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# FINITE-TIME $H_\infty$ CONTROL FOR NETWORKED CONTROL SYSTEMS WITH TIME DELAY AND BOUNDED DISTURBANCE

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Abstract. *In this paper, the finite-time $H_\infty$ control problem of a class of networked control systems (NCSs) with time delay is investigated. The main results provided in the paper are sufficient conditions for finite-time robust stability with an $H_\infty$ normal bound $\bar{\gamma}$ via state feedback. Firstly, an augmentation approach is proposed to model NCSs with time delay as linear system. Secondly, based on finite time stability theory, the sufficient conditions which guarantee that the underlying system is robustly stable with an $H_\infty$ normal bound $\bar{\gamma}$ over a finite-time interval are derived via linear matrix inequalities (LMIs) formulation. Lastly, an illustrative example is given to demonstrate the effectiveness of the proposed results.*
**Keywords:** Networked control systems, Finite time control, Linear matrix inequalities

1. **Introduction.** Networked control systems (NCSs) are control systems in which sensor data and control commands are being communicated over a wired or wireless communication network. Compared with the traditional point-to-point wiring, the use of the communication channels can reduce the costs of cables and power, simplify the installation and maintenance of the whole system, and increase the reliability. Moreover, NCSs are applied in a broad range of systems, such as mobile sensor networks, remote surgery, automated highway systems, unmanned aerial vehicles and multi-agent systems [1-4]. However, the insertion of communication networks in feedback control loops makes the NCSs analysis and synthesis complex [5], where much attention has been paid to the delayed data packets of an NCSs due to network transmissions.

On the other hand, finite-time boundedness and stability can be used in all those applications where large values of the state should not be attained, for instance in the presence of saturations. However, most of the results in the literature focus on Lyapunov stability. Some early results on finite-time stability (FTS) can be found in [6]. More recently, the concept of FTS has been revisited in the light of recent results coming from linear matrix inequalities (LMIs) theory, which has made it possible to find less conservative conditions for guaranteeing FTS and finite time stabilization of discrete-time and continuous-time systems [7-12]. In [13], the definition of finite-time $H_\infty$ control is presented and a state feedback controller is designed which ensures that the closed-loop system is finite-time bounded and reduces the effect of the disturbance input on the controlled output to a prescribed level. However, a defect occurred in Lemma 3 in [13], which plays a key role in $H_\infty$ finite-time bounded controller design. In [14], the defect is addressed, and the corrected results are given. In [15], robust finite-time stabilization problem for a family of uncertain singular Markovian jump systems is proposed.

To the best of our knowledge, the finite-time $H_\infty$ control problem for NCSs with time delay has not been fully investigated to date. Especially for the case where the plant subjects to external interference, very few results related to NCSs are available in the existing literature, which motivates the study of this paper. In this paper, the $H_\infty$ control problem of a class of NCSs with time delay is studied. The sufficient conditions which guarantee that the underlying system is robustly stable with an $H_\infty$ normal bound $\bar{\gamma}$ over a finite-time interval are derived via LMIs formulation. Lastly, an illustrative example is given to demonstrate the effectiveness of the proposed methods.

This paper is organized as follows. An augmentation approach is proposed to model NCSs with time delay as linear systems in Section 2. The sufficient conditions which guarantee that the underlying system is robustly stable over a finite-time interval are given via LMIs formulation in Section 3. Section 4 provides a numerical example to illustrate the effectiveness of our results. Finally, Section 5 gives some concluding remarks.

2. **Problem Formulation and Preliminaries.** Consider NCS depicted in Figure 1 consists of three components: a plant to be controlled, a network such as the Internet, and a controller.

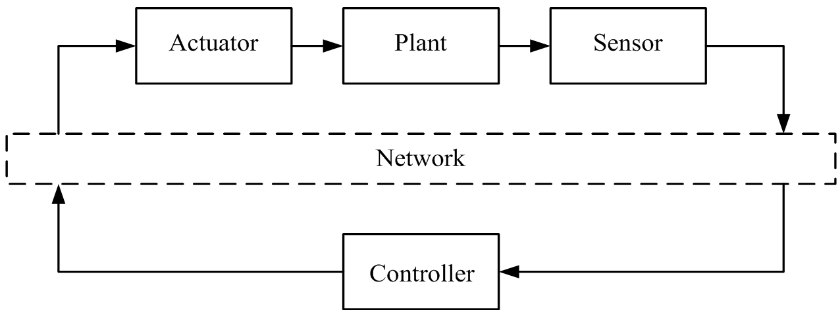


FIGURE 1. Illustration of NCSs over communication network

In this paper, it is assumed that the plant is described by

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) + Gw(t), \\ z(t) &= Cx(t) + D_1u(t) + D_2w(t), \end{aligned} \tag{1}$$

