathcal{CC}$ of $\mathcal{NFFOMAS}$ (2.2) under protocol (3.1) is achieved. □

Note 3.1. Moreover, from Lemma 2.4, by applying the following inequality in the previous proof:

$$
\begin{aligned}
&2\Xi^{\top}(\tau)[\mathcal{I}_j \otimes \mathbb{Y}(\mathcal{N} + \Omega_3\Psi\Omega_4)]\Xi(\tau-\sigma) \\
&\leq \theta_4\Xi^{\top}(\tau)\Xi(\tau) + \frac{1}{\theta_4}\Xi^{\top}(\tau-\sigma)(\mathcal{I}_j \otimes \mathbb{Y}(\mathcal{N} + \Omega_3\Psi\Omega_4)(\mathcal{N} + \Omega_3\Psi\Omega_4)^{\top}\mathbb{Y})\Xi(\tau-\sigma),
\end{aligned}
$$

where $\theta_4 > 0$, the subsequent corollary can be directly obtained.

Corollary 3.1. *Assuming that all assumptions of Theorem 3.1 are met, the $\mathcal{CC}$ of $\mathcal{NFFOMAS}$* (2.2) *under protocol* (3.1) *can be achieved provided that the following inequality is satisfied:*

$$
\begin{pmatrix} \overline{\Lambda}_{11} & 0 \\ 0 & \mathcal{I}_j \otimes \left(\frac{\varphi_2^2}{\theta_2}\mathcal{I}_n - \theta_3\mathbb{Y} + \frac{1}{\theta_4}\mathbb{Y}(\mathcal{N} + \Omega_3\Psi\Omega_4)(\mathcal{N} + \Omega_3\Psi\Omega_4)^{\top}\mathbb{Y}\right) \end{pmatrix} < 0, \tag{3.10}
$$

where $\overline{\Lambda}_{11} = \mathcal{I}_j \otimes \left(\mathbb{Y}\mathcal{M} + \mathcal{M}^{\top}\mathbb{Y} + 2\mathbb{Y}\Omega_1\Psi\Omega_2 + \left(\frac{\varphi_1^2}{\theta_1} + \theta_4\right)\mathcal{I}_n + (\theta_1 + \theta_2)\mathbb{Y}^2 + \theta_3\mathbb{Y} + (\mathbb{Y} + \mathbb{Y}^{\top})\frac{\Delta u(\tau)}{\beta}\right) - \mathcal{H}_1 \otimes (\mathbb{Y}(\mathcal{K}_1 + \Omega_5\Psi\Omega_6) + (\mathcal{K}_1 + \Omega_5\Psi\Omega_6)^{\top}\mathbb{Y})$*, and* $\theta_4 > 0$.

3.2. CC investigation through delayed communication strategy

The delayed communication strategy is constructed by

$$u_p(\tau) = \begin{cases} (\mathcal{K}_2 + \Delta\mathcal{K}_2) \sum\limits_{q \in \mathcal{F}_1 \cup \mathcal{F}_2} m_{pq}(z_q(\tau - \sigma) - z_p(\tau - \sigma)) + \Delta u_p(\tau), \quad p \in \mathcal{F}_1, \\ 0, \quad p \in \mathcal{F}_2, \end{cases} \tag{3.11}$$

where $\mathcal{K}_2 \in \mathbb{R}^{n \times n}$ is the gain matrix, $\Delta\mathcal{K}_2 = \Omega_7\Psi(\tau)\Omega_8$, and $\Delta u_p(\tau)$ is the disturbance term. Using (3.11) into (2.2), one has

$$\begin{cases} {}^C_{\tau_0}\mathcal{D}^\kappa_\tau Z_{\mathcal{F}_1}(\tau) &= (\mathcal{I}_j \otimes (\mathcal{M} + \Delta\mathcal{M}))Z_{\mathcal{F}_1}(\tau) + (\mathcal{I}_j \otimes (\mathcal{N} + \Delta\mathcal{N}))Z_{\mathcal{F}_1}(\tau - \sigma) + \mathcal{G}_1(\tau, Z_{\mathcal{F}_1}(\tau)) \\ & \quad + \mathcal{G}_2(\tau, Z_{\mathcal{F}_1}(\tau - \sigma)) - (\mathcal{H}_1 \otimes (\mathcal{K}_2 + \Omega_7\Psi\Omega_8))Z_{\mathcal{F}_1}(\tau - \sigma) \\ & \quad - (\mathcal{H}_2 \otimes (\mathcal{K}_2 + \Omega_7\Psi\Omega_8))Z_{\mathcal{F}_2}(\tau - \sigma) + \Delta u(\tau), \\ {}^C_{\tau_0}\mathcal{D}^\kappa_\tau Z_{\mathcal{F}_2}(\tau) &= (\mathcal{I}_{i-j} \otimes (\mathcal{M} + \Delta\mathcal{M}))Z_{\mathcal{F}_2}(\tau) + (\mathcal{I}_{i-j} \otimes (\mathcal{N} + \Delta\mathcal{N}))Z_{\mathcal{F}_2}(\tau - \sigma) + \mathcal{G}_1(\tau, Z_{\mathcal{F}_2}(\tau)) \\ & \quad + \mathcal{G}_2(\tau, Z_{\mathcal{F}_2}(\tau - \sigma)). \end{cases} \tag{3.12}$$

The corresponding error dynamics are described by:

$$\begin{aligned} {}^C_{\tau_0}\mathcal{D}^\kappa_\tau \Xi(\tau) = &(\mathcal{I}_j \otimes (\mathcal{M} + \Delta\mathcal{M}))\Xi(\tau) + (\mathcal{I}_j \otimes (\mathcal{N} + \Delta\mathcal{N}))\Xi(\tau - \sigma) \\ &- (\mathcal{H}_1 \otimes (\mathcal{K}_2 + \Omega_7\Psi\Omega_8))\Xi(\tau - \sigma) + \Delta u(\tau) + \mathcal{G}_1(\tau, Z_{\mathcal{F}_1}) + (\mathcal{H}_1^{-1}\mathcal{H}_2 \otimes \mathcal{I}_n)\mathcal{G}_1(\tau, Z_{\mathcal{F}_2}) \\ &+ \mathcal{G}_2(\tau, Z_{\mathcal{F}_2}(\tau - \sigma)) + (\mathcal{H}_1^{-1}\mathcal{H}_2 \otimes \mathcal{I}_n)\mathcal{G}_2(\tau, Z_{\mathcal{F}_2}(\tau - \sigma)). \end{aligned} \tag{3.13}$$

The subsequent theorem can thus be established.

Theorem 3.2. *Assume that conditions (H1) and (H2) are satisfied. Then, the CC of $\mathcal{NFFOMAS}$* (2.2) *under protocol* (3.11) *will be achieved if there exist three positive scalars θ_r for $r = 1, 2, 3$, along with a symmetric matrix $\mathbb{Y} > 0$, such that:*

$$\mathscr{D} = \begin{pmatrix} \widetilde{\Lambda}_{11} & \begin{matrix} \mathcal{I}_j \otimes \mathbb{Y}(\mathcal{N} + \Omega_3\Psi\Omega_4) \\ -\mathcal{H}_1 \otimes \mathbb{Y}(\mathcal{K}_2 + \Omega_7\Psi\Omega_8) \end{matrix} \\ \begin{matrix} \mathcal{I}_j \otimes (\mathcal{N} + \Omega_3\Psi\Omega_4)^\top\mathbb{Y} \\ -\mathcal{H}_1 \otimes (\mathcal{K}_2 + \Omega_7\Psi\Omega_8)^\top\mathbb{Y} \end{matrix} & \mathcal{I}_j \otimes \left(\frac{\varphi_2^2}{\theta_2}\mathcal{I}_n - \theta_3\mathbb{Y}\right) \end{pmatrix} < 0, \tag{3.14}$$

where $\widetilde{\Lambda}_{11} = \mathcal{I}_j \otimes \left(\mathbb{Y}\mathcal{M} + \mathcal{M}^\top\mathbb{Y} + 2\mathbb{Y}\Omega_1\Psi\Omega_2 + \frac{\varphi_1^2}{\theta_1}\mathcal{I}_n + (\theta_1 + \theta_2)\mathbb{Y}^2 + \theta_3\mathbb{Y} + (\mathbb{Y} + \mathbb{Y}^\top)\frac{\Delta u(\tau)}{\beta}\right)$.

