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RESEARCH ARTICLE

Secure H_∞ control for fractional-order fuzzy networked control systems subject to distributed delays and actuator faults

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ABSTRACT

The current study addresses the stability analysis in fractional-order fuzzy networked control systems with actuator faults and uncertainties. In contrast to existing studies on networked control systems, we carry out a comprehensive analysis using H_∞ control for fractional-order networked control systems with distributed delays, aiming to improve system performance and robustness against denial-of-service attacks while accounting for actuator faults. A fuzzy controller is first designed for uncertain fractional-order fuzzy networked control systems with external disturbances. Subsequently, sufficient conditions based linear matrix inequalities (LMIs) are established using Lyapunov-Krasovskii functionals to ensure the asymptotic stability of the closed-loop system. The effectiveness of the proposed strategy is numerically validated using MATLAB® with different parameter settings. Finally, the comparative results show that the proposed method yields less conservative results than existing approaches.

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1. Introduction

In recent decades, networked control systems (NCSs) have emerged as an active research topic. An NCS closes the control loop through a communication network linking sensors, actuators, and the controller. However, the communication medium is inherently composed of multiple channels, many of which are vulnerable to security threats.[1,2] NCSs provide reduced implementation costs and enhanced functional versatility, leading to their application in numerous sectors such as electrical infrastructure, UAV systems, smart manufacturing, telesurgical procedures, and geological research.[3–5]

Most existing studies assume fully reliable actuators and control components. However, practical systems inevitably suffer from faults and network imperfections, motivating the need for reliable controllers that can tolerate such uncertainties and communication constraints. In,[6] the design of fault-tolerant controllers for NCSs was studied under non-ideal conditions, such as parameter uncertainty, packet loss, and time delays. In,[7,8] the probabilistic sensor and actuator faults in continuous-time NCS are investigated, the Takagi-Sugeno (T-S) fuzzy NCS, actuator fault, and external disturbance are investigated via a non-fragile mixed event-triggered control, respectively. The design of fault-tolerant controllers for discrete-time NCS with uncertain parameters, using an actuator fault is investigated.[9]

Owing to their wide range of real-world applications, fractional-order differential equations have attracted significant attention in recent years. Using dynamical theory and analytical measures, both qualitative and quantitative behaviors of fractional-order systems are analyzed, reflecting their widespread occurrence in nature. Fractional- order mod-

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els are widely studied for capturing complex dynamics in physics, biology, chemistry, electrical engineering, and chaotic systems. Due to their inherent memory properties, fractional-order differential equations retain complete functional information, motivating extensive recent research with significant theoretical and numerical advances.[10–13]

The T-S fuzzy representations approximate nonlinear dynamics through linear models weighted by fuzzy membership functions and are widely applied in practical systems owing to their simplicity and effectiveness in addressing complex nonlinearities.[14,15] However, many complex systems, such as viscoelastic and biological processes, cannot be captured by integer-order models.[16–18] Unlike integer-order derivatives, fractional derivatives exhibit memory, heredity, and nonlocality, making the control of nonlinear fractional-order systems a rapidly growing research area. Multiple techniques have been developed to examine the stability and stabilization of fractional-order fuzzy systems.[10,12,19,20]

In NCSs, time delays commonly arise during data transmission among devices connected via a shared medium, which may result in system instability or degraded network performance.[21] In real-world systems, parametric uncertainties and external disturbances are frequently encountered. Moreover, achieving an exact controller implementation that fully satisfies real-time operational requirements is particularly challenging, as modeling errors and uncertainties may arise during the controller development process (see[18,22–24] and references there in.)

Nevertheless, these advantages introduce additional challenges, particularly with respect to network latency and system safety (see[25–30] and references therein). NCSs are vulnerable to various cyber attacks, particularly denial-of-service attacks (DoSAs), deception attacks, and replay attacks. The sliding-mode event-triggered control of NCSs under DoSAs is investigated.[31] The primary objective of these attacks is to deny legitimate users access to the intended system, service, or network. DoSAs overwhelm targeted systems by exhausting server, infrastructure, and service resources, thereby disrupting or completely halting regular transmission traffic. Addressing these problems has motivated substantial recent research on controller design and stability analysis (see[16,32–35] for instance).

As stated above, the objective of this study is to investigate the dynamics of NCSs subject to time-varying and distributed delays, DoSAs, actuator faults, and system uncertainties under a fractional-order framework. For this purpose, security-based H_∞ control is applied to delayed NCSs with actuator faults. A summary of the paper's major contributions is provided below:

(1) In contrast to (see[10,12,36]), this study presents a comprehensive framework for NCSs that seamlessly integrates time-varying and distributed delay, DoSAs, actuator faults, and system uncertainties under a fractional-order setting.
(2) Specifically, a secure fuzzy H_∞ control strategy is proposed, which guarantees the robust asymptotic stability of the proposed fractional-order fuzzy networked control systems (F-OFNCSs).
(3) Using Lyapunov stability theory and linear matrix inequalities (LMIs) based on Lyapunov-Krasovskii functionals, asymptotic stability is established with H_∞ performance index. Numerical examples and simulations confirm the reduced conservatism of the obtained results.

The paper is organized as follows. Section 2 presents the formulation of the F-OFNCSs along with the necessary definitions and lemmas. A detailed stability analysis is given in Section 3. In Section 4, two numerical simulations with graphical illustrations are provided to validate the theoretical results. Finally, the conclusions are presented in Section 5.

1.1. Notations

The set of n dimensional real numbers is denoted by $\mathbb{R}^n$. The transpose, inverse, and symmetric terms of a matrix are denoted by "T", "-1", and "$*$", respectively.