and time-invariant controller

$$u(kh) = -Kx(kh), \quad k = 0, 1, 2, \cdots, \tag{2}$$

where $x(t) \in \mathbb{R}^n$ is the state, $u(t) \in \mathbb{R}^m$ is the control input, $w(t) \in \mathbb{R}^p$ is the exogenous input, and $z(t) \in \mathbb{R}^p$ is the controlled output. $A$, $B$, $G$, $C$, $D_1$, and $D_2$ are known real constant matrices with appropriate dimensions. We make the following assumption about NCSs.

**Assumption 2.1.** *During the finite time $T$, the exogenous input $w(t)$ satisfies*

$$\int_0^T w^T(t)w(t)dt \le d^2,$$

*where $d$ is a positive constant.*

Then the system equation can be written as

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) + Gw(t), \quad t \in [kh + \tau, (k+1)h + \tau), \\ z(t) &= Cx(t) + D_1u(t) + D_2w(t), \\ u(t^+) &= -Kx(t - \tau), \quad t \in \{kh + \tau, k = 1, 2, \cdots\}. \end{aligned} \tag{3}$$

Sampling the system with period $h$, we obtain

$$x(k+1) = \Phi x(k) + \Gamma_0(\tau)u(k) + \Gamma_1(\tau)u(k-1) + \Psi w(k),$$

$$z(k) = Cx(k) + D_1u(k) + D_2w(k),$$

where

$$\Phi = e^{Ah}, \quad \Psi = \int_0^h e^{As}Gds, \quad \Gamma_0(\tau) = \int_0^{h-\tau} e^{As}Bds, \quad \Gamma_1(\tau) = \int_{h-\tau}^h e^{As}Bds.$$

Define $\tilde{x}(k) = [x^T(k), u^T(k-1)]^T$, $\tilde{z}(k) = [z^T(k), u^T(k-1)]^T$, and $\tilde{w}(k) = [w^T(k), 0^T]^T$. Then we have the augmented closed-loop systems

$$\tilde{x}(k+1) = \left(\tilde{A} + \tilde{B}\tilde{K}\right)\tilde{x}(k) + \tilde{G}\tilde{w}(k), \tag{4}$$

$$\tilde{z}(k) = \left(\tilde{C} + \tilde{D}_1\tilde{K}\right)\tilde{x}(k) + \tilde{D}_2\tilde{w}(k), \tag{5}$$

where

$$\tilde{A} = \begin{bmatrix} \Phi & \Gamma_1(\tau) \\ 0 & 0 \end{bmatrix}, \quad \tilde{B} = \begin{bmatrix} -\Gamma_0(\tau) \\ -I \end{bmatrix}, \quad \tilde{C} = \begin{bmatrix} C & 0 \\ 0 & I \end{bmatrix},$$

$$\tilde{D}_1 = \begin{bmatrix} D_1 \\ 0 \end{bmatrix}, \quad \tilde{D}_2 = \begin{bmatrix} D_2 & 0 \\ 0 & 0 \end{bmatrix}, \quad \tilde{G} = \begin{bmatrix} \Psi & 0 \\ 0 & 0 \end{bmatrix},$$

and $\tilde{K}$ is defined as follows

$$\tilde{K} = \begin{bmatrix} K & 0 \end{bmatrix}. \tag{6}$$

**Remark 2.1.** *According to Assumption 2.1, for finite positive integer $N$, the augmented exogenous input vector $\tilde{w}(k)$ satisfies the following condition*

$$\sum_{k=1}^{N} \tilde{w}^T(k)\tilde{w}(k) \le d^2. \tag{7}$$

**Remark 2.2.** *When the delay is longer than one sampling period, that is to say, $h < \tau < lh$, where $l > 1$, the augmented state vector $\tilde{x}(k)$ is defined as*

$$\tilde{x}(k) = [x(k), u(k-l), \cdots, u(k-1)]^T.$$

The main aim of this paper is to find some sufficient conditions which guarantee that the system (4) is robustly stable with an $H_\infty$ normal bound $\gamma$ over a finite-time interval. The general idea of finite-time stability concerns the boundedness of the state of a system over a finite time interval for given initial conditions, and this concept can be formalized through the following definitions.

