Event-triggered state feedback control for nonlinear fractional-order interconnected systems

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Abstract

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SUMMARY

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KEY WORDS: Fractional-order systems, interconnected systems, event-triggered mechanisms (ETM), state feedback control, linear matrix inequality (LMI).

1. INTRODUCTION

Unlike traditional calculus, which considers integrals and derivatives of integer orders, fractional calculus considers integrals and derivatives of any order. Fractional order systems describe a large of systems that are more complicated than classical integer order systems. They often appear in various practical applications such as electrical circuits [1], chaotic Lu systems [2], diffusion of heat [3], fractional-order systems of PID, sliding mode, adaptive and cement mill controllers [4], image encryption [5], Cohen-Grossberg BAM neural networks [6], viscoelastic mechanical systems [7], electrochemistry [8], economy [9], biology systems [10] and so on [11]. Due to its importance in both theoretical study and practical applications, such systems attract increasing attention, especially with respect to state feedback control [12, 13, 14, 15, 16, 17, 18].

In contrast to the traditional control [12, 13, 14, 15, 16, 17, 18], where the control signal is transferred to the actuator in actual time, which may lead to unnecessary sampling and communication, event-triggered control can eliminate unnecessary sampling and transmission. It thus can improve the efficiency in resource utilization of the network components (see, for example, [19], [20], [21], [22], [23], [24], [25]). In particular, event-triggered stabilization problem [19], event-triggered tracking problem [20], event-triggered output regulation problem [21], continuous-time event-triggered control [22], [23], [24], discrete-time event-triggered control [25]. Nevertheless, the methods reported in [19], [20], [21], [22], [23], [24], [25] are only applicable to integer-order dynamical systems. Since the Leibniz rule does not hold for fractional-order derivatives, it is not easy to extend the methods of designing event-triggered control from integer-order systems to fractional-order ones. Recently, by combining the Lyapunov function and the dynamic surface control design technique, the authors of the work [26] proposed an adaptive fuzzy

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output-feedback event-triggered control algorithm for a class of fractional-order nonlinear system, while an event-triggered control scheme for fractional-order linear multi-agent systems is introduced in [27]. However, to the best of our knowledge, the method reported in [26] and [27] can not be applied to design an event-triggered control to stabilize the nonlinear fractional-order interconnected systems, which motivates the present study.

In this study, we propose a new method for the design of event-triggered stabilizing state feedback controllers for nonlinear fractional-order interconnected systems. Firstly, a new event-triggered mechanism without the Zeno phenomenon is designed and used in the framework of designing state feedback control for nonlinear fractional-order interconnected systems. Secondly, a new condition in terms of a linear matrix inequality is proposed to ensure the existence of the event-triggered controller. Thirdly, a numerical example with simulation results is provided to demonstrate the effectiveness of the proposed design method.

In the next section, we present some preliminaries and the problem statement. The design of an event-triggered mechanism and a state feedback controller is presented in Section 3. A numerical example with simulation results is presented in Section 4. In Section 5 we provide the conclusion of the paper.

Notation: X^T denotes the matrix transpose. $||\cdot||$ is the Euclidean norm. $\mathbb{R}^n$ is the $n-$ dimensional linear vector space over $\mathbb{R}$. * is the entries of a matrix implied by symmetry and diag is a block-diagonal matrix. $\Gamma(\nu)=\int\limits_0^\infty e^{-t}t^{\nu-1}dt$ is the gamma function. $I^\alpha v(t)=\frac{1}{\Gamma(\alpha)}\int_0^t(t-\tau)^{\alpha-1}v(\tau)\,d\tau$ denotes the Riemann-Liouville fractional integral operator of order $\alpha>0$. $D^\alpha v(t)=\frac{1}{\Gamma(1-\alpha)}\int_0^t(t-\tau)^{-\alpha}\dot{v}(\tau)d\tau$ denotes the Caputo derivative of function $v(t)$ with order $\alpha\in(0,1)$.