2. Problem formulation

Using the Caputo fractional derivative (CFD), we examine the stability problem of fractional-order networked control systems (F-ONCSs) in this section. Unlike integer-order derivatives, which focus on adjacent points, fractional derivatives capture information from the entire function. Thus, the CFD of a function $\psi(\xi)$ of the order $\alpha > 0$ is defined as

$$\begin{aligned} {}^{C}D^{\alpha}_{\xi_0}\psi(\xi) &= \mathcal{I}^{\beta-\alpha}_{\xi_0}\frac{d^\beta}{d\xi^\beta}\psi(\xi) \\ &= \frac{1}{\Gamma(\beta-\alpha)}\int_{\xi_0}^{\xi}\frac{\psi^{(\beta)}(\tau)d\tau}{(\xi-\beta)^{\beta-\alpha-1}}, \end{aligned} \tag{1}$$

where β is a positive integer satifying $0 \le \beta - 1 \le \alpha < \beta$, $\Gamma(\cdot)$ denotes the gamma function, and $\mathcal{I}^{\alpha}_{\xi_0}\psi(\xi) = \frac{1}{\Gamma(\xi)}\int_{\xi_0}^{\xi}(\xi-\nu)^{\alpha-1}\psi(\nu)d\nu$. Henceforth, D^α denotes the CFD.

The nonlinear F-ONCS with time-varying and distributed delays, consisting of q rules, is expressed as

Rule i: If $\Omega_1(\xi)$ is $\Psi_{i1},\ \Omega_2(\xi)$ is $\Psi_{i2},\dots,\ \Omega_l(\xi)$ is Ψ_{il}, then

$$\begin{cases} D^\alpha x(\xi) = (\mathsf{N}_{1i} + \Delta\mathsf{N}_{1i}(\xi))x(\xi) + (\mathsf{N}_{2i} \\ \qquad +\Delta\mathsf{N}_{2i}(\xi))x(\xi-\delta(\xi)) \\ \qquad +\mathcal{N}_{3i}\int_{\xi-\tau(\xi)}^{\xi} x(\hbar)d\hbar \\ \qquad +\mathcal{N}_{4i}u(\xi) + \mathcal{N}_{5i}\omega(\xi), \\ y(\xi) = \mathcal{N}_{6i}x(\xi), \end{cases} \tag{2}$$

where $x(\xi) \in \mathbb{R}^n, u(\xi) \in \mathbb{R}^m, y(\xi) \in \mathbb{R}^l$, and $\omega(\xi) \in L_2[0,\infty)$ denote the state, control input, output, and external disturbance vectors, respectively. The time-varying and distributed delays are denoted by $\delta(\xi)$ and $\tau(\xi)$, which satify $0 < \delta_1 \le \{\delta(\xi), \tau(\xi)\} \le \delta_2$ and $\dot{\delta}(\xi) \le \rho_1$, where $\delta_2 > 0$, ρ_1 are real constants, and $\alpha \in (0,1)$. The matrices $\mathsf{N}_{1i},\ \mathsf{N}_{2i},\ \mathcal{N}_{3i},\ \mathcal{N}_{4i},\ \mathcal{N}_{5i}$ and $\mathcal{N}_{6i}$ are constant matrices of appropriate dimensions. Additionally, $\mathcal{N}_{1i} = \mathsf{N}_{1i} + W^T\mathcal{Z}(\xi)\mathcal{J}_{1i}$ and $\mathcal{N}_{2i} = \mathsf{N}_{2i} + W^T\mathcal{Z}(\xi)\mathcal{J}_{2i}$. Accordingly, the system can be described as follows

$$\begin{cases} D^\alpha x(\xi) = \sum_{i=1}^{q}\lambda_i(\Omega(\xi))[\mathcal{N}_{1i}x(\xi) \\ \qquad +\mathcal{N}_{2i}x(\xi-\delta(\xi)) \\ \qquad +\mathcal{N}_{3i}\int_{\xi-\tau(\xi)}^{\xi} x(\hbar)d\hbar + \mathcal{N}_{4i}u(\xi) \\ \qquad +\mathcal{N}_{5i}\omega(\xi)], \\ y(\xi) = \sum_{i=1}^{q}\lambda_i(\Omega(\xi))\mathcal{N}_{6i}x(\xi). \end{cases} \tag{3}$$

The fuzzy basis functions are defined as

$$\lambda_i(\Omega(\xi)) = \frac{\prod_{c=1}^{l} N_{ic}(\Omega_c(\xi))}{\sum_{c=1}^{q}\prod_{c=1}^{l} N_{ic}(\Omega_c(\xi))}, \tag{4}$$

where $N_{i1}(\Omega_c(\xi))$ is the grade of membership of $\Omega_c(\xi)$ in the fuzzy set N_{ic} and it is straightforward to verify that $\prod_{c=1}^{l} N_{ic}(\Omega_c(\xi)) \ge 0$ and $\sum_{c=1}^{l} N_{ic}(\Omega_c(\xi)) > 0, \forall\ \xi$. Thus, $\lambda_i(\Omega(\xi)) \ge 0$ for $i = 1,2,\dots,c$, and $\sum_{i=1}^{c}\lambda_i(\Omega(\xi)) = 1$. Then the control input signal is

$$\bar{u}(\xi) = \sum_{i=1}^{q}\lambda_i(\Omega(\xi))\mathcal{K}_i x(\xi-\eta(\xi)), \tag{5}$$

where $\mathcal{K}_i$ is the controller gain, the transmission delay is denoted by $\eta(\xi)$, such that $0 < \eta_1 \le \eta(\xi) \le \eta_2$ with the real constant ρ_2 we have $\dot{\eta}(\xi) \le \rho_2$.