Proof. Choose the Lyapunov function

$$W(\tau) = \Xi^\top(\tau)(\mathcal{I}_j \otimes \mathbb{Y})\Xi(\tau).$$

By differentiating $W(\tau)$ along the solution trajectories of system (3.3) and applying Lemma 2.1, we obtain:

$$\begin{aligned} {}^C_{\tau_0}\mathcal{D}^\kappa_\tau W(\tau) &\leq 2\Xi^\top(\tau)(\mathcal{I}_j \otimes \mathbb{Y}){}^C_{\tau_0}\mathcal{D}^\kappa_\tau \Xi(\tau) \\ &= 2\Xi^\top(\tau)(\mathcal{I}_j \otimes \mathbb{Y})\Big[(\mathcal{I}_j \otimes (\mathcal{M} + \Delta\mathcal{M}))\Xi(\tau) + (\mathcal{I}_j \otimes (\mathcal{N} + \Delta\mathcal{N}))\Xi(\tau - \sigma) \\ &\quad - (\mathcal{H}_1 \otimes (\mathcal{K}_2 + \Delta\mathcal{K}_2))\Xi(\tau - \sigma) + \Delta u(\tau) + \mathcal{G}_1(\tau, Z_{\mathcal{F}_1}) + (\mathcal{H}_1^{-1}\mathcal{H}_2 \otimes \mathcal{I}_n)\mathcal{G}_1(\tau, Z_{\mathcal{F}_2}) \\ &\quad + \mathcal{G}_2(\tau, Z_{\mathcal{F}_2}(\tau - \sigma)) + (\mathcal{H}_1^{-1}\mathcal{H}_2 \otimes \mathcal{I}_n)\mathcal{G}_2(\tau, Z_{\mathcal{F}_2}(\tau - \sigma))\Big]. \end{aligned} \tag{3.15}$$

From (3.6)–(3.8) and (3.15), one has

$$
\begin{aligned}
{}_{\tau_0}^{C}\mathcal{D}_{\tau}^{\kappa}W(\tau) \le\ & \Xi^{\top}\left[\mathcal{I}_j\otimes(\mathbb{Y}\mathcal{M}+\mathcal{M}^{\top}\mathbb{Y}+2\mathbb{Y}\Omega_1\Psi\Omega_2)\right]\Xi(\tau)+\Xi^{\top}(\tau)[\mathcal{I}_j\otimes\mathbb{Y}(\mathcal{N}+\Omega_3\Psi\Omega_4)]\Xi(\tau-\sigma)\\
&+\Xi^{\top}(\tau-\sigma)[\mathcal{I}_j\otimes\mathbb{Y}(\mathcal{N}+\Omega_3\Psi\Omega_4)]\Xi(\tau)+2\Xi^{\top}(\tau)(\mathcal{I}_j\otimes\mathbb{Y})\frac{\Delta u(\tau)}{\beta}\Xi(\tau)\\
&-\Xi^{\top}(\tau)\left[\mathcal{H}_1\otimes(\mathbb{Y}(\mathcal{K}_2+\Omega_7\Psi\Omega_8)\right]\Xi(\tau-\sigma)-\Xi^{\top}(\tau-\sigma)\left[\mathcal{H}_1\otimes(\mathcal{K}_2+\Omega_7\Psi\Omega_8)^{\top}\mathbb{Y}\right]\Xi(\tau)\\
&+\frac{\varphi_1^2}{\theta_1}\Xi^{\top}(\tau)(\mathcal{I}_j\otimes\mathcal{I}_n)\Xi(\tau)+\theta_1\Xi^{\top}(\tau)(\mathcal{I}_j\otimes\mathbb{Y}^2)\Xi(\tau)+\theta_2\Xi^{\top}(\tau)(\mathcal{I}_j\otimes\mathbb{Y}^2)\Xi(\tau)\\
&+\frac{\varphi_2^2}{\theta_2}\Xi^{\top}(\tau-\sigma)(\mathcal{I}_j\otimes\mathcal{I}_n)\Xi(\tau-\sigma).
\end{aligned}
$$

For any $\theta_3>0$, one has

$$
\begin{aligned}
&{}_{\tau_0}^{C}\mathcal{D}_{\tau}^{\kappa}W(\tau)\\
&\le \Xi^{\top}\left[\mathcal{I}_j\otimes(\mathbb{Y}\mathcal{M}+\mathcal{M}^{\top}\mathbb{Y}+2\mathbb{Y}\Omega_1\Psi\Omega_2)\right]\Xi(\tau)+\Xi^{\top}(\tau)[\mathcal{I}_j\otimes\mathbb{Y}(\mathcal{N}+\Omega_3\Psi\Omega_4)]\Xi(\tau-\sigma)\\
&\quad+\Xi^{\top}(\tau-\sigma)[\mathcal{I}_j\otimes\mathbb{Y}(\mathcal{N}+\Omega_3\Psi\Omega_4)]\Xi(\tau)+\Xi^{\top}(\tau)(\mathcal{I}_j\otimes(\mathbb{Y}+\mathbb{Y}^{\top}))\frac{\Delta u(\tau)}{\beta}\Xi(\tau)\\
&\quad-\Xi^{\top}(\tau)\left[\mathcal{H}_1\otimes(\mathbb{Y}(\mathcal{K}_2+\Omega_7\Psi\Omega_8))\right]\Xi(\tau-\sigma)-\Xi^{\top}(\tau-\sigma)\left[\mathcal{H}_1\otimes((\mathcal{K}_2+\Omega_7\Psi\Omega_8)^{\top}\mathbb{Y})\right]\Xi(\tau)\\
&\quad+\frac{\varphi_1^2}{\theta_1}\Xi^{\top}(\tau)(\mathcal{I}_j\otimes\mathcal{I}_n)\Xi(\tau)+\theta_1\Xi^{\top}(\tau)(\mathcal{I}_j\otimes\mathbb{Y}^2)\Xi(\tau)+\theta_2\Xi^{\top}(\tau)(\mathcal{I}_j\otimes\mathbb{Y}^2)\Xi(\tau)\\
&\quad+\frac{\varphi_2^2}{\theta_2}\Xi^{\top}(\tau-\sigma)(\mathcal{I}_j\otimes\mathcal{I}_n)\Xi(\tau-\sigma)+\theta_3\left[\rho\Xi^{\top}(\tau)(\mathcal{I}_j\otimes\mathbb{Y})\Xi(\tau)-\Xi^{\top}(\tau-\sigma)(\mathcal{I}_j\otimes\mathbb{Y})\Xi(\tau-\sigma)\right]\\
&=\xi^{\top}(\tau)\begin{pmatrix}\widetilde{\Lambda}_{11}^{*} & \begin{matrix}\mathcal{I}_j\otimes\mathbb{Y}(\mathcal{N}+\Omega_3\Psi\Omega_4)\\-\mathcal{H}_1\otimes\mathbb{Y}(\mathcal{K}_2+\Omega_7\Psi\Omega_8)\end{matrix}\\ \begin{matrix}\mathcal{I}_j\otimes(\mathcal{N}+\Omega_3\Psi\Omega_4)^{\top}\mathbb{Y}\\-\mathcal{H}_1\otimes(\mathcal{K}_2+\Omega_7\Psi\Omega_8)^{\top}\mathbb{Y}\end{matrix} & \mathcal{I}_j\otimes\left(\frac{\varphi_2^2}{\theta_2}\mathcal{I}_n-\theta_3\mathbb{Y}\right)\end{pmatrix}\xi(\tau),
\end{aligned}
$$

where $\xi(\tau)=(\Xi^{\top}(\tau),\Xi^{\top}(\tau-\sigma))^{\top}$, $\widetilde{\Lambda}_{11}^{*}=\mathcal{I}_j\otimes\Big(\mathbb{Y}\mathcal{M}+\mathcal{M}^{\top}\mathbb{Y}+2\mathbb{Y}\Omega_1\Psi\Omega_2+\frac{\varphi_1^2}{\theta_1}\mathcal{I}_n+(\theta_1+\theta_2)\mathbb{Y}^2$ $+\theta_3\rho\mathbb{Y}+(\mathbb{Y}+\mathbb{Y}^{\top})\frac{\Delta u(\tau)}{\beta}\Big)$, and $\beta=\Xi(\tau)$.