2. PRELIMINARIES AND PROBLEM STATEMENT

We now consider the following fractional-order time-varying interconnected system with time-varying delays:

$$D^{\alpha_i}x_i(t) = (A_{ii}+\Delta A_{ii}(t))x_i(t)+B_iu_i(t)+\sum_{j=1,j\neq i}^{N}A_{ij}x_j(t)+f_i(x_i(t)),\ t\geq 0, \quad (1)$$

$$x_i(0) = \phi_i(0), \quad (2)$$

where $N\in\mathbb{N}$, $N\geq 2$, $0<\alpha_i\leq 1$, $x_i(t)\in\mathbb{R}^{n_i}$, $x_j(t)\in\mathbb{R}^{n_j}$ and $u_i(t)\in\mathbb{R}^{m_i}$ are the local state, remote state, and control input vectors, respectively. Each $\phi_i(0)\in\mathbb{R}^{n_i}$ is an initial condition. Matrices $A_{ii}\in\mathbb{R}^{n_i\times n_i}$, $A_{ij}\in\mathbb{R}^{n_i\times n_j}$, and $B_i\in\mathbb{R}^{n_i\times m_i}$ are constant matrices. $\Delta A_{ii}(t)=E_iF_i(t)H_i$, where E_i, H_i, are known real constant matrices of appropriate dimensions, $F_i(t)$ is unknown real time-varying matrix satisfying

$$F_i^T(t)F_i(t)\leq I, \forall t\geq 0. \quad (3)$$

By $D^{\alpha_i}x_i(t)$ we meant that $D^{\alpha_i}x_i(t)=\begin{bmatrix} D^{\alpha_i}x_{i1}(t)\\ D^{\alpha_i}x_{i2}(t)\\ \vdots\\ D^{\alpha_i}x_{in_i}(t)\end{bmatrix}$. In (1), the nonlinear function $f_i(x_i(t))$ is assumed to be satisfied conditions $f_i(0)=0$ and

$$||f_i(v_1)-f_i(v_2)||\leq L_i, \forall v_1,v_2\in\mathbb{R}^{n_i},\ i=1,2,\ldots,N, \quad (4)$$

where $L_i\in(0,\infty)$.

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In the following, we will propose an ETM and design a robust state feedback controller based on the proposed ETM to stabilize the fractional-order interconnected system.

We first express the system (1)-(2) into the following form

$$D^{\alpha}x(t) = (A+\Delta A(t))x(t) + Bu(t) + f(x(t)),\ t \geqslant 0, \tag{5}$$

$$x(0) = \phi(0), \tag{6}$$

where $n = \sum_{i=1}^{N} n_i$, $m = \sum_{i=1}^{N} m_i$, and

$$x(t) = \begin{bmatrix} x_1(t) \\ x_2(t) \\ \vdots \\ x_N(t) \end{bmatrix},\ u(t) = \begin{bmatrix} u_1(t) \\ u_2(t) \\ \vdots \\ u_N(t) \end{bmatrix},\ D^{\alpha}x(t) = \begin{bmatrix} D^{\alpha_1}x_1(t) \\ D^{\alpha_2}x_2(t) \\ \vdots \\ D^{\alpha_N}x_N(t) \end{bmatrix},$$

$$A = \begin{bmatrix} A_{11} & A_{12} & \dots & A_{1N} \\ A_{21} & A_{22} & \dots & A_{2N} \\ \vdots & \vdots & \dots & \vdots \\ A_{N1} & A_{N2} & \dots & A_{NN} \end{bmatrix},\ f(x(t)) = \begin{bmatrix} f_1(x_1(t)) \\ f_2(x_1(t)) \\ \vdots \\ f_N(x_N(t))) \end{bmatrix},$$

$$\Delta A(t) = \text{diag}(\Delta A_{11}(t), \Delta A_{22}(t), \dots, \Delta A_{NN}(t)),\ B = \text{diag}(B_1, B_2, \dots, B_N).$$

Remark 1. The following conditions hold:

$$f(0) = 0,\ \|f(x) - f(y)\| \leq L\|x - y\| \tag{7}$$

for any $x, y \in \mathbb{R}^n$, $L = n\max\{L_1, L_2, \dots, L_N\}$, and

$$\Delta A(t) = EF(t)H, \tag{8}$$

where $E = \text{diag}(E_1, E_2, \dots, E_N)$, $F(t) = \text{diag}(F_1(t), F_2(t), \dots, F_N(t))$, $H = \text{diag}(H_1, H_2, \dots, H_N)$, and $F^T(t)F(t) \leq I,\ \forall t \geq 0$.