2.1. Actuator fault

The behavior of faulty devices can be described as

$$u_A(\xi) = \mathcal{C}\bar{u}(\xi), \tag{6}$$

where $\mathcal{C} = diag\{c^1, c^2, \dots, c^\kappa\}$ is the actuator fault matrix such that $0 \le c_{\min} \le c^l \le c_{\max} \le 1,\ l \in \{1,2,\dots,\kappa\}$. The actuator works normally, experiences complete failure, and partial failure at $\mathcal{C}_1, \mathcal{C}_0$, and $\mathcal{C}$, respectively. Next, define the auxiliary matrices

$$\mathcal{C}_0 = diag\{c_0^1, c_0^2, \dots, c_0^\kappa\},$$
$$\mathcal{C}_1 = diag\{c_1^1, c_1^2, \dots, c_1^\kappa\},$$

where $c_0^\kappa = \frac{c_{\max}+c_{\min}}{2}$, and $c_1^\kappa = \frac{c_{\max}-c_{\min}}{2}$. Then the matrix $\mathcal{C} = \mathcal{C}_0 + \mathcal{C}_1\mathcal{S}$ where $\mathcal{S} = diag\{s_1, s_2, \dots, s_l\}$ with $s_l \in [-1,1]$.

2.2. DoS attacks

The DoSA attack signals can be expressed as

$$\mathfrak{F}_{DoS}(\xi) = \begin{cases} 1, & \xi \in \mathfrak{D}_{1,n} = [\mathfrak{V}_n, \mathfrak{V}_n + \mathfrak{L}_n) \\ 0, & \xi \in \mathfrak{D}_{2,n} = [\mathfrak{V}_n + \mathfrak{L}_n, \mathfrak{V}_{n+1}) \end{cases} \tag{7}$$

where $\mathfrak{D}_{1,n}$ and $\mathfrak{D}_{2,n}$ denote the dormant and active periods of the jamming signal, respectively. Each jamming period is bounded as $\mathfrak{L}_n^{\min} \le \mathfrak{L}_n \le \mathfrak{L}_n^{\max}$, where $\mathfrak{L}_n^{\max} \ge \sup_{n\in\mathbb{N}}\{\mathfrak{V}_{n+1} - \mathfrak{V}_n - \mathfrak{L}_n\}$. DoSAs are assumed to disrupt communication between the controller and actuator. Hence, the control input $u(\xi)$ is given as

$$u(\xi) = \begin{cases} u_A(\xi), & \xi \in \mathfrak{D}_{1,n} \cap [\xi_{k,n+1}h, \xi_{k+1,n+1}h) \\ 0, & \xi \in \mathfrak{D}_{2,n} \end{cases} \tag{8}$$

where $\{\xi_{k,n+1}h\}$ denotes the successful control updates of the proposed controller.

Therefore, applying the control input to **(3)** yields

$$D^\alpha x(\xi) = \begin{cases} \sum_{i=1}^{q}\lambda_i(\Omega(\xi))[\mathcal{N}_{1i}x(\xi) \\ \quad +\mathcal{N}_{2i}x(\xi-\delta(\xi)) \\ \quad +\mathcal{N}_{3i}\int_{\xi-\tau(\xi)}^{\xi} x(\hbar)d\hbar + \mathcal{N}_{4i}\mathcal{C}\mathcal{K}_i \\ \quad \times x(\xi-\eta(\xi)) + \mathcal{N}_{5i}\omega(\xi)], \\ \quad \xi \in \mathfrak{D}_{1,n} \cap [\xi_{k,n+1}h, \xi_{k+1,n+1}h) \\ \sum_{i=1}^{q}\lambda_i(\Omega(\xi))[\mathcal{N}_{1i}x(\xi) + \mathcal{N}_{2i} \\ \quad \times x(\xi-\delta(\xi)) + \mathcal{N}_{3i}\int_{\xi-\tau(\xi)}^{\xi} x(\hbar) \\ \quad \times d\hbar + \mathcal{N}_{5i}\omega(\xi)],\ \xi \in \mathfrak{D}_{2,n} \end{cases}$$

$$y(\xi) = \sum_{i=1}^{q}\lambda_i(\Omega(\xi))\mathcal{N}_{6i}x(\xi). \tag{9}$$

In the analysis, the following definitions and lemmas are employed.

Definition 1. [37] *For a given H_∞ performance level γ, **System (9)** achieves asymptotic stability with zero initial conditions provided that for every nonzero $\omega(\xi) \in L_2[0,\infty)$, there exists a scalar $\gamma > 0$ such that the following inequality holds:*

$$\int_0^\infty y^T(\xi)y(\xi)d\xi - \int_0^\infty \omega^T(\xi)\gamma^2\omega(\xi)d\xi \le 0. \tag{10}$$

Lemma 1. [38] *Let $G : [u,v] \to \mathbb{R}^n$ be an integral function and let $\varphi > 0$ be a given positive definite matrix. Then, provided the integrals are well defined, the following inequality holds:*

$$\frac{1}{(v-u)}\Big(\int_u^v G(\xi)d\xi\Big)^T \varphi \Big(\int_u^v G(\xi)d\xi\Big) \le \int_u^v G^T(\xi)\varphi G(\xi)d\xi.$$

Lemma 2. [12] *Let $x(\xi) \in \mathbb{R}^n$ be differentiable and $\mathcal{P} \in \mathbb{R}^{n\times n}$ be a constant positive definite matrix. Then, for all $\xi > \xi_0$ the following holds*

$$\frac{1}{2}\, {}^C_{\xi_0}D^\alpha_\xi (x^T(\xi)\mathcal{P}x(\xi)) \le x^T(\xi)\mathcal{P}\, {}^C_{\xi_0}D^\alpha_\xi x(\xi), \forall\ \alpha \in (0,1). \tag{11}$$

3. Main results

In this section, we analyze the delayed F-OFNCS **(9)** to derive sufficient stability conditions.

