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A NEW DELAY-DEPENDENT STABILITY CRITERIA FOR NETWORKED CONTROL SYSTEMS

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ABSTRACT

In this paper, the problem of stability for networked control systems (NCSs) is investigated. Considering both the time-varying network-induced delay and data packet dropouts, NCSs are transformed into typical linear systems with interval time-varying delay. Based on the obtained model, a new delay-dependent stability criteria in terms of linear matrix inequalities (LMIs) is provided by constructing a novel time-dependent Lyapunov-Krasovskii functional. The tighter integral inequalities are used to deal with the cross-product terms arose from the time derivative of the Lyapunov-Krasovskii functional for obtaining much less conservative result. Compared with some previous ones, the proposed method introduces fewer matrix variables and has less conservatism. A numerical example is provided to demonstrate the effectiveness and the benefits of the proposed method.

Keywords: *Stability Criteria, Networked Control Systems, Time-Varying Network-Induced Delay*

1. INTRODUCTION

As is well known, networked control systems (NCSs) are widely used in various fields due to their low costs, flexible architecture, simpler installation and efficiency. Nevertheless, the introduction of a network brings some new challenges such as network-induced delay and data packet dropouts which may result in the instability and poor performance. All of these will make system analysis and synthesis more difficult.

Recently, the issue of stability analysis for networked control systems has received considerable attention [1-6]. As pointed out by Yue [1], NCSs are typical systems with interval time-varying delay. Thus, the existing results about systems with interval time-varying delay can be applied directly to deal with the problems of NCSs. The idea has been adopted widely for stability analysis of NCSs [4-6]. Park [2] calculated the maximum allowable delay bound (MADB) by using Moon inequality for NCSs. Wu [8] gained a result with less conservatism through introducing free-weighting matrix method. Fridman [11] proposed a descriptor model and given the delay-dependent stability conditions in terms of LMIs. The works of Liu [3] investigated the stability for NCSs with constant delay. Yue [4] studied the design of robust H_∞ controllers for uncertain NCSs by introducing some slack matrix variables. Jiang [5] presented H_∞ stabilization criterion by using a new Lyapunov-Krasovskii functional. Zhang [6] made use of the information both the lower, upper bounds and the middle point of the time-varying delay to obtain a less conservative stability criterion than previous results. Nevertheless, the criteria still leave room for improvement.

In this paper, we are concerned with the problem of stability for NCSs with the effects of both network-induced delay and data packet dropouts. We also adopt the same method as the above mentioned to consider NCSs as systems with interval time-varying delay. A new type of augmented delay-dependent Lyapunov-Krasovskii functional is introduced in which the lower bound of the delay is partitioned. A new improved stability criteria is derived without introducing any free-weighting matrices. Finally, a numerical example is provided to illustrate the effectiveness of the proposed method.

Notation: The notation used throughout the paper is fairly standard. R^n denotes the $n-$dimensional Euclidean space and the $P>0$ means that P is real symmetric and positive definite. $R(Z)$ denote the set of real numbers (integers). The superscript ‘T’stands for the inverse and transpose of matrix. The symmetric elements of the symmetric matrix will be denoted by $*$.

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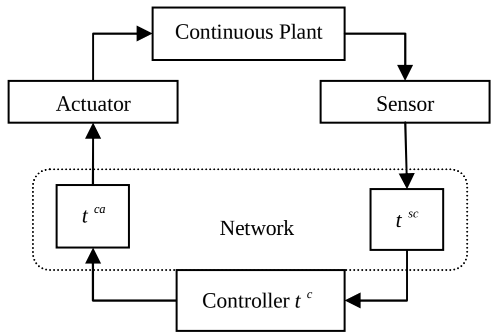

Figure 1: A typical network control system

2. PROBLEM FORMULATION

Consider the following system through a network which is shown in Fig.1:

$$\dot{x}(t) = Ax(t) + Bu(t) \quad (1)$$

where $x(t) \in R^n$, $u(t) \in R^m$ are the system state vector and the controlled input vector, A , B are the constant matrices with appropriate dimensions. By considering the communication delay τ^{sc} between the sensor and the controller and the communication delay τ^{c} in the controller, the following control law is employed for the system(1):

$$\begin{cases} u(t) = Kx(t - \tau_k^{sc} - \tau_k^{c}) \\ t \in \{kh + \tau_k^{sc} + \tau_k^{c}\}, k = 1, 2\cdots \end{cases} \quad (2)$$

where h is the sampling period and K is a controller gain.