To reduce the data transmission as much as possible while keeping the desired control performance, we propose the following event-triggered mechanism (ETM):

$$t_0 = 0,\ t_{k+1} = \inf\Big\{t > t_k : ||x(t) - x(t_k)|| \geq \gamma||x(t)||\Big\}, \tag{9}$$

where $\gamma \in (0, \infty)$ will be designed.

Provided that the ETM (9) is designed, we propose an event-triggered controller $u(t) = Kx(t_k)$, such that the following closed-loop system is asymptotically stable

$$D^{\alpha}x(t) = (A + \Delta A(t) + BK)x(t) + BK\epsilon(t) + f(x(t)),\ t \in [t_k, t_{k+1}), \tag{10}$$

$$x(0) = x_0 \in \mathbb{R}^n, \tag{11}$$

where $K \in \mathbb{R}^{m\times n}$ is determined later and $\epsilon(t)$ is the error between $x(t)$ and $x(t_k)$, i.e. $\epsilon(t) = x(t_k) - x(t),\ t \in [t_k, t_{k+1})$.

3. MAIN RESULTS

Lemma 3.1

The distance between two arbitrary triggering instants t_k and t_{k+1} of the dynamic ETM (9) is satisfied condition $\inf\Big\{t_{k+1} - t_k\Big\} > 0$, i.e. there is no Zeno-behavior for this ETM.

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Proof. For $t \in [t_k, t_{k+1})$, taking the right-hand upper Dini fractional-order derivative (see [28]) with note that $D^\alpha x(t_k) = 0$, the following inequality is obtained

$$\begin{aligned} D^{\alpha+}||\epsilon(t)|| &\leq ||D^\alpha x(t)|| \leq ||(A + \Delta A(t))x(t) + Bu(t) + f(x(t))|| \\ &\leq \delta_1||\epsilon(t)|| + \delta_2||x(t_k)||, \end{aligned} \tag{12}$$

where $\delta_1 = \sup\{||A + \Delta A(t)|| + L\}$ and $\delta_2 = \sup\{||A + \Delta A(t)|| + L + ||BK||\}$.

By integrating inequality (12) from t_k to t, one gets

$$\begin{aligned} ||\epsilon(t)|| - ||\epsilon(t_k)|| &\leq \frac{1}{\Gamma(\alpha)}\Big(\int_{t_k}^{t} \delta_1||\epsilon(s)||(t-s)^{\alpha-1}ds \\ &\quad + \int_{t_k}^{t} \delta_2||x(t_k)||(t-s)^{\alpha-1}ds\Big) \\ &\leq \frac{1}{\Gamma(\alpha+1)}\delta_2||x(t_k)||(t-t_k)^\alpha \\ &\quad + \frac{1}{\Gamma(\alpha)}\int_{t_k}^{t} \delta_1||\epsilon(s)||(t-s)^{\alpha-1}ds. \end{aligned} \tag{13}$$

Since $||\epsilon(t_k)|| = 0$ and $\lim_{t \to t_{k+1}^-} ||\epsilon(t)|| = ||\epsilon(t_{k+1}^-)|| \geq ||\epsilon(t)||, \ \ t \in [t_k, t_{k+1})$, the following inequality is obtained

$$\begin{aligned} ||\epsilon(t)|| &\leq \frac{1}{\Gamma(\alpha+1)}\delta_2||x(t_k)||(t-t_k)^\alpha \\ &\quad + \frac{1}{\Gamma(\alpha)}\int_{t_k}^{t} \delta_1||\epsilon(t_{k+1}^-)||(t-s)^{\alpha-1}ds \\ &\leq \frac{\delta_2||x(t_k)|| + \delta_1||\epsilon(t_{k+1}^-)||}{\Gamma(\alpha+1)}(t-t_k)^\alpha. \end{aligned} \tag{14}$$