Theorem 1. *For given scalars ρ_1, ρ_2, and $\mu > 0$, the **System (9)** via **(8)** is asymptotically stable with H_∞ performance, if there exists diagonal positive definite matrices $\mathcal{G}_1$, $\mathcal{G}_2$, and $\mathcal{M}$, symmetric positive definite matrices $\mathcal{P}$, $\mathcal{E}$, and $\mathcal{F}$, such that the following LMIs hold*

$$\bar{\Theta} = \begin{bmatrix} \bar{\Theta}_{1,1} & \mathcal{P}\mathcal{N}_{2i} & \mathcal{P}\mathcal{N}_{4i}\mathcal{C}\mathcal{K}_i & \mathcal{P}\mathcal{N}_{3i} - \mathcal{G}_2\mathcal{M} & \mathcal{P} \\ * & -(1-\rho_1)\mathcal{E} & 0 & 0 & 0 \\ * & * & -(1-\rho_2)\mathcal{F} & 0 & 0 \\ * & * & * & -\mathcal{M} & 0 \\ * & * & * & * & -\gamma^2 I \end{bmatrix} < 0, \tag{12}$$

$$\tilde{\Theta} = \begin{bmatrix} \tilde{\Theta}_{1,1} & \mathcal{P}\mathcal{N}_{2i} & \mathcal{P}\mathcal{N}_{3i} - \mathcal{G}_2\mathcal{M} & \mathcal{P} \\ * & -(1-\rho_1)\mathcal{E} & 0 & 0 \\ * & * & -(1-\rho_2)\mathcal{F} - \mathcal{M} & 0 \\ * & * & * & -\gamma^2 I \end{bmatrix} < 0, \tag{13}$$

where $\bar{\Theta}_{1,1} = \tilde{\Theta}_{1,1} = 2\mathcal{P}\mathcal{N}_{1i} + \mathcal{E} + \mathcal{F} + \mathcal{N}_{6i}^T\mathcal{N}_{6i} - \mathcal{G}_1\mathcal{M}$.

Proof. Two cases are considered in this theorem.
Case 1: Consider the system in the absence of DoSA. Then, propose the Lyapunov-Krasovskii functionals as

$$\mathcal{V}^1(\xi) = x^T(\xi)\mathcal{P}x(\xi) + \int_{\xi-\delta(\xi)}^{\xi} x^T(\theta)\mathcal{E}x(\theta)d\theta + \int_{\xi-\eta(\xi)}^{\xi} x^T(\theta)\mathcal{F}x(\theta)d\theta. \tag{14}$$

Thus, $D^\alpha\mathcal{V}^1(\xi)$ is given by

$$\begin{aligned} D^\alpha\mathcal{V}^1(\xi) = {}& 2x^T(\xi)\mathcal{P}D^\alpha x(\xi) - (1-\rho_1)x^T(\xi-\delta(\xi)) \\ & \mathcal{E}x(\xi-\delta(\xi)) + x^T(\xi)[\mathcal{E}+\mathcal{F}]x(\xi) \\ & - (1-\rho_2)x^T(\xi-\eta(\xi))\mathcal{F}x(\xi-\eta(\xi)) \\ = {}& 2x^T(\xi)\mathcal{P}\Bigg[\mathcal{N}_{1i}x(\xi) + \mathcal{N}_{2i}x(\xi-\delta(\xi)) \\ & + \mathcal{N}_{3i}\int_{\xi-\tau(\xi)}^{\xi} x(\hbar)d\hbar + \mathcal{N}_{4i}\mathcal{C}\mathcal{K}_i \\ & x(\xi-\eta(\xi)) + \mathcal{N}_{5i}\omega(\xi)\Bigg] - (1-\rho_1) \\ & x^T(\xi-\delta(\xi))\mathcal{E}x(\xi-\delta(\xi)) \\ & - (1-\rho_2)x^T(\xi-\eta(\xi))\mathcal{F}x(\xi-\eta(\xi)) \\ & + x^T(\xi)[\mathcal{E}+\mathcal{F}]x(\xi). \end{aligned} \tag{15}$$

For any diagonal matrix $\mathcal{M} = \mathrm{diag}(m_{11},\ldots,m_{1n})$ with $m_{1i} > 0$, the following inequality holds:

$$\begin{bmatrix} x(\xi) \\ \int_{\xi-\eta(\xi)}^{\xi} x(\xi)d\xi \end{bmatrix}^T \times \begin{bmatrix} -\mathcal{G}_1\mathcal{M} & -\mathcal{G}_2\mathcal{M} \\ * & -\mathcal{M} \end{bmatrix} \times \begin{bmatrix} x(\xi) \\ \int_{\xi-\eta(\xi)}^{\xi} x(\xi)d\xi \end{bmatrix} \le 0 \tag{16}$$

Combining **Equations (14)–(16)** yields

$$\begin{aligned} D^\alpha\mathcal{V}^1(\xi) &\le D^\alpha\mathcal{V}^1(\xi) + \omega^T(\xi)(-\gamma^2)\omega(\xi) \\ &\quad + x^T(\xi)\mathcal{N}_{6i}^T\mathcal{N}_{6i}x(\xi) \\ &\le \Phi_1^T(\xi)\bar{\Theta}_1\Phi_1(\xi), \end{aligned} \tag{17}$$

where $\Phi_1(\xi) = [x(\xi)\ \ x(\xi-\delta(\xi))\ \ x(\xi-\eta(\xi))\ \int_{\xi-\tau(\xi)}^{\xi} x(\xi)d\xi\ \omega(\xi)]$.