Inequality (3.14) shows that when $\lambda>0$, is sufficiently small, and $\rho=\lambda+1$, one has

$$
\begin{pmatrix}\widetilde{\Lambda}_{11}^{*} & \begin{matrix}\mathcal{I}_j\otimes\mathbb{Y}(\mathcal{N}+\Omega_3\Psi\Omega_4)\\-\mathcal{H}_1\otimes\mathbb{Y}(\mathcal{K}_2+\Omega_7\Psi\Omega_8)\end{matrix}\\ \begin{matrix}\mathcal{I}_j\otimes(\mathcal{N}+\Omega_3\Psi\Omega_4)^{\top}\mathbb{Y}\\-\mathcal{H}_1\otimes(\mathcal{K}_2+\Omega_7\Psi\Omega_8)^{\top}\mathbb{Y}\end{matrix} & \mathcal{I}_j\otimes\left(\frac{\varphi_2^2}{\theta_2}\mathcal{I}_n-\theta_3\mathbb{Y}\right)\end{pmatrix}<0.
$$

Therefore, based on Lemma 2.2, the error system (3.13) is asymptotically stable, implying that

$$
\|Z_{\mathcal{F}_1}(\tau)-(-\mathcal{H}_1^{-1}\mathcal{H}_2\otimes\mathcal{I}_n)Z_{\mathcal{F}_2}(\tau)\|\to 0\quad\text{as}\quad\tau\to\infty,
$$

which confirms that the $\mathcal{CC}$ of $\mathcal{NFFOMAS}$ (2.2) under protocol (3.11) is achieved. □

Note 3.2. If $\Delta\mathcal{M}=0$, $\mathcal{N}=0$, $\Delta\mathcal{N}=0$, and $g_2(\tau,\cdot)=0$, then $\mathcal{NFFOMAS}$ (2.2) is simplified to

$$
{}_{\tau_0}^{C}\mathcal{D}_{\tau}^{\kappa}z_p(\tau)=\mathcal{M}z_p(\tau)+g_1\left(\tau,z_p(\tau)\right)+u_p(\tau),\quad p=1,2,\dots,i. \tag{3.16}
$$

From Theorems 3.1 and 3.2, the following results can be easily deduced.

Corollary 3.2. *Assume that conditions (H1) and (H2) are satisfied. Then, the CC of* $\mathcal{NFFOMAS}$ (3.16) *under protocol* (3.1) *will be achieved if there exists a positive scalar* θ_1*, along with a symmetric matrix* $\mathbb{Y} > 0$*, such that:*

$$\begin{aligned} &\mathcal{I}_j \otimes \Big(\mathbb{Y}\mathcal{M} + \mathcal{M}^\top\mathbb{Y} + \frac{\varphi_1^2}{\theta_1}\mathcal{I}_n + \theta_1\mathbb{Y}^2 + (\mathbb{Y} + \mathbb{Y}^\top)\frac{\Delta u(\tau)}{\beta}\Big) \\ &-\mathcal{H}_1 \otimes (\mathbb{Y}(\mathcal{K}_1 + \Omega_5\Psi\Omega_6) + (\mathcal{K}_1 + \Omega_5\Psi\Omega_6)^\top\mathbb{Y}) < 0. \end{aligned} \tag{3.17}$$

Corollary 3.3. *Assume that conditions (H1) and (H2) are satisfied. Then, the CC of* $\mathcal{NFFOMAS}$ (3.16) *under protocol* (3.11) *will be achieved if there exist two scalars* $\theta_1 > 0, \theta_3 > 0$*, along with a symmetric matrix* $\mathbb{Y} > 0$*, such that:*

$$\widetilde{\mathscr{D}} = \begin{pmatrix} \widetilde{\Lambda}_{11}^{**} & -\mathcal{H}_1 \otimes \mathbb{Y}(\mathcal{K}_2 + \Omega_7\Psi\Omega_8) \\ -\mathcal{H}_1 \otimes (\mathcal{K}_2 + \Omega_7\Psi\Omega_8)^\top\mathbb{Y} & -\theta_3\left(\mathcal{I}_j \otimes \mathbb{Y}\right) \end{pmatrix} < 0, \tag{3.18}$$

where $\widetilde{\Lambda}_{11}^{**} = \mathcal{I}_j \otimes \Big(\mathbb{Y}\mathcal{M} + \mathcal{M}^\top\mathbb{Y} + \frac{\varphi_1^2}{\theta_1}\mathcal{I}_n + \theta_1\mathbb{Y}^2 + \theta_3\mathbb{Y} + (\mathbb{Y} + \mathbb{Y}^\top)\frac{\Delta u(\tau)}{\beta}\Big)$.

Remark 3.1. Unlike the *CC* results in [24, 37], where the idealized assumptions of perfect controllers and no communication delay are assumed, the current paper drops such restrictions, and makes the explicit assumption that there exist uncertainties in both the system and control matrices that are norm-bounded. A non-fragile delayed control protocol is proposed to overcome actuator degradation and implementation errors and directly incorporate communication delays into the control design. These enhancements significantly improve the robustness and practical applicability of the proposed method, enabling reliable *CC* of $\mathcal{FOMAS}s$ under more realistic and adverse operating conditions.

4. Numerical simulations

We provide some examples to illustrate the effectiveness of the obtained results.

Example 4.1.

The nonlinear system governed by Eqs (2.2) and (3.1) consists of two leaders and three followers, as illustrated in Figure 1.

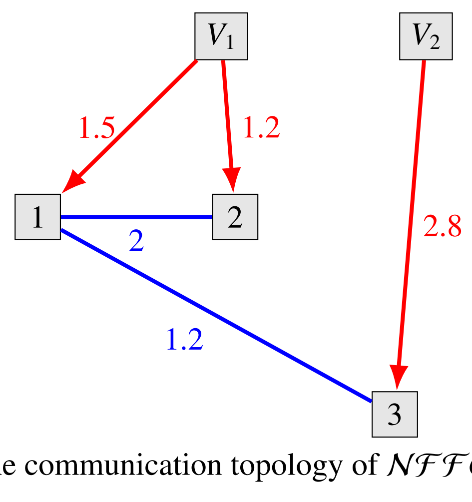

Figure 1. The communication topology of $\mathcal{NFFOMAS}$ (2.2).