Letting $t \to t_{k+1}^-$ on both side of (14), we obtain

$$||\epsilon(t_{k+1}^- t)|| \leq \frac{\delta_2||x(t_k)|| + \delta_1||\epsilon(t_{k+1}^-)||}{\Gamma(\alpha+1)}(t_{k+1}-t_k)^\alpha. \tag{15}$$

It follows from (15) and the event-triggered condition in (4) that

$$\gamma||x(t_k)|| \leq ||\epsilon(t_{k+1}^-)|| \leq \frac{\delta_2||x(t_k)||(t_{k+1}-t_k)^\alpha}{\Gamma(\alpha+1) - \delta_1(t_{k+1}-t_k)^\alpha}. \tag{16}$$

Inequality (16) implies that

$$(t_{k+1}-t_k)^\alpha \geq \frac{\gamma\Gamma(\alpha+1)}{\gamma\delta_1 + \delta_2}. \tag{17}$$

Therefore, we obtain

$$t_{k+1} - t_k \geq e^{\frac{1}{\alpha}\ln\left(\frac{\gamma\Gamma(\alpha+1)}{\gamma\delta_1+\delta_2}\right)} > 0. \tag{18}$$

The proof is completed.

We first obtain the following result which provides a sufficient condition to guarantee the stabilizability of the nonlinear system (10).

Theorem 3.2
Given a positive scalar ξ. The closed-loop system (10) is globally asymptotically stable if there exist positive scalars ν_1, ν_2, θ, a symmetric positive definite matrix P, and a matrix Y with appropriate

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dimensions such that the following LMI is satisfied:

$$\begin{bmatrix} \Omega_{11} & P^{-1}H^T & LP^{-1} & P^{-1} & BY \\ * & -\nu_1 I & 0 & 0 & 0 \\ * & * & -\nu_2 I & 0 & 0 \\ * & * & * & -\theta I & 0 \\ * & * & * & * & \xi(1-2P^{-1}) \end{bmatrix} < 0, \tag{19}$$

where $\gamma = \frac{1}{\sqrt{\theta\xi}}$ and

$$\Omega_{11} = AP^{-1} + P^{-1}A^T + BY + Y^T B^T + \nu_1 EE^T + \nu_2 I.$$

Moreover, the event-triggered controller is obtained as follows:

$$u(t) = YPx(t_k), \quad t \in [t_k, t_{k+1}). \tag{20}$$

Proof. Let us consider the following Lyapunov functional candidate:

$$V(t) = x^T(t)Px(t). \tag{21}$$

By taking the Caputo derivative of $V(t)$ along the trajectories of the closed-loop system (10) and using Theorem 2 in [29], we obtain

$$\begin{aligned} D^\alpha V(t) \leq 2x^T(t)D^\alpha x(t) = x^T(t)\Big[PA + A^T P + PBK \quad + K^T B^T P\Big]x(t) \\ + 2x^T(t)EF(t)Hx(t) + 2x^T(t)PBK\epsilon(t) + 2x^T(t)Pf(x(t)). \end{aligned} \tag{22}$$

Combining inequality (7) with the Cauchy matrix inequality yields

$$2x^T(t)PEF(t)Hx(t) \leq \nu_1 x^T(t)PEE^T Px(t) + \nu_1^{-1}x^T(t)H^T Hx(t), \tag{23}$$

$$2x^T(t)Pf(x(t)) \leq \nu_2 x^T(t)PPx(t) + \nu_2^{-1}f^T(x(t))f(x(t)) \leq \nu_2 x^T(t)PPx(t) + \nu_2^{-1}L^2 x^T(t)x(t). \tag{24}$$

and

$$\begin{aligned} 2x^T(t)PBK\epsilon(t)) &\leq \xi e^T(t)\epsilon(t) + \xi^{-1}x^T(t)PBKK^T B^T Px(t) \\ &\leq \xi\gamma^2 x^T(t)x(t) + \xi^{-1}x^T(t)PBKK^T B^T Px(t). \end{aligned} \tag{25}$$