Substituting (2) into (1), yields

$$\begin{cases} \dot{x}(t) = Ax(t) + BKx(kh) \\ t \in [kh + \tau_k, (k+1)h + \tau_{k+1}), \quad k = 1, 2\cdots \end{cases} \quad (3)$$

where $\tau_k = \tau_k^{sc} + \tau_k^{c} + \tau_k^{ca}$, τ^{ca} is the communication delay between the controller and the actuator.

Using the method as [4], the system (3) can be modified as (4) which considered the data packet dropout.

$$\begin{cases} \dot{x}(t) = Ax(t) + BKx(i_k h) \\ t \in [i_k h + \tau_k, i_{k+1} h + \tau_{k+1}), \quad k = 1, 2\cdots \end{cases} \quad (4)$$

where $i_k \subset \{1, 2, \cdots\}$ .Throughout this paper, the following assumptions are needed.

Assume1 The sensor is clock-driven, the controller and actuator are event-driven.

Assume2 $i_{k+1} > i_k$, $k = 1, 2\cdots$.

By defining $\tau(t) = t - i_k h$, $t \in [i_k h + \tau_k, i_{k+1} h + \tau_{k+1})$ $k = 1, 2\cdots$, system (4) is rewritten as the following continuous system with interval time-varying delay:

$$\begin{cases} \dot{x}(t) = Ax(t) + BKx(t - \tau(t)), \\ x(t) = \phi(t), \qquad t \in [-\tau_M, -\tau_m] \end{cases} \quad (5)$$

where $\tau(t)$ is piecewise-linear such that

$$\tau_m \le \tau_k \le \tau(t) \le (i_{k+1} - i_k)h + \tau_{k+1} \le \tau_M \quad (6)$$

with derivative $\dot{\tau}(t) = 1$ for $t \ne i_k h + \tau_k$ and $\tau(t)$ is discontinuous at the point $t = i_k h + \tau_k$.

To establish our results, we introduce the following lemmas.

Lemma 1[9] For any constant matrix $M \in R^{n \times n}$, $W = W^T > 0$, scalar $\sigma > 0$, and vector function $\dot{x} : [-\sigma, 0] \to R^n$ such that the following integration is well defined, then it holds that

$$-\sigma \int_{t-\sigma}^{t} \dot{x}^T(m) W \dot{x}(m) dm \le \begin{bmatrix} x(t) \\ x(t-\sigma) \end{bmatrix}^T \begin{bmatrix} -W & W \\ * & -W \end{bmatrix} \begin{bmatrix} x(t) \\ x(t-\sigma) \end{bmatrix}$$

Lemma 2[12] Suppose $\gamma_1 \le \gamma(t) \le \gamma_2$, where $\gamma(\cdot) : R_+ (or Z_+) \to R_+ (or Z_+)$, then, for any constant matrix Ξ_1 , Ξ_2 and Θ of appropriate dimensions, the following matrix inequality $\Theta + (\gamma(t) - \gamma_1)\Xi_1 + (\gamma_2 - \gamma(t))\Xi_2 < 0$ holds, if and only if $\Theta + (\gamma_2 - \gamma_1)\Xi_1 < 0$, $\Theta + (\gamma_2 - \gamma_1)\Xi_2 < 0$

Lemma 3[15] Given any square matrices $Q = Q^T$, M and E , then under $F^T(t)F(t) \le I$, $Q + MF(t)E + E^T F^T(t) M^T < 0$ is obtained if a constant $\varepsilon > 0$ makes $Q + \varepsilon M M^T + \varepsilon^{-1} E^T E < 0$.

3. NEW STABILITY CRITERIA

In this section, we consider stability for system(5). By constructing a novel Lyapunov-Krasovskii functional and using tighter integral inequalities to deal with cross-product terms, we have the following result.

Theorem 1 For some given constants $0 \le \tau_m \le \tau_M$, system (5) subject to (6) is asymptotically stable, if there exist real symmetric

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matrices $P>0$, $Q_1>0$, $Q_2>0$, $R_1>0$, $R_2