Let the matrices $\mathcal{M}$ and $\mathcal{N}$ be defined as follows:

$$\mathcal{M} = \begin{pmatrix} -6 & -0.2 \\ -0.5 & -7 \end{pmatrix} \quad \text{and} \quad \mathcal{N} = \begin{pmatrix} -1 & 1 \\ 1 & 1.5 \end{pmatrix}. \tag{4.1}$$

From Figure 1, we have

$$\mathcal{H}_1 = \begin{pmatrix} 4.7 & -2 & -1.2 \\ -2 & 3.2 & 0 \\ -1.2 & 0 & 4 \end{pmatrix} \quad \text{and} \quad \mathcal{H}_2 = \begin{pmatrix} -1.5 & 0 \\ -1.2 & 0 \\ 0 & -2.8 \end{pmatrix}. \tag{4.2}$$

Define $z_p(\tau) = (z_p^1(\tau), z_p^2(\tau))^\top$, $g_1(\tau, z_p(\tau)) = (0.5\sin z_p^1(\tau), 0.5\sin z_p^2(\tau))^\top$, $g_2(\tau, z_p(\tau)) = (0.3\sin z_p^1(\tau-\sigma), 0.3\sin z_p^2(\tau-\sigma))^\top$, with parameters: $\kappa = 0.65$, and $\sigma = 0.3$; and the following values can be chosen: $\varphi_1 = 1.5$, $\varphi_2 = 0.5$, $\theta_1 = 4$, $\theta_2 = 4$, $\theta_3 = 2, \theta_4 = 4.5$, $\Delta u = 0.3\sin(0.5), \Omega_1 = \begin{pmatrix} 0.1 & 0.05 \end{pmatrix}$, $\Omega_2 = \begin{pmatrix} 0.05 \\ 0.1 \end{pmatrix}$, $\Omega_3 = \begin{pmatrix} 0.2 & 0.1 \end{pmatrix}$, $\Omega_4 = \begin{pmatrix} 0.05 \\ 0.1 \end{pmatrix}$, $\beta = 2$, and $\mathbb{Y} = \mathcal{I}_2$. From these values, one can easily verify the following inequality:

$$\left(\frac{\varphi_2^2}{\theta_2}\mathcal{I}_n - \theta_3\mathbb{Y} + \frac{1}{\theta_4}\mathbb{Y}(\mathcal{N} + \Omega_3\Psi\Omega_4)(\mathcal{N} + \Omega_3\Psi\Omega_4)^\top\mathbb{Y} \right) = \begin{pmatrix} -1.4929 & 0.1224 \\ 0.1224 & -1.1929 \end{pmatrix} < 0.$$

Then, choose $\mathcal{K}_1 = \begin{pmatrix} 1.5 & 0.5 \\ 0.5 & 1.5 \end{pmatrix}$, $\Omega_5 = \begin{pmatrix} 0.2 \\ 0.15 \end{pmatrix}$, and $\Omega_6 = \begin{pmatrix} 0.02 & 0.02 \end{pmatrix}$ in protocol (3.1); after a simple calculation, one obtains

$$\overline{\Lambda}_{11} = \begin{pmatrix} -10.9832 & -5.4329 & 6.0160 & 2.0140 & 3.6096 & 1.2084 \\ -5.4329 & -12.9738 & 2.0140 & 6.0120 & 1,2084 & 3.6072 \\ 6.0160 & 2.0140 & -6.4712 & -3.9224 & 0 & 0 \\ 2.0140 & 6.0120 & -3.9224 & -8.4648 & 0 & 0 \\ 3.6096 & 1.2084 & 0 & 0 & -8.8776 & -4.7280 \\ 1.2084 & 3.6072 & 0 & 0 & -4.7280 & -10.8696 \end{pmatrix} < 0. \tag{4.3}$$

Let us choose the initial states $z_{\mathcal{F}_{21}}(0) = \begin{bmatrix} 0.5 & -0.5 \end{bmatrix}^\top$, $z_{\mathcal{F}_{22}}(0) = \begin{bmatrix} 0.5 & 1 \end{bmatrix}^\top$, $z_{\mathcal{F}_{11}}(0) = \begin{bmatrix} -1 & 1.2 \end{bmatrix}^\top$, $z_{\mathcal{F}_{12}}(0) = \begin{bmatrix} -0.5 & 0.8 \end{bmatrix}^\top$, and $z_{\mathcal{F}_{13}}(0) = \begin{bmatrix} -1.2 & 1 \end{bmatrix}^\top$. Thus, from Corollary 3.1, the $\mathcal{CC}$ of $\mathcal{NFFOMAS}$ (2.2) and (3.1) is achieved, and the state trajectories and error states $\Xi_p(\tau)$ are illustrated in Figures 2 and 3, respectively.

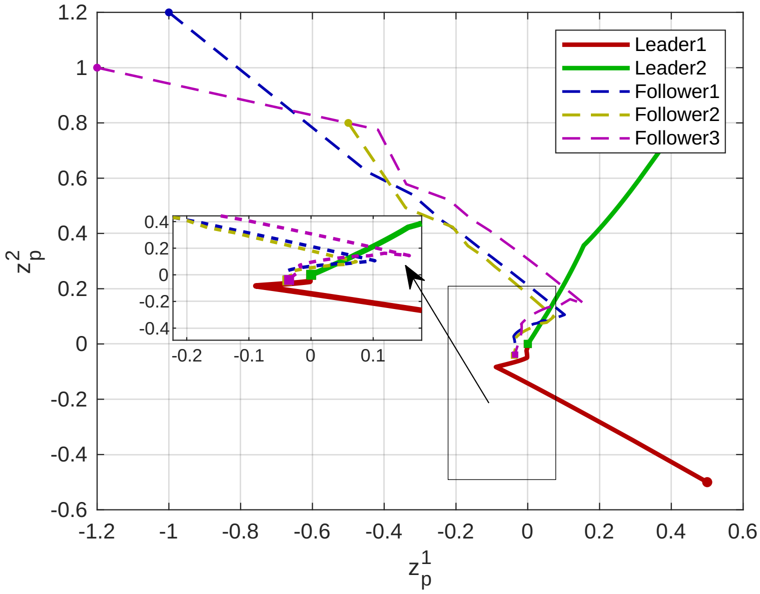

Figure 2. Dynamics of state trajectories of two leaders and three agents.

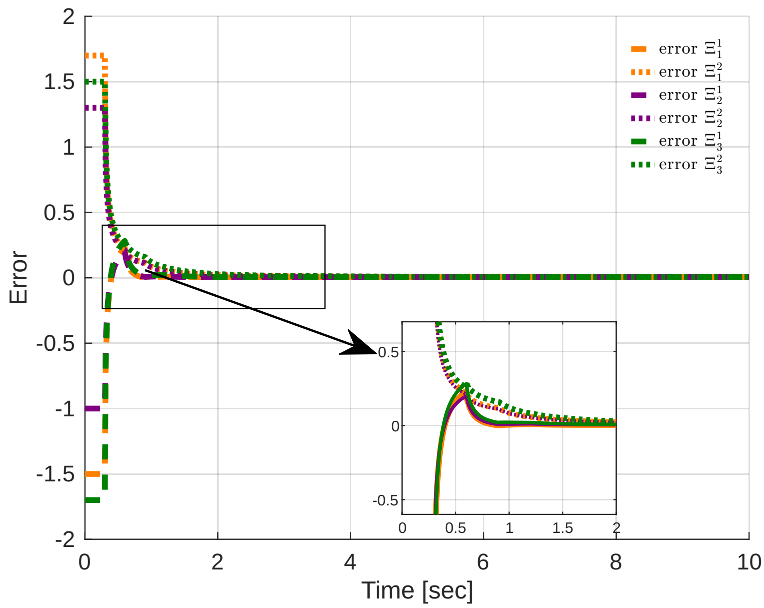

Figure 3. The error state $\Xi_p(\tau)$ of $\mathcal{FOMAS}s$ (2.2) and (3.1).

Example 4.2.

The nonlinear system governed by Eqs (2.2) and (3.11) consists of two leaders and three followers, as illustrated in Figure 1.