Case 2: Let a DoSA occur, i.e., $\xi \in \mathfrak{D}_{2,n}$ and $\mathcal{V}^2(\xi) = \mathcal{V}^1(\xi)$.
Following the same procedure as in Case 1, the

following expression is obtained.

$$\begin{aligned} D^\alpha \mathcal{V}^2(\xi) &\le D^\alpha \mathcal{V}^2(\xi) + \omega^T(\xi)(-\gamma^2)\omega(\xi) \\ &\quad + x^T(\xi)\mathcal{N}_{6i}^T \mathcal{N}_{6i} x(\xi) \\ &\le \Phi_2^T(\xi)\tilde{\Theta}\Phi_2(\xi), \end{aligned} \tag{18}$$

where $\Phi_2(\xi) = [x(\xi)\; x(\xi-\delta(\xi))\; \int_{\xi-\tau(\xi)}^{\xi} x(\xi)d\xi\; \omega(\xi)]$. Using **(12)** and **(13)** in conjunction with **(17)** and **(18)**, it follows that

$$D^\alpha \mathcal{V}(\xi) = \begin{cases} D^\alpha \mathcal{V}^1(\xi) < 0, \\ \quad \xi \in \mathfrak{D}_{1,n} \cap [\xi_{k,n+1}h, \xi_{k+1,n+1}h) \\ D^\alpha \mathcal{V}^2(\xi) < 0,\; \xi \in \mathfrak{D}_{2,n}. \end{cases}$$

Thus $D^\alpha \mathcal{V}(\xi) < 0$. Therefore, the F-OFNCSs **(9)** is asymptotically stable with H_∞ performance, when $\omega(\xi) = 0$, and Definition 1 holds with zero initial condition. Thus, the proof is complete. □

Theorem 2. *For given scalars ρ_1, ρ_2, and $\mu > 0$, the system **(9)** via **(8)** is asymptotically stable with H_∞ performance and the controller gain $\mathcal{K}_i = \Upsilon\mathcal{H}$, if there exists symmetric positive definite matrices $\mathcal{P}$, $\mathcal{E}$, and $\mathcal{F}$, diagonal positive definite matrices $\mathcal{G}_1$, $\mathcal{G}_2$, and $\mathcal{M}$ such that the following LMIs hold:*

$$\bar{\Lambda} = \begin{bmatrix} \bar{\Lambda}_{1,1} & \mathcal{P}\mathcal{N}_{2i} & \mathcal{N}_{4i}\mathcal{C}\mathcal{H} & \mathcal{P}\mathcal{N}_{3i} - \mathcal{G}_2\mathcal{M} & \mathcal{P} \\ * & -(1-\rho_1)\mathcal{E} & 0 & 0 & 0 \\ * & * & -(1-\rho_2)\mathcal{F} & 0 & 0 \\ * & * & * & -\mathcal{M} & 0 \\ * & * & * & * & -\gamma^2 I \end{bmatrix} < 0, \tag{19}$$

$$\tilde{\Lambda} = \begin{bmatrix} \tilde{\Lambda}_{1,1} & \mathcal{P}\mathcal{N}_{2i} & \mathcal{P}\mathcal{N}_{3i} - \mathcal{G}_2\mathcal{M} & \mathcal{P} \\ * & -(1-\rho_1)\mathcal{E} & 0 & 0 \\ * & * & -(1-\rho_2)\mathcal{F} - \mathcal{M} & 0 \\ * & * & * & -\gamma^2 I \end{bmatrix} < 0, \tag{20}$$

where $\bar{\Lambda}_{1,1} = \tilde{\Lambda}_{1,1} = 2\mathcal{P}\mathcal{N}_{1i} + \mathcal{E} + \mathcal{F} + \mathcal{N}_{6i}^T\mathcal{N}_{6i} - \mathcal{G}_1\mathcal{M}$.

Proof. Define $\Upsilon = \mathcal{P}^{-1}$. Then we get $\mathcal{K}_i = \mathcal{P}^{-1}\mathcal{H}$, substituting this in **(12)** and **(13)** yields **(19)** and **(20)**. Based on **(19)** and **(20)**, $D^\alpha \mathcal{V}(\xi) < 0$ under both cases of with and without DoSAs. Therefore, it implies that system **(9)** is asymptotically stable and satisfies the H_∞ performance criterion subject to time-varying delay, distributed delays and actuator faults. □