**Definition 2.1.** *System (4) is said to be finite-time bounded with respect to $(\alpha, d, \beta, R, N)$, where $R$ is a positive-definite matrix, $0 < \alpha < \beta$, if*

$$\begin{cases} \tilde{x}^T(0)R\tilde{x}(0) \le \alpha^2 \\ \sum_{k=1}^N \tilde{w}^T(k)\tilde{w}(k) \le d^2 \end{cases} \Longrightarrow \tilde{x}^T(k)R\tilde{x}(k) \le \beta^2, \quad k \in \{1, \cdots, N\}.$$

**Definition 2.2.** *System (4) with $w(k) = 0$ is said to be finite-time stable with respect to $(\alpha, \beta, R, N)$, where $R$ is a positive-definite matrix, $0 < \alpha < \beta$, if*

$$\tilde{x}^T(0)R\tilde{x}(0) \le \alpha^2 \Longrightarrow \tilde{x}^T(k)R\tilde{x}(k) \le \beta^2, \quad k \in \{1, \cdots, N\}.$$

**Definition 2.3.** *The closed-loop networked control systems (4) and (5) are said to be robustly stable with an $H_\infty$ normal bound $\gamma$, if the following hold*

- *System (4) is finite time boundedness.*
- *Under the assumption of zero initial condition, the controlled output $\tilde{z}(k)$ satisfies*

$$\sum_{k=1}^{N} \tilde{z}^T(k)\tilde{z}(k) < \gamma^2 \sum_{k=1}^{N} \tilde{w}^T(k)\tilde{w}(k).$$

To this end, the following lemma will be essential for the proofs in the next section and their proofs can be found in the cited references.

**Lemma 2.1.** (see [16]). *For given state feedback control matrix $K$, system (4) is finite-time bounded with respect to $(\alpha, d, \beta, R, N)$, if there exists a symmetric positive definite matrix $P$ and two scalars $\mu \geq 1$, $\gamma \geq 0$, such that the following conditions hold*

$$\begin{bmatrix} \left(\tilde{A}+\tilde{B}\tilde{K}\right)^T P\left(\tilde{A}+\tilde{B}\tilde{K}\right)-\mu P & \left(\tilde{A}+\tilde{B}\tilde{K}\right)^T P\tilde{G} \\ \tilde{G}^T P\left(\tilde{A}+\tilde{B}\tilde{K}\right) & \tilde{G}^T P\tilde{G}-\gamma^2 I \end{bmatrix} < 0, \tag{8}$$

$$\frac{\lambda_2}{\lambda_1}\mu^N\alpha^2 + \frac{1}{\lambda_1}\mu^N\gamma^2 d^2 < \beta^2, \tag{9}$$

*where*

$$\lambda_1 = \lambda_{\min}\left(\tilde{P}\right), \quad \lambda_2 = \lambda_{\max}\left(\tilde{P}\right), \quad \tilde{P} = R^{-1/2}PR^{-1/2}.$$

3. **Main Results.** In this section, we will find a state feedback control matrix $K$, such that systems (4) and (5) are robustly stable with an $H_\infty$ normal bound $\bar{\gamma}$ over a finite-time interval. We have the following theorem.

**Theorem 3.1.** *For given state feedback control matrix $K$, systems (4) and (5) are robustly stable with an $H_\infty$ normal bound $\bar{\gamma} = \gamma\mu^{\frac{N-1}{2}}$, if there exists a symmetric positive definite matrix $P$ and two scalars $\mu \geq 1$, $\gamma > 0$, such that the following conditions hold*

$$\begin{bmatrix} \bar{A}^T P\bar{A} + \bar{C}^T\bar{C} - \mu P & \bar{A}^T P\tilde{G} + \bar{C}^T\tilde{D}_2 \\ \tilde{G}^T P\bar{A} + \tilde{D}_2^T\bar{C} & \tilde{G}^T P\tilde{G} + \tilde{D}_2^T\tilde{D}_2 - \gamma^2 I \end{bmatrix} < 0, \tag{10}$$

$$\frac{1}{\lambda_3}\mu^N\gamma^2 d^2 < \beta^2, \tag{11}$$

*where*

$$\bar{A} = \tilde{A} + \tilde{B}\tilde{K}, \quad \bar{C} = \tilde{C} + \tilde{D}_1\tilde{K}, \quad \tilde{P} = R^{-1/2}PR^{-1/2}, \quad \lambda_3 = \lambda_{\min}(\tilde{P}).$$