It follows from (22) to (25) that

$$D^\alpha V(t) \leq x^T(t)\Omega x(t), \quad \forall t \geq 0, \tag{26}$$

where

$$\begin{aligned} \Omega = PA + A^T P + PBK + K^T B^T P + \nu_1 PEE^T P + \nu_2 PP + \xi\gamma^2 I \\ + \nu_1^{-1}H^T H + \nu_2^{-1}L^2 I + \xi^{-1}PBKK^T B^T P. \end{aligned}$$

We will prove that $\Omega < 0$. For this, by denoting $\Phi = P^{-1}\Omega P^{-1}$, it gives

$$\begin{aligned} \Phi = AP^{-1} + P^{-1}A^T + BY + Y^T B^T + \nu_1 EE^T + \nu_2 I \\ + \xi\gamma^2 P^{-1}P^{-1} + \nu_1^{-1}P^{-1}H^T HP^{-1} + \nu_2^{-1}L^2 P^{-1}P^{-1} + \xi^{-1}BYP^2Y^T B^T. \end{aligned} \tag{27}$$

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It follows from the Schur complement lemma that $\Phi < 0$ is equivalent to the following inequality

$$\begin{bmatrix} \Omega_{11} & P^{-1}H^T & LP^{-1} & P^{-1} & BY \\ * & -\nu_1 I & 0 & 0 & 0 \\ * & * & -\nu_2 I & 0 & 0 \\ * & * & * & -\theta I & 0 \\ * & * & * & * & -\xi P^{-2} \end{bmatrix} < 0. \quad (28)$$

Now, by combining inequality $I - 2P^{-1} \geq -P^{-2}$ with inequality (19), one obtains inequality (28). Thus, we can conclude that $D^{\alpha}V(t) < 0$, i.e system (10) is asymptotically stable. The proof is completed.

Remark 2. If the assumptions of Theorem 3.2 are satisfied then the closed-loop system (10) is globally asymptotically stable, i.e. under the event-triggered controller $u(t) = Kx(t_k)$, the state vector $x(t) = \begin{bmatrix} x_1(t) \\ x_2(t) \\ \vdots \\ x_N(t) \end{bmatrix}$ of (10) converges to zero as t goes to infinity. As a result, the state vector $x_i(t) = \begin{bmatrix} x_{i1}(t) \\ x_{i2}(t) \\ \vdots \\ x_{in_i}(t) \end{bmatrix}$ converges to zero as t goes to infinity for all $i = 1, 2, \ldots .N$.

The following algorithm allows us to design ETM (9) and matrix K.

Algorithm 1

Step 1: Given an interconnected system of the form (1)-(2). Check if conditions (3) and (4) are satisfied. Obtain $L = n \max\{L_1, L_2, \ldots, L_N\}$.
Step 2: Given a positive scalar ξ, solve the convex problem (19) to obtain γ, P and Y.
Step 3: Obtain the event-triggered mechanism (9) and matrix $K = YP$.

4. AN EXAMPLE

Let us consider the following system of the form (1)-(2), where $\alpha = 0.87$ and

$$x_1(t) = \begin{bmatrix} x_{11}(t) \\ x_{12}(t) \\ x_{13}(t) \end{bmatrix}, \; x_2(t) = \begin{bmatrix} x_{21}(t) \\ x_{22}(t) \\ x_{23}(t) \end{bmatrix}, \; A_{11} = \begin{bmatrix} -5 & 0 & 0 \\ 0.2 & -4 & 0 \\ 0.1 & 0.2 & 0.1 \end{bmatrix},$$

$$A_{12} = \begin{bmatrix} 1 & 2 & 0 \\ 1 & 0 & 0 \\ 0 & 2 & 1 \end{bmatrix}, \; A_{21} = \begin{bmatrix} 3 & 2 & 0 \\ 1 & 1 & 0 \\ 1 & 0 & 0 \end{bmatrix}, \; A_{22} = \begin{bmatrix} -4 & 0 & 0 \\ 1 & -5 & 0.2 \\ 0.1 & 0 & -3 \end{bmatrix},$$