Remark 1. *If we exclude the uncertain parameters (i.e., $\Delta \mathsf{N}_{1i}(\xi) = \Delta \mathsf{N}_{2i}(\xi) = 0$), **(9)** can be recast as*

$$D^\alpha x(\xi) = \begin{cases} \sum_{i=1}^{q} \lambda_i(\Omega(\xi))[\mathsf{N}_{1i}x(\xi) + \mathsf{N}_{2i} \\ \quad \times x(\xi - \delta_1(\xi)) + \mathcal{N}_{3i}\int_{\xi-\tau(\xi)}^{\xi} x(\hbar)d\hbar \\ \quad + \mathcal{N}_{4i}\mathcal{C}\mathcal{K}_i x(\xi - \eta(\xi))\mathcal{N}_{5i}\omega(\xi)], \\ \quad \xi \in \mathfrak{D}_{1,n} \cap [\xi_{k,n+1}h, \xi_{k+1,n+1}h) \\ \sum_{i=1}^{q} \lambda_i(\Omega(\xi))[\mathsf{N}_{1i}x(\xi) + \mathsf{N}_{2i} \\ \quad \times x(\xi - \delta_1(\xi)) + \mathcal{N}_{3i}\int_{\xi-\tau(\xi)}^{\xi} x(\hbar)d\hbar \\ \quad + \mathcal{N}_{5i}\omega(\xi)],\; \xi \in \mathfrak{D}_{2,n} \end{cases}$$

$$y(\xi) = \sum_{i=1}^{q} \lambda_i(\Omega(\xi))\mathcal{N}_{6i}x(\xi). \tag{21}$$

Following a procedure similar to that of Theorem 2, the following results are obtained; therefore, the proof is omitted.

Corollary 1. *For given scalars ρ_1, ρ_2, and $\mu > 0$, the **System (21)** via **(8)** is asymptotically stable with H_∞ performance and the controller gain $\mathcal{K}_i = \Upsilon\mathcal{H}$, if there exists symmetric positive definite matrices $\mathcal{P}$, $\mathcal{E}$, and $\mathcal{F}$, diagonal positive definite matrices $\mathcal{G}_1$, $\mathcal{G}_2$, and $\mathcal{M}$ such that the following LMIs **(19)** and **(20)** hold with $\Delta \mathsf{N}_i = 0$ $\{i = 1, 2\}$.*

4. Numerical examples

This section presents numerical experiments and generated figures to validate the results.

Example 1. *Consider **System (9)** with the following matrix variables:*

$$\mathcal{N}_{11} = \begin{bmatrix} -0.9968 & 0 \\ 0 & -1.0032 \end{bmatrix},$$

$$\mathcal{N}_{12} = \begin{bmatrix} -0.9968 & 0 \\ 0.1000 & -1.0032 \end{bmatrix},$$

$$\mathcal{N}_{21} = \begin{bmatrix} -1.0697 & 0 \\ 0 & -0.1460 \end{bmatrix},$$

$$\mathcal{N}_{22} = \begin{bmatrix} -0.4254 & 0 \\ 0.0143 & -0.4317 \end{bmatrix},$$

$$\mathcal{N}_{31} = \mathcal{N}_{32} = 10^{-5} \times \begin{bmatrix} 0.3142 & 0 \\ 0 & 0.0031 \end{bmatrix},$$

$$\mathcal{N}_{41} = \begin{bmatrix} 0.01 & 0 \\ 0.07 & 0 \end{bmatrix},\; \mathcal{N}_{42} = \begin{bmatrix} 0.1230 & 0 \\ 0 & 0.2600 \end{bmatrix},$$

$$\mathcal{N}_{51} = -\mathcal{N}_{52} = \begin{bmatrix} 0.1 & 0 \\ 0.1 & 0.1 \end{bmatrix},$$

$$\mathcal{C}_{11} = \begin{bmatrix} 0.4 & 0.6 \\ 0.2 & 0.8 \end{bmatrix}, \ \mathcal{C}_{12} = \begin{bmatrix} 0.1 & 0.9 \\ 0.6 & 0.4 \end{bmatrix},$$

$\mathcal{N}_{61} = 10^{-7}\mathcal{I}_2, \ \mathcal{N}_{62} = 10^{-6}\mathcal{I}_2, \ \mathcal{Z}(\xi) = sin(0.1\xi).$

Case (i): Without DoSAs

The parameters are chosen as $\rho_1 = \rho_2 = 0.1$, $\gamma = 2.21$, *and* $\mu = 6.1862 \times 10^{-5}$. *The AS of* ***System (9)*** *is verified by solving the LMI* ***(19)****. The resulting gain matrices are*

$$\mathcal{K}_1 = \begin{bmatrix} -1.9607 & -0.0605 \\ -0.4199 & 0.3263 \end{bmatrix},$$

$$\mathcal{K}_2 = \begin{bmatrix} 5.1813 & -0.2189 \\ -0.4917 & 0.7396 \end{bmatrix}.$$

Case (ii): With DoSAs

The required parameters are taken as in Case (i). Solving the LMI ***(20)*** *shows that* ***System (9)*** *is asymptotically stable. The resulting gain matrices are*

$$\mathcal{K}_1 = 1.0e+08 \times \begin{bmatrix} 2.5240 & 0.0232 \\ 0.0232 & 0.7815 \end{bmatrix},$$

$$\mathcal{K}_2 = 1.0e+08 \times \begin{bmatrix} 2.5240 & 0.0232 \\ 0.0232 & 0.7815 \end{bmatrix}.$$

Let $\delta(\xi) = 1 + 0.2\sin\xi$, $\eta(\xi) = 1 + 0.2\cos\xi$, *and* $\tau(\xi) = \frac{0.07|sin(0.0025\xi)|}{0.05}$. *In addition, the external disturbance function is chosen as* $\omega(\xi) = [\sin(\pi\xi) \ \ \sin(\pi\xi)]^T$, *with membership functions* $\lambda_1 = \frac{1+\sin(0.1\xi)}{2}$ *and* $\lambda_2 = 1 - \lambda_1$. *Using the above details, we obtain* ***Figures 1–6****.* ***Figure 1*** *represents the chaotic behavior of* ***(9)*** *under three different* α *values namely* 0.1, 0.68, *and* 0.9. *The convergence dynamics of* ***(9)*** *under* $\alpha = 2.21$ *without DoSAs and with DoSAs as shown in* ***Figures 2*** *and* ***3****, respectively. The evolution of the fuzzy membership function is depicted in* ***Figure 4****. For three different* α *values the state response without DoSAs and with DoSAs is depicted in* ***Figures 5*** *and* ***6****, respectively.*