Let the matrices $\mathcal{M}$ and $\mathcal{N}$ be defined as follows:

$$\mathcal{M} = \begin{pmatrix} -8 & -0.5 \\ -0.8 & -9 \end{pmatrix} \quad \text{and} \quad \mathcal{N} = \begin{pmatrix} -1 & 1 \\ 1 & 1.5 \end{pmatrix}. \tag{4.4}$$

Define $z_p(\tau) = (z_p^1(\tau), z_p^2(\tau))^\top$, $g_1(\tau, z_p(\tau)) = (\sin z_p^1(\tau), \sin z_p^2(\tau))^\top$, $g_2(\tau, z_p(\tau))$ $=(0.5\sin z_p^1(\tau-\sigma), 0.5\sin z_p^2(\tau-\sigma))^\top$, with parameters: $\kappa = 0.8$ and $\sigma = 0.3$; and the following values can be chosen: $\varphi_1 = 1$, $\varphi_2 = 0.5$, $\theta_1 = 0.5$, $\theta_2 = 1.2$, $\theta_3 = 0.15, \theta_4 = 2$, $\Delta u = 0.1\sin(0.5), \Omega_1 = \begin{pmatrix} 0.005 & 0.01 \end{pmatrix}$, $\Omega_2 = \begin{pmatrix} 0.1 \\ 0.05 \end{pmatrix}, \Omega_3 = \begin{pmatrix} 0.01 & 0.005 \end{pmatrix}$, $\Omega_4 = \begin{pmatrix} 0.1 \\ 0.05 \end{pmatrix}$, $\beta = 2$, and $\mathbb{Y} = \mathcal{I}_2$. Then, choose $\mathcal{K}_2 = \begin{pmatrix} 1.0 & -0.5 \\ 0.5 & -1.0 \end{pmatrix}$, $\Omega_7 = \begin{pmatrix} 0.02 & 0.01 \end{pmatrix}$, and $\Omega_8 = \begin{pmatrix} 0.005 \\ 0.01 \end{pmatrix}$ in protocol (3.11); after a simple calculation, one obtains

$$\mathscr{D} = \begin{pmatrix} -878.0703 & -582.5419 & 441.4399 & 313.6971 & 285.4386 & 204.6754 \\ -582.5419 & -820.9666 & 313.6971 & 407.0972 & 204.6754 & 264.8265 \\ 441.4399 & 313.6971 & -516.1283 & -322.5833 & -51.4368 & -41.1429 \\ 313.6971 & 407.0972 & -322.5833 & -484.7915 & -41.1429 & -51.4203 \\ 285.4386 & 204.6754 & -51.4368 & -41.1429 & -625.8364 & -394.5764 \\ 204.6754 & 264.8265 & -41.1429 & -51.4203 & -394.5764 & -580.7839 \end{pmatrix} < 0. \quad (4.5)$$

Let us choose the initial states $z_{\mathcal{F}_{21}}(0) = \begin{bmatrix} 1 & -1 \end{bmatrix}^\top$, $z_{\mathcal{F}_{22}}(0) = \begin{bmatrix} 1 & 2 \end{bmatrix}^\top$, $z_{\mathcal{F}_{11}}(0) = \begin{bmatrix} -0.5 & 0.5 \end{bmatrix}^\top$, $z_{\mathcal{F}_{12}}(0) = \begin{bmatrix} 0.2 & 0.3 \end{bmatrix}^\top$, and $z_{\mathcal{F}_{13}}(0) = \begin{bmatrix} -0.2 & 0.4 \end{bmatrix}^\top$. Thus, from Theorem 3.2, the *CC* of $\mathcal{NFFOMAS}$ (2.2) and (3.11) is achieved, and the state trajectories and error states $\Xi_p(\tau)$ are illustrated in Figures 4 and 5, respectively.

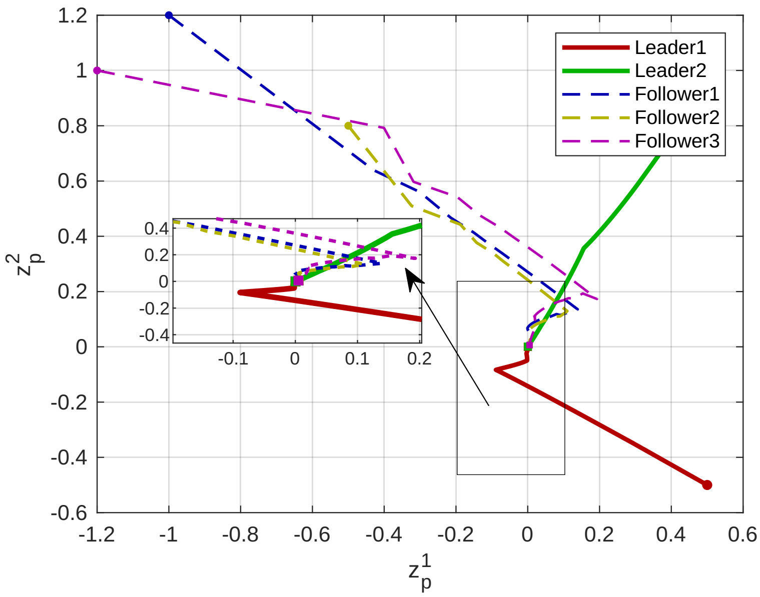

Figure 4. Dynamics of state trajectories of two leaders and three agents.

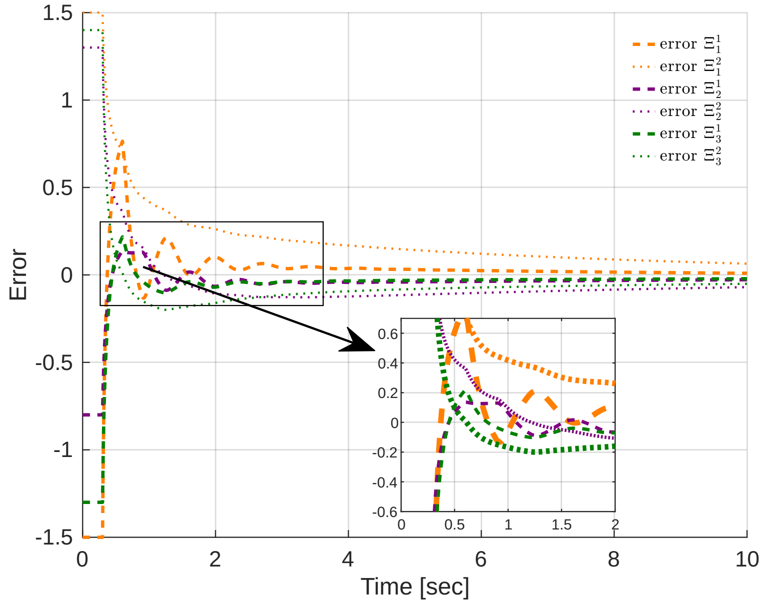

Figure 5. The error state $\Xi_p(\tau)$ of $\mathcal{FOMAS}s$ (2.2) and (3.11).

Example 4.3.

The nonlinear system governed by Eqs (3.16) and (3.1) consists of two leaders and three followers, as illustrated in Figure 1.