**Proof:** Note that

$$\begin{bmatrix} \bar{C}^T\bar{C} & \bar{C}^T\tilde{D}_2 \\ \tilde{D}_2^T\bar{C} & \tilde{D}_2^T\tilde{D}_2 \end{bmatrix} = \begin{bmatrix} \bar{C}^T \\ \tilde{D}_2^T \end{bmatrix} \begin{bmatrix} \bar{C} & \tilde{D}_2 \end{bmatrix} \geq 0.$$

Therefore, condition (10) implies that

$$\begin{bmatrix} \bar{A}^T P\bar{A} - \mu P & \bar{A}^T P\tilde{G} \\ \tilde{G}^T P\bar{A} & \tilde{G}^T P\tilde{G} - \gamma^2 I \end{bmatrix} < 0. \tag{12}$$

From Lemma 2.1, conditions (11) and (12) guarantee that the system (4) is finite-time bounded with respect to $(0, d, \beta, R, N)$. On the other hand, let $V(\tilde{x}(k)) = \tilde{x}^T(k)P\tilde{x}(k)$, and then we have

$$V(\tilde{x}(k+1)) = \begin{bmatrix} \tilde{x}^T(k) & \tilde{w}^T(k) \end{bmatrix} \begin{bmatrix} \bar{A}^T P\bar{A} & \bar{A}^T P\tilde{G} \\ \tilde{G}^T P\bar{A} & \tilde{G}^T P\tilde{G} \end{bmatrix} \begin{bmatrix} \tilde{x}(k) \\ \tilde{w}(k) \end{bmatrix}.$$

Due to condition (10), we have

$$V(\tilde{x}(k+1)) \leq \mu V(\tilde{x}(k)) + \gamma^2\tilde{w}^T(k)\tilde{w}(k) - \tilde{z}^T(k)\tilde{z}(k). \tag{13}$$

Applying iteratively (13) and noting that $V(\tilde{x}(0)) = 0$, we have

$$V(\tilde{x}(k)) < \gamma^2\sum_{j=1}^{k}\mu^{k-j}\tilde{w}^T(j-1)\tilde{w}(j-1) - \sum_{j=1}^{k}\mu^{k-j}\tilde{z}^T(j-1)\tilde{z}(j-1), \tag{14}$$

which implies that

$$\sum_{j=1}^{k}\mu^{k-j}\tilde{z}^T(j-1)\tilde{z}(j-1) < \gamma^2\sum_{j=1}^{k}\mu^{k-j}\tilde{w}^T(j-1)\tilde{w}(j-1). \tag{15}$$

Noting that $\mu \geq 1$, we have

$$\sum_{j=1}^{k}\mu^{k-j}\tilde{w}^T(j-1)\tilde{w}(j-1) \leq \mu^{k-1}\sum_{j=1}^{k}\tilde{w}^T(j-1)\tilde{w}(j-1), \tag{16}$$

and

$$\sum_{j=1}^{k}\mu^{k-j}\tilde{z}^T(j-1)\tilde{z}(j-1) \geq \sum_{j=1}^{k}\tilde{z}^T(j-1)\tilde{z}(j-1). \tag{17}$$

From (15)-(17), we can obtain

$$\sum_{j=1}^{N}\tilde{z}^T(j)\tilde{z}(j) < \gamma^2\mu^{N-1}\sum_{j=1}^{N}\tilde{w}^T(j)\tilde{w}(j) = \bar{\gamma}^2\sum_{j=1}^{N}\tilde{w}^T(j)\tilde{w}(j). \tag{18}$$

This completes the proof. □

Now we turn back to our original problem, that is to find sufficient conditions which guarantee that the system (3) with the controller (2) is finite-time bounded with respect to $(\alpha, d, \beta, R, N)$. The solution of this problem is given by the following theorem.