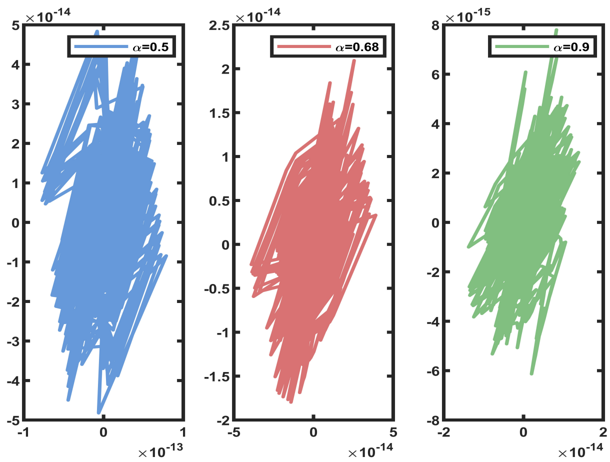

Figure 1. Chaotic behavior of **System (9)**

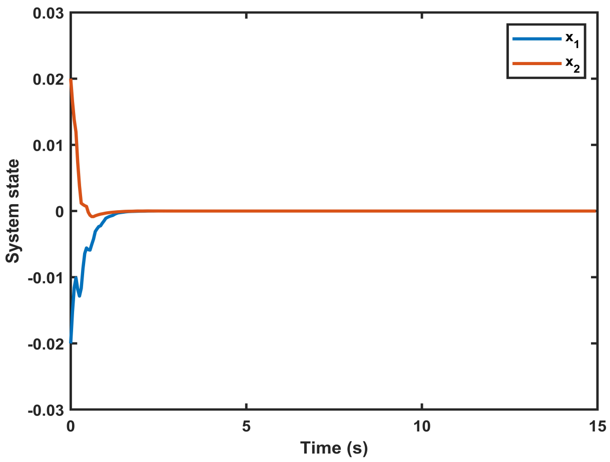

Figure 2. Response of **System (9)** without DoSAs

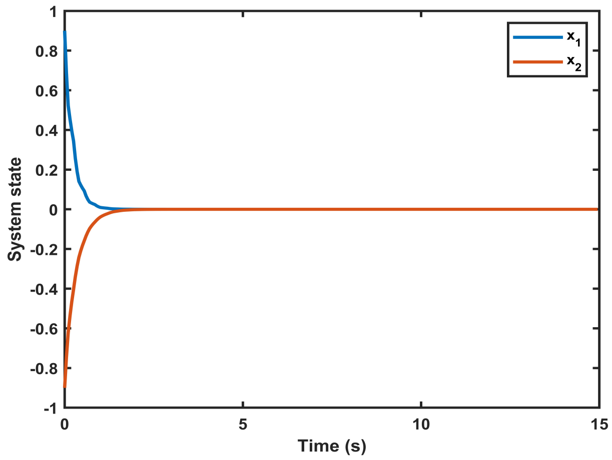

Figure 3. Response of **System (9)** with DoSAs

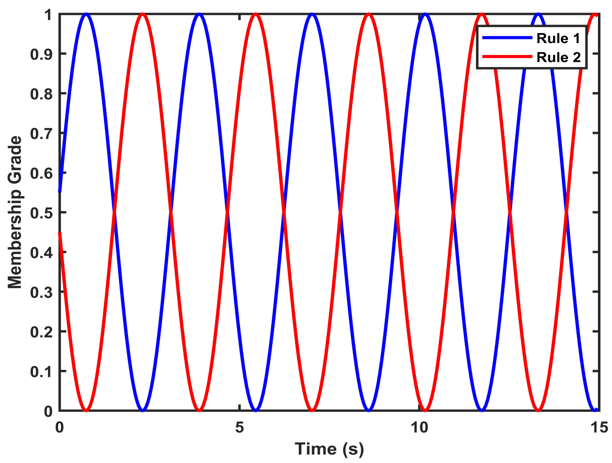

Figure 4. Fuzzy membership function

Example 2. *For* ***System (21)****, let* $\gamma = 0.105$, *where the remaining required parameters are chosen as in Example 1. Using MATLAB, a feasible solution confirms the asymptotic stability of* ***System (21)****. Accordingly, the controller gain* *matrices in the presence of DoSAs are*

$$\mathcal{K}_1 = \begin{bmatrix} 4.9340 & 0.5501 \\ -0.8571 & 0.3313 \end{bmatrix}, \text{ and}$$

$$\mathcal{K}_2 = \begin{bmatrix} -3.5226 & -0.3670 \\ 0.3745 & 0.6857 \end{bmatrix}.$$

The controller gain matrices in the absence of DoSAs are

$$\mathcal{K}_1 = 1.0e+05 \times \begin{bmatrix} 3.8388 & 0.0167 \\ 0.0167 & 1.0314 \end{bmatrix}, \text{ and}$$

$$\mathcal{K}_2 = 1.0e+05 \times \begin{bmatrix} 3.8473 & 0.0168 \\ 0.0168 & 1.0348 \end{bmatrix}.$$

*For three α values 0.1, 0.68, 0.9, the state response under zero uncertainty without DoSAs and with DoSAs are shown in **Figure 7** and **8**, respectively.*