Let the matrix $\mathcal{M}$ be defined as follows:

$$\mathcal{M} = \begin{pmatrix} -8 & -1 \\ 1 & -8 \end{pmatrix}. \tag{4.6}$$

Define $z_p(\tau) = (z_p^1(\tau), z_p^2(\tau))^\top$, $g_1(\tau, z_p(\tau)) = (\sin z_p^1(\tau), \sin z_p^2(\tau))^\top$, with parameters: $\kappa = 0.8$, $\varphi_1 = 1$, $\theta_1 = 0.5$, $\Delta u = 0.1\sin(0.1)$, $\beta = 2$, and $\mathbb{Y} = \mathcal{I}_2$. Then, choose $\mathcal{K}_1 = \begin{pmatrix} 1.5 & 0.5 \\ 0.5 & 1.5 \end{pmatrix}$, $\Omega_5 = \begin{pmatrix} 0.2 \\ 0.15 \end{pmatrix}$, and $\Omega_6 = \begin{pmatrix} 0.02 & 0.02 \end{pmatrix}$ in protocol (3.1); after a simple calculation, one obtains

$$\begin{aligned}
&\mathcal{I}_j \otimes \Big(\mathbb{Y}\mathcal{M} + \mathcal{M}^\top\mathbb{Y} + \frac{\varphi_1^2}{\theta_1}\mathcal{I}_n + \theta_1\mathbb{Y}^2 + (\mathbb{Y} + \mathbb{Y}^\top)\frac{\Delta u(\tau)}{\beta}\Big) \\
&-\mathcal{H}_1 \otimes (\mathbb{Y}(\mathcal{K}_1 + \Omega_5\Psi\Omega_6) + (\mathcal{K}_1 + \Omega_5\Psi\Omega_6)^\top\mathbb{Y}) \\
&= \begin{pmatrix} -27.4233 & -4.7329 & 6.0160 & 2.0140 & 3.6096 & 1.2084 \\ -4.7329 & -27.4139 & 2.0140 & 6.0120 & 1.2084 & 3.6072 \\ 6.0160 & 2.0140 & -22.8669 & -3.2224 & 0 & 0 \\ 2.0140 & 6.0120 & -3.2224 & -22.8605 & 0 & 0 \\ 3.6096 & 1.2084 & 0 & 0 & -25.2733 & -4.0280 \\ 1.2084 & 3.6072 & 0 & 0 & -4.0280 & -25.2653 \end{pmatrix} < 0.
\end{aligned}$$

Let us choose the initial states $z_{\mathcal{F}_{21}}(0) = \begin{bmatrix} 1 & -1 \end{bmatrix}^\top$, $z_{\mathcal{F}_{22}}(0) = \begin{bmatrix} 1 & 2 \end{bmatrix}^\top$, $z_{\mathcal{F}_{11}}(0) = \begin{bmatrix} -2 & 2.5 \end{bmatrix}^\top$, $z_{\mathcal{F}_{12}}(0) = \begin{bmatrix} -1 & 1.5 \end{bmatrix}^\top$, and $z_{\mathcal{F}_{13}}(0) = \begin{bmatrix} -2.5 & 2 \end{bmatrix}^\top$. Thus, from Corollary 3.2, the

$\mathcal{CC}$ of $\mathcal{NFFOMAS}$ (3.16) and (3.1) is achieved, and the state trajectories and error states $\Xi_p(\tau)$ are illustrated in Figures 6 and 7, respectively.

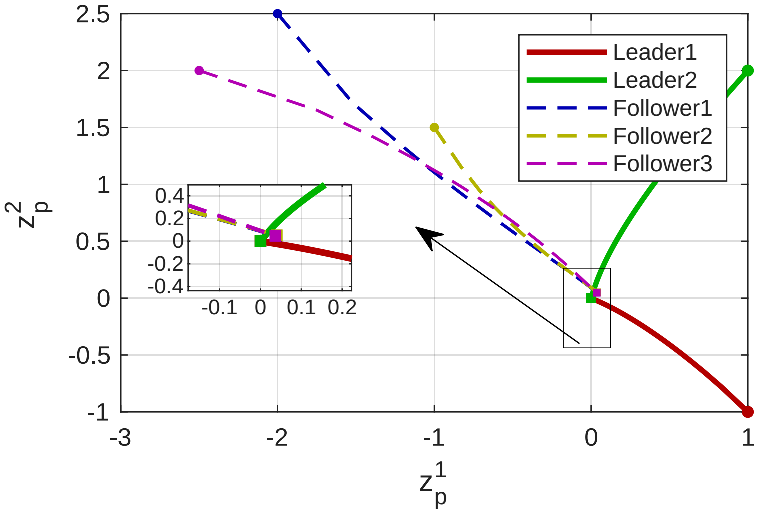

Figure 6. Dynamics of state trajectories of two leaders and three agents.

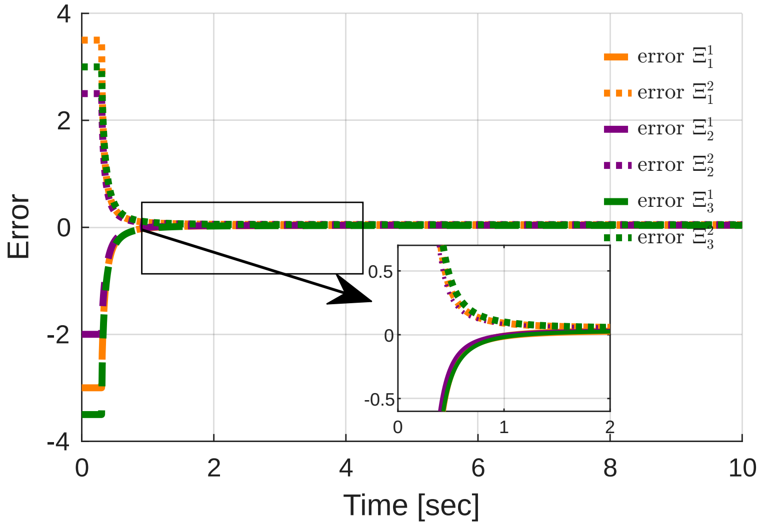

Figure 7. The error state $\Xi_p(\tau)$ of $\mathcal{FOMAS}s$ (3.16) and (3.1).

Example 4.4.

The nonlinear system governed by Eqs (3.16) and (3.11) consists of two leaders and three followers, as illustrated in Figure 8.

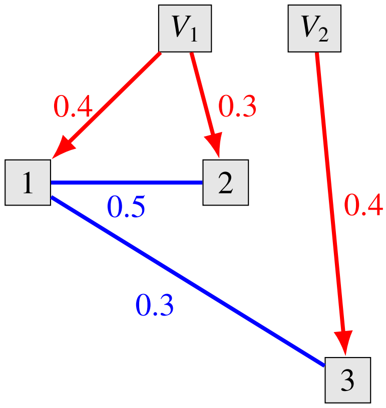

Figure 8. The communication topology of $\mathcal{NFFOMAS}$ (3.16).

Let the matrix $\mathcal{M}$ be defined as follows:

$$\mathcal{M} = \begin{pmatrix} -6 & -0.2 \\ -0.5 & -7 \end{pmatrix}. \tag{4.7}$$

From Figure 8, we have

$$\mathcal{H}_1 = \begin{pmatrix} 1.2 & -0.5 & -0.3 \\ -0.5 & 0.8 & 0 \\ -0.3 & 0 & 0.7 \end{pmatrix} \quad \text{and} \quad \mathcal{H}_2 = \begin{pmatrix} -0.4 & 0 \\ -0.3 & 0 \\ 0 & -0.4 \end{pmatrix}. \tag{4.8}$$

Define $z_p(\tau) = (z_p^1(\tau), z_p^2(\tau))^\top$, $g_1(\tau, z_p(\tau)) = (0.1\sin z_p^1(\tau), 0.1\sin z_p^2(\tau))^\top$, with parameters: $\kappa = 0.65$, $\sigma = 0.3$, $\varphi_1 = 1$, $\theta_1 = 1$, $\theta_3 = 2$, $\Delta u = 0.5\sin(10)$, $\Omega_7 = \begin{pmatrix} 0.001 & 0.001 \end{pmatrix}$, $\Omega_8 = \begin{pmatrix} 0.001 \\ 0.001 \end{pmatrix}$, $\beta = 0.5$, and $\mathbb{Y} = \mathcal{I}_2$. Then, choose $\mathcal{K}_2 = \begin{pmatrix} 0.5 & -0.2 \\ 0.3 & -0.5 \end{pmatrix}$, in protocol (3.11); after a simple calculation, one obtains

$$\widetilde{\mathscr{D}} = \begin{pmatrix} -8.8299 & -0.4775 & -0.1450 & -0.1250 & -0.0827 & -0.0713 \\ -0.4775 & -10.7854 & -0.1250 & -0.1700 & -0.0713 & -0.0969 \\ -0.1450 & -0.1250 & -8.9590 & -0.5887 & 0.0218 & 0.0188 \\ -0.1250 & -0.1700 & -0.5887 & -10.9367 & 0.0188 & 0.0255 \\ -0.0827 & -0.0713 & 0.0218 & 0.0188 & -9.0039 & -0.6275 \\ -0.0713 & -0.0969 & 0.0188 & 0.0255 & -0.6275 & -10.9894 \end{pmatrix} < 0. \tag{4.9}$$