**Theorem 3.2.** *System (4) and (5) are robustly stable with an $H_\infty$ normal bound $\bar{\gamma} = \gamma\mu^{\frac{N-1}{2}}$, if there exist symmetric positive definite matrices $Q_1$, $Q_2$, a matrix $L$, and two scalars $\mu \geq 1$, $\gamma > 0$, such that the following conditions hold*

$$\begin{bmatrix} -\mu Q & 0 & \left(\tilde{A}Q + \tilde{B}LS\right)^T & \left(\tilde{C}Q + \tilde{D}_1LS\right)^T \\ 0 & -\gamma^2 I & \tilde{G}^T & \tilde{D}_2^T \\ \tilde{A}Q + \tilde{B}LS & \tilde{G} & -Q & 0 \\ \tilde{C}Q + \tilde{D}_1LS & \tilde{D}_2 & 0 & -I \end{bmatrix} < 0, \tag{19}$$

$$\lambda_4\mu^N\gamma^2 d^2 < \beta^2, \tag{20}$$

*where*

$$\tilde{Q} = R^{1/2}QR^{1/2}, \quad \lambda_4 = \lambda_{\max}(\tilde{Q}).$$

*$S$ and $Q$ are defined as follows*

$$S = \begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix}, \quad Q = \begin{bmatrix} Q_1 & 0 \\ 0 & Q_2 \end{bmatrix}.$$

*In this case, the controller $K$ is given by the first $p$ columns of $\tilde{K} = LSQ^{-1}$, which is in the form (6).*

**Proof:** From condition (10) in Theorem 3.1, we have

$$\begin{bmatrix} \bar{C}^T\bar{C} - \mu P & \bar{C}^T\tilde{D}_2 \\ \tilde{D}_2^T\bar{C} & \tilde{D}_2^T\tilde{D}_2 - \gamma^2 I \end{bmatrix} + \begin{bmatrix} \bar{A}^T \\ \tilde{G}^T \end{bmatrix} P \begin{bmatrix} \bar{A} & \tilde{G} \end{bmatrix} < 0. \tag{21}$$

Applying Schur complement, we can obtain

$$\begin{bmatrix} \bar{C}^T\bar{C} - \mu P & \bar{C}^T\tilde{D}_2 & \bar{A}^T \\ \tilde{D}_2^T\bar{C} & \tilde{D}_2^T\tilde{D}_2 - \gamma^2 I & \tilde{G}^T \\ \bar{A} & \tilde{G} & -P^{-1} \end{bmatrix} < 0, \tag{22}$$

which implies that

$$\begin{bmatrix} -\mu P & 0 & \bar{A}^T \\ 0 & -\gamma^2 I & \tilde{G}^T \\ \bar{A} & \tilde{G} & -P^{-1} \end{bmatrix} + \begin{bmatrix} \bar{C}^T \\ \tilde{D}_2^T \\ 0 \end{bmatrix} \begin{bmatrix} \bar{C} & \tilde{D}_2 & 0 \end{bmatrix} < 0. \tag{23}$$

Using Schur complement again, (23) is equivalent to

$$\begin{bmatrix} -\mu P & 0 & \bar{A}^T & \bar{C}^T \\ 0 & -\gamma^2 I & \tilde{G}^T & \tilde{D}_2^T \\ \bar{A} & \tilde{G} & -P^{-1} & 0 \\ \bar{C} & \tilde{D}_2 & 0 & -I \end{bmatrix} < 0. \tag{24}$$

Pre- and post-multiplying (24) by the symmetric matrix

$$\begin{bmatrix} -P^{-1} & 0 & 0 & 0 \\ 0 & I & 0 & 0 \\ 0 & 0 & I & 0 \\ 0 & 0 & 0 & -I \end{bmatrix},$$

we can obtain the equivalent condition of (10)

$$\begin{bmatrix} -\mu P^{-1} & 0 & P^{-1}\bar{A}^T & P^{-1}\bar{C}^T \\ 0 & -\gamma^2 I & \tilde{G}^T & \tilde{D}_2^T \\ \bar{A}P^{-1} & \tilde{G} & -P^{-1} & 0 \\ \bar{C}P^{-1} & \tilde{D}_2 & 0 & -I \end{bmatrix} < 0. \tag{25}$$