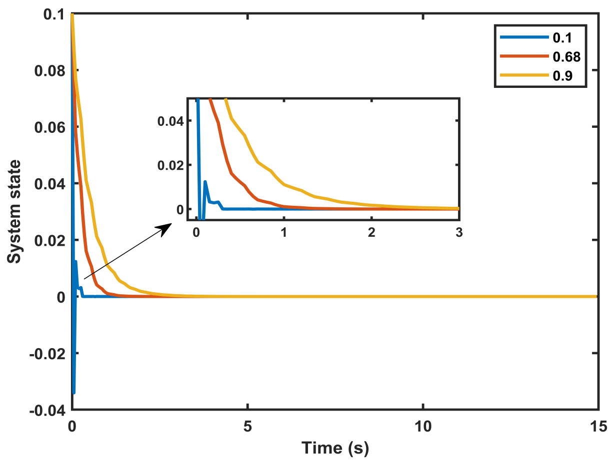

Figure 5. State response of **(9)** without DoSAs for different α values

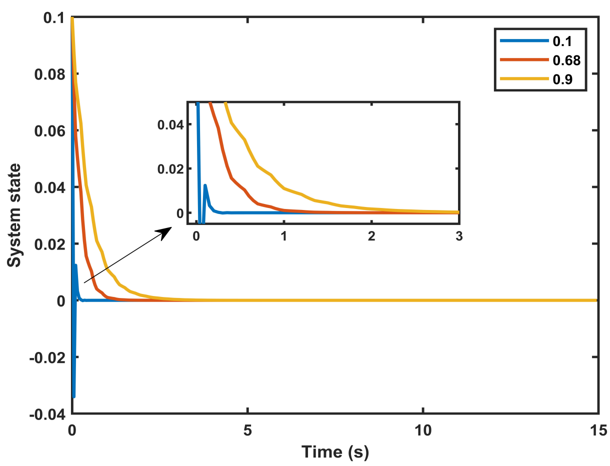

Figure 6. State response of **(9)** with DoSAs for different α values

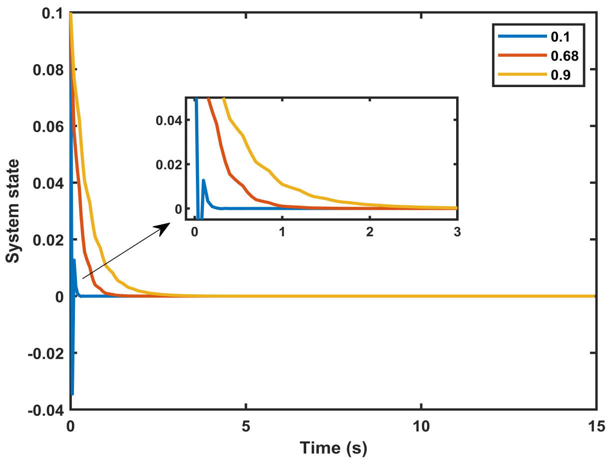

Figure 7. Trajectories of **System (21)** without DoSAs for different α values

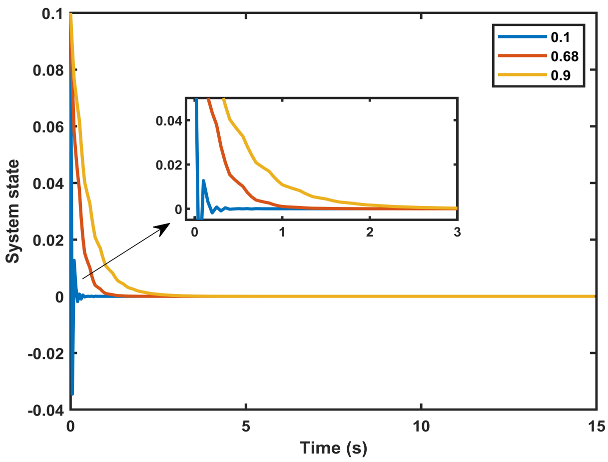

Figure 8. Trajectories of **System (21)** with DoSAs for different α values

Remark 2. *The H_∞ performance index γ, compared with recent literature is given in **Table 1**. From these results, it is evident that the proposed approach yields less conservative results.*

Table 1. Comparison of the H_∞ performance index γ

Methods	γ
In,[39] Ex. 4.1	5.5
In,[39] Ex. 4.2	2.854
In[40]	2.75
In[41]	3.5
Theorem 2	2.21

5. Conclusion

The stability problem of uncertain F-OFNCSs with time-varying and distributed delays, actuator faults, and external disturbances is investigated using security-oriented H_∞ control. Asymptotic stability is ensured through matrix inequalities using the Lyapunov-Krasovskii functional approach, considering both the presence and absence of DoSAs. Finally, numerical examples are presented under both uncertain and uncertainty-free cases, where the controller gains are obtained by solving the LMIs using standard software. Furthermore, figures illustrating chaotic behavior and state responses are provided. The proposed criteria exhibit lower conservatism compared to recent studies. Future research will focus on addressing more diverse cyber attack mechanisms in networked communication environments for more complex dynamic systems, such as stochastic F-ONCSs. In addition, future work will investigate real-time applications to validate the proposed control strategy.

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Conflict of interest

The authors declare they have no competing interests.

Author contributions

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Investigation: Narenshakthi Thiruvelavan
Methodology: Dharani Shanmugavel
Supervision: Dharani Shanmugavel
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Validation: Sivakumar Muthusamy
Visualization: Sivakumar Muthusamy
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Writing - review and editing: Dharani Shanmugavel, Sivakumar Muthusamy

Availability of data

Not applicable.

AI tools statement

All authors confirm that no AI tools were used in the preparation of this manuscript.

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