$$B_1 = \begin{bmatrix} 1 \\ 1 \\ 42 \end{bmatrix}, \; B_2 = \begin{bmatrix} 1 \\ 2 \\ 1 \end{bmatrix}, E_1 = \begin{bmatrix} 1 \\ 0 - 0.1 \end{bmatrix}, \; H_1 = \begin{bmatrix} 0.1 & 0 & 0.01 \end{bmatrix},$$

$$E_2 = \begin{bmatrix} 2 \\ 0 \\ -0.2 \end{bmatrix}, \; H_2 = \begin{bmatrix} 0.2 & 0 & 0.02 \end{bmatrix}, \; F_1(t) = F_2(t) = \sin t, \; \forall t \geq 0,$$

$$f_1(x_1(t)) = \begin{bmatrix} 0.01\sin(x_{11}(t)) \\ 0 \\ 0.05\sin(x_{13}(t)) \end{bmatrix}, \; f_2(x_2(t)) = \begin{bmatrix} 0.04\cos(x_{21}(t)) \\ 0 \\ 0.04\cos(x_{23}(t)) \end{bmatrix}.$$

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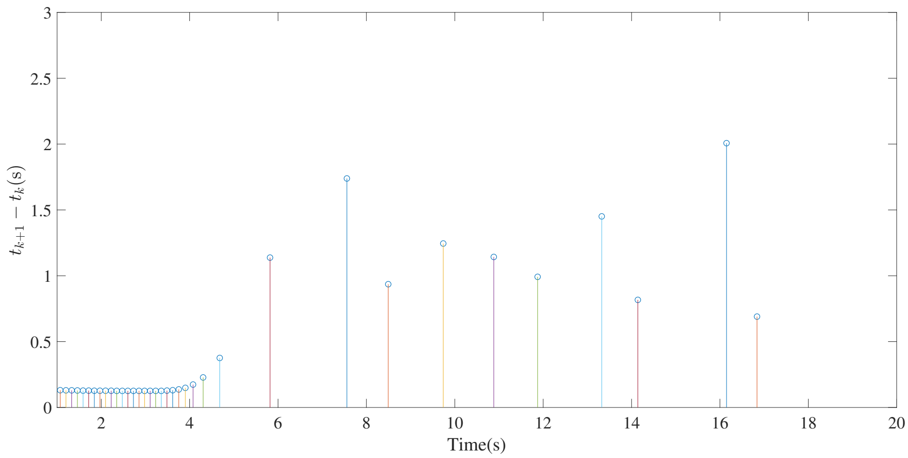

Figure 1. Triggering instants and intervals of ETM (9)

Now, we follow Algorithm 1 to design an event-triggered controller for this example.

Step 1: We can check that nonlinear functions $f_1(x_1(t))$ and $f_2(x_2(t))$ are Lipschitz with $L_1 = 0.05$ and $L_2 = 0.04$, respectively. Therefore, we obtain $L = 2\max\{L_1, L_2\} = 0.1$.

Step 2: Given $\xi = 0.95$, the LMI condition (19) is feasible with $\gamma = 0.0306$, and

$$P = \begin{bmatrix} 0.0041 & -0.0006 & 0.0001 & -0.0015 & -0.0009 & -0.0002 \\ -0.0006 & 0.0041 & -0.0003 & -0.0011 & -0.0002 & 0.0001 \\ 0.0001 & -0.0003 & 0.0029 & 0 & -0.0013 & -0.0006 \\ -0.0015 & -0.0011 & 0 & 0.0031 & 0 & 0.0003 \\ -0.0009 & -0.0002 & -0.0013 & 0 & 0.0047 & -0.0004 \\ -0.0002 & 0.0001 & -0.0006 & 0.0003 & -0.0004 & 0.00341 \end{bmatrix},$$

$$Y = \begin{bmatrix} -38.5 & -33.0843 & -193.5221 & -38.2461 & -82.3415 & -54.1894 \\ -146.8294 & -112.0405 & -16.7805 & -189.5149 & -15.5388 & 19.6974 \end{bmatrix}.$$

Step 3: The event triggering mechanisms is

$$t_0 = 0,\ t_{k+1} = \inf\Big\{t > t_k : ||x(t) - x(t_k)|| \geq 0.0306||x(t)||\Big\},$$

and the event-triggered state feedback controller is obtained as

$$u(t) = \begin{bmatrix} -0.0117 & -0.0116 & -0.4119 & -0.0327 & -0.0656 & -0.0414 \\ -0.2514 & -0.165 & -0.0148 & -0.2523 & 0.1075 & 0.0453 \end{bmatrix} x(t_k),$$

for $t \in [t_k, t_{k+1})$.