Let us choose the initial states $z_{\mathcal{F}_{21}}(0) = \begin{bmatrix} 1 & -1 \end{bmatrix}^\top$, $z_{\mathcal{F}_{22}}(0) = \begin{bmatrix} 0.7 & 2 \end{bmatrix}^\top$, $z_{\mathcal{F}_{11}}(0) = \begin{bmatrix} -0.5 & 1.5 \end{bmatrix}^\top$, $z_{\mathcal{F}_{12}}(0) = \begin{bmatrix} 0.5 & 3 \end{bmatrix}^\top$, and $z_{\mathcal{F}_{13}}(0) = \begin{bmatrix} -2.5 & 2 \end{bmatrix}^\top$. Thus, from Corollary 3.3, the $\mathcal{CC}$ of $\mathcal{NFFOMAS}$ (3.16) and (3.11) is achieved, and the state trajectories and error states $\Xi_p(\tau)$ are illustrated in Figures 9 and 10, respectively.

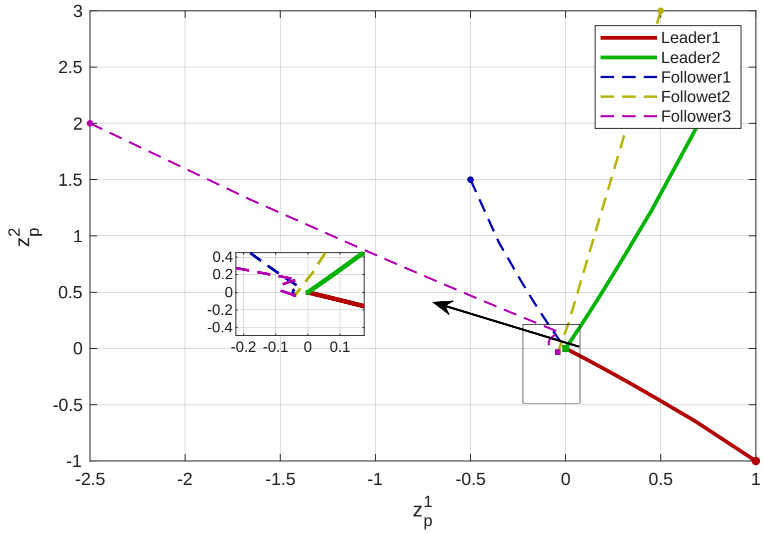

Figure 9. Dynamics of state trajectories of two leaders and three agents.

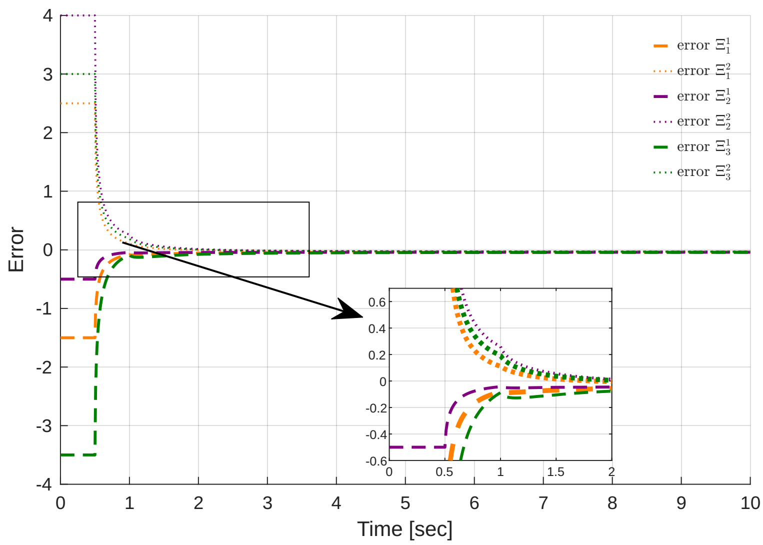

Figure 10. The error state $\Xi_p(\tau)$ of $\mathcal{FOMAS}s$ (3.16) and (3.11).

Example 4.5. Control of synchronization in nonlinear circuits

This experimental investigation utilizes a conventional multi-agent network, with each agent symbolizing a functional fractional-order tunnel diode circuit. Figure 1 shows the communication architecture between agents, and Figure 11 shows the electrical design of each circuit. The main goal is to develop a distributed cooperative control technique that ensures that all of the follower circuits are in accordance with the state trajectory of the leader circuit, which is called agent 0. Both the capacitive and inductive parts of these circuits indicate fractional-order dynamics, which is extremely significant. The tunnel diodes, on the other hand, show nonlinear behavior on each other.

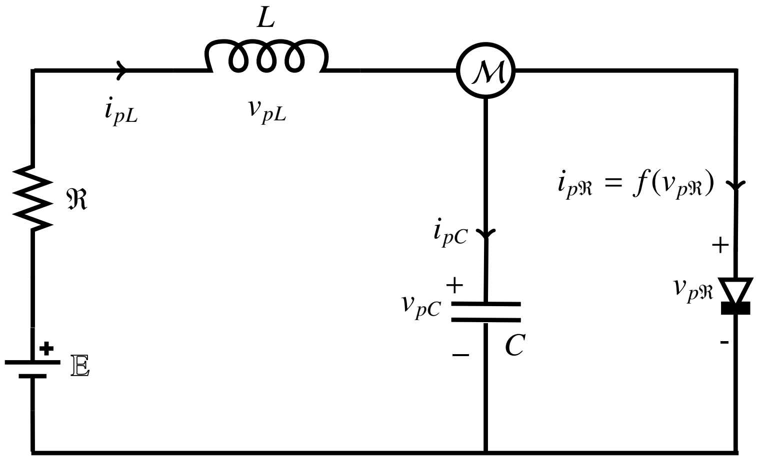

Figure 11. Electrical circuit schematic diagram of each agent for Example 4.5: Tunnel diode circuit.

In accordance with Kirchhoff's rules, the state space model for each agent can be expressed as follows:

$$\begin{cases} {}_0^C\mathcal{D}_\tau^\kappa v_{pC}(\tau) = \frac{1}{C} i_{pL}(\tau) - \frac{1}{C} f(v_{p\Re}(\tau)) + u_p(v_{pC}(\tau)), \\ {}_0^C\mathcal{D}_\tau^\kappa i_{pL}(\tau) = \frac{\mathbb{E}}{L} - \frac{1}{L} v_{pC}(\tau) - \frac{\Re}{L} i_{pL}(\tau) + u_p(i_{pL}(\tau)), \end{cases} \tag{4.10}$$

which is identical to (3.16) in accordance with $\kappa = 0.95$. In particular, $z_p(\tau) = [v_{pC}(\tau), i_{pL}(\tau)]^\top$, $g(\tau, z_p(\tau)) = [(-1/C)f(v_{pC}(\tau)) + \sin(1.5\tau), (\mathbb{E}/L) + \cos(2\tau)]^\top$, and $\mathcal{M} = \begin{bmatrix} 0 & 1/C \\ -1/L & -\Re/L \end{bmatrix}$. The terminal voltage of the battery is $\mathbb{E} = 1.2$ V, the resistance value is $\Re = 1.5\,k\Omega = 1.5 \times 10^3\ \Omega$, and the capacitance is $C = 2\,pF = 2 \times 10^{-12}\,F$, while $L = \mu H = 5 \times 10^{-6}\,H$ represents the inductance. $f(v_{p\Re}(\tau)) = f(v_{pC}(\tau)) = v_{pC}^2(\tau)$ denotes the nonlinear function without loss of generality, whereas $u_p(v_{pC}(\tau))$ and $u_p(i_{pL}(\tau))$ signify the external voltage and current control inputs for each tunnel diode circuit, which have the same composition as (3.1), respectively.

The initial state of leader agents is set to be $z_{\mathcal{F}_{21}}(0) = \begin{bmatrix} 1V & 1.5A \end{bmatrix}^\top$, $z_{\mathcal{F}_{22}}(0) = \begin{bmatrix} 1V & 2A \end{bmatrix}^\top$, and the initial state of following agents is selected as $z_{\mathcal{F}_{11}}(0) = \begin{bmatrix} 3 & 1 \end{bmatrix}^\top$, $z_{\mathcal{F}_{12}}(0) = \begin{bmatrix} 2 & 4 \end{bmatrix}^\top$, and $z_{\mathcal{F}_{13}}(0) = \begin{bmatrix} 2 & 1 \end{bmatrix}^\top$. The rest of the parameters are the same as defined in Example 4.3. Consequently, it can be confirmed that all assumptions and conditions of Corollary 3.2 are satisfied. The outcomes of the consensus tracking are illustrated in Figures 12 and 13.

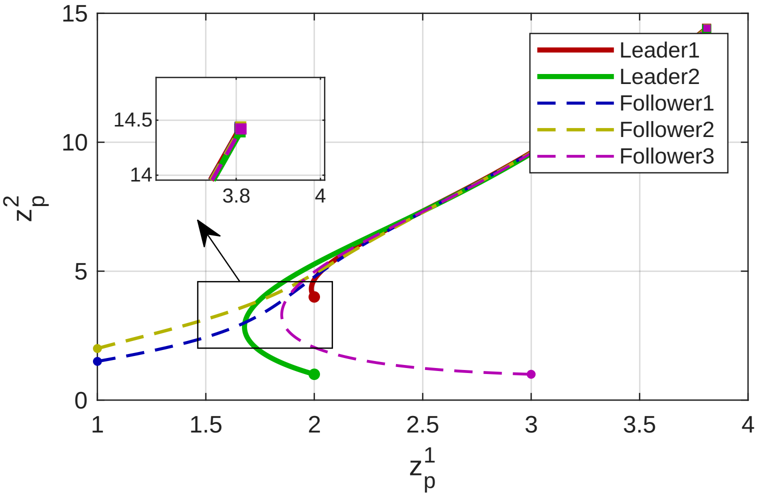

Figure 12. Dynamics of state trajectories of two leaders and three followers.

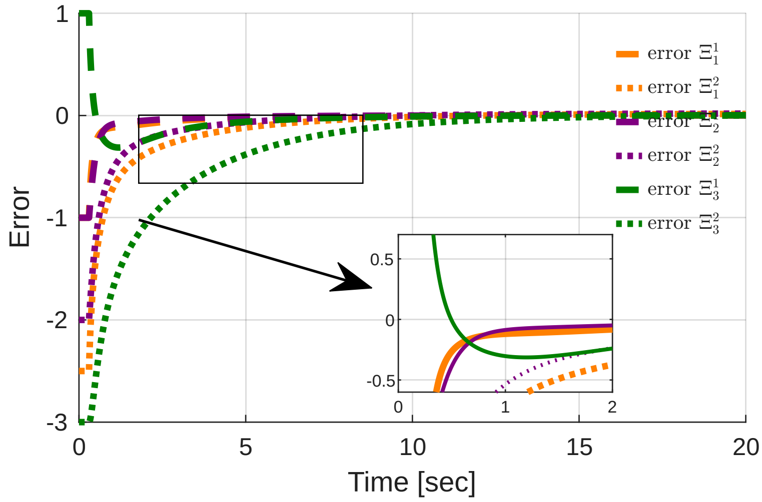

Figure 13. The error state $\Xi_p(\tau)$ of $\mathcal{FOMASs}$ (4.10) under the control (3.1).

4.1. Discussion and analysis

The system analysis examines important situations using Schur's lemma, uncertainties, non-fragile control, and disturbance effects to derive robust consensus criteria for leader-follower systems (2.2). The initial example examines nonlinear non-delayed dynamics influenced by disturbance Δu (including sinusoidal functions), governed by parameters θ_i (where $i = 1, 2, 3, 4$), β, and matrices $\mathcal{K}_1$ and $\mathbb{Y}$, to demonstrate the effects of disturbance on consensus error $\Xi_p(\tau)$. Figure 3 demonstrates the response under protocol (3.1). The second example utilizes system (2.2) with three followers and two leaders. It uses protocol (3.11) and constant matrices $\mathcal{M}$ and $\mathcal{N}$ to set up how the agents interact. In this case, Schur's lemma builds stability inequalities like (3.14), with $\mathcal{K}_2$ and Δu carefully chosen to make sure that consensus performance is robust, as shown in Figure 5. The third and fourth examples examine system (3.16) (three followers, two leaders) utilizing protocols (3.1) and (3.11), respectively. The constant matrix $\mathcal{M}$ and gains $\mathcal{K}_1$, $\mathcal{K}_2$ are adjusted for resilience under severe conditions. Schur's lemma again gives us important inequalities, and the error matrices verified using (3.17) and (3.18) provide us information about robustness, as shown in Figures 7 and 10. Finally, the fifth example analyzes system (4.10) under protocol (3.1), adjusting matrix $\mathcal{M}$ for resilience. Schur's lemma ensures consensus maintenance, with error matrices verified through (3.17) and outcomes shown in Figures 12 and 13.

Recent methodologies address difficulties in separation: [11, 24] handle time-delay while concentrating on additional factors; [44] formulates non-fragile control with varying scope concerns; [23] integrates disturbances within particular problem. Conversely, our methodology concurrently addresses the extensive obstacles, encompassing leader-follower consensus, consensus control, uncertainty, time delay, robust control, and external disturbances. This cohesive approach substantially enhances robustness assurances for $\mathcal{MAS}s$ amid various simultaneous disruptions.

5. Conclusions

In the present paper, we addressed the problem of delayed nonlinear $\mathcal{FOMAS}s$ using the $\mathcal{CC}$ framework in the presence of external disturbances, uncertainties in the system, and imperfections in the controller. We identified some helpful algebraic requirements to ensure robust $\mathcal{CC}$ through an improved Razumikhin approach by giving non-delayed and delayed communication protocols, together with techniques of graph theory, algebra, and matrix analysis. Theorem 3.1 provides sufficient conditions under which resilient $\mathcal{CC}$ is provided under uncertainty and non-fragile control of the non-delayed scenario, whereas Theorem 3.2 makes these observations extend to time delays by resorting to delay-dependent estimates. The proposed approach is suitable for addressing the problem of fractional-order dynamics and communication delays and can be highly robust to real-world imperfections. The theoretical conclusions are validated and deemed effective based on the simulation results. A promising future research direction is the formulation of event-based control strategies to enhance communication efficiency, decrease computational burden, and improve robust containment performance with $\mathcal{FOMAS}s$.

Author contributions

R. S. G: Conceptualization, methodology, formal analysis, writing—original draft, visualization; M. M. A: Data curation, investigation, validation, writing—review and editing; J. H. J: Supervision, project administration, funding acquisition, writing—review and editing.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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The first and second authors dedicate this paper with heartfelt gratitude to the vibrant celebration of our university's 40th anniversary, honoring its excellence, innovation, and inspirational legacy.

Conflict of interest

The authors declare that they have no conflict of interest.

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