Recalling that $\bar{A} = \tilde{A} + \tilde{B}\tilde{K}$, $\bar{C} = \tilde{C} + \tilde{D}_1\tilde{K}$, and letting $Q = P^{-1}$, $\tilde{K}Q = LS$, we obtain that condition (25) is equivalent to (19). On the other hand, noting that $Q = P^{-1}$, we can obtain that

$$\lambda_{\max}(Q) = \frac{1}{\lambda_{\min}(P)}. \tag{26}$$

Thus, condition (11) can be rewritten as in (20). This completes the proof. □

**Remark 3.1.** *The chosen structures for matrices $S$ and $Q$ guarantee that $\tilde{K}$ is in the form (6). In fact*

$$\tilde{K} = LSQ^{-1} = L\begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} Q_1 & 0 \\ 0 & Q_2 \end{bmatrix}^{-1} = L\begin{bmatrix} Q_1^{-1} & 0 \\ 0 & 0 \end{bmatrix} = \begin{bmatrix} K & 0 \end{bmatrix}. \tag{27}$$

**Remark 3.2.** *Condition (20) is not LMI. However, it is easy to check that condition (20) can be guaranteed by*

$$0 < \tilde{Q} < I, \tag{28}$$

$$\gamma^2 d^2 - \mu^{-N}\beta^2 < 0. \tag{29}$$

## 4. **Numerical Example.**

Consider the following system

$$\begin{aligned} \dot{x}(t) &= \begin{bmatrix} 0 & 1 \\ 0 & -0.1 \end{bmatrix} x(t) + \begin{bmatrix} 0 \\ 0.1 \end{bmatrix} u(t) + \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} w(t), \\ z(t) &= \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} x(t) + \begin{bmatrix} 0.1 \\ 0.2 \end{bmatrix} u(t) + \begin{bmatrix} 0.5 & 0 \\ 0 & 0.5 \end{bmatrix} w(t). \end{aligned} \tag{30}$$

It is assumed that $h = 0.3s$, $\tau = 0.1s$, $\alpha = 0.3$, $d = 0.4$, $\beta = 0.5$, $R = I$, $N = 10$. Applying Theorem 3.2 with $\mu = 1$ and $\gamma = 1$, it is found that the desired controller gain is given by

$$\tilde{K} = LSQ^{-1} = \begin{bmatrix} K & 0 \end{bmatrix} = \begin{bmatrix} -3.1623 & -7.0775 & 0 \end{bmatrix}.$$

The states of the closed-loop system caused by the obtained controller are shown in Figure 2 when the initial state is $x(0) = \begin{bmatrix} 0.5 & -0.5 \end{bmatrix}$. It can be seen that the closed-loop system is robustly stable.

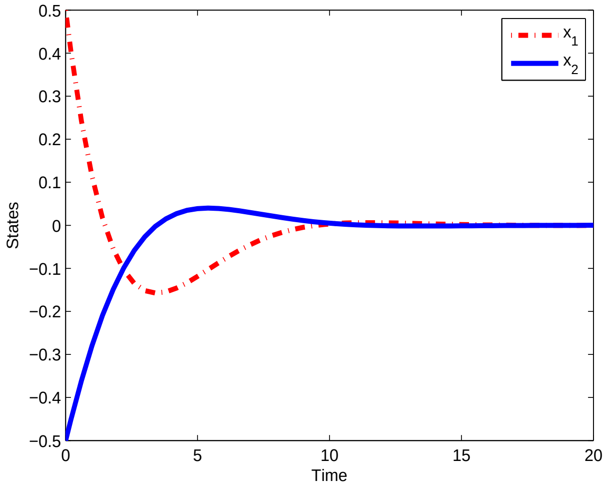


FIGURE 2. The states of the closed-loop system

5. **Conclusions.** In this paper, we have considered the finite-time $H_\infty$ control problem of a class of networked control systems (NCSs) subject to disturbance. Based on the augmentation approach, the NCS with time delay is modeled as a linear system. The sufficient conditions which guarantee that the underlying system is robustly stable with an $H_\infty$ normal bound $\bar{\gamma}$ over a finite-time interval are derived via LMIs formulation. Lastly, an illustrative example is given to demonstrate the effectiveness of the proposed results. The finite-time $H_\infty$ stabilization problem for NCSs with both packet dropout and time delay is future work.

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