For simulation, we choose the initial condition $\begin{bmatrix} x_{11}(0) \\ x_{12}(0) \\ x_{13}(0) \end{bmatrix} = \begin{bmatrix} 1 \\ 2 \\ 3 \end{bmatrix}$ and $\begin{bmatrix} x_{21}(0) \\ x_{22}(0) \\ x_{23}(0) \end{bmatrix} = \begin{bmatrix} 4 \\ 5 \\ 6 \end{bmatrix}$. Figure 1 shows the triggering instants and intervals of the ETM (9). Figure 2 and Figure 3 show the responses of $x_{11}(t)$, $x_{12}(t)$, $x_{13}(t)$, $x_{21}(t)$, $x_{22}(t)$, $x_{23}(t)$ of the open-loop system and the closed-loop system, respectively. It is shown from Figure 1 that time intervals between two consecutive triggering events of the measurement transmission instant sequence are positive, i.e., the Zeno behavior does not happen for this ETM. Figure 2 and Figure 3, we see that the open-loop system is not asymptotically stable while the closed-loop system is asymptotically stable.

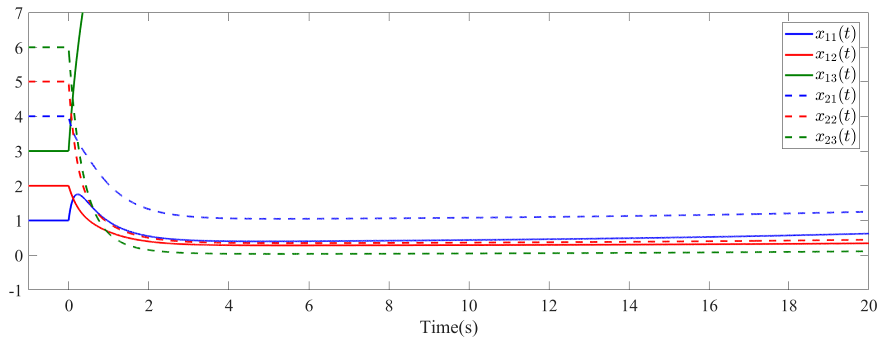

Figure 2. Responses of the open-loop system

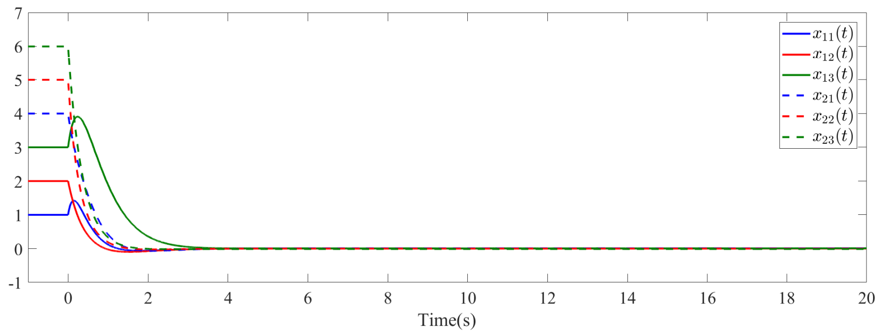

Figure 3. Responses of the closed-loop system

5. CONCLUSION

We have considered the design of event-triggered stabilizing state feedback controllers for nonlinear fractional-order interconnected systems. A new Zeno-free event-triggered mechanism has been first proposed, and then the event-triggered state feedback controller is designed in terms of a convex linear matrix inequality. A numerical example with simulation results is provided to demonstrate the effectiveness of the proposed design method.

DATA AVAILABILITY STATEMENT

All data generated or analyzed during this study are included in this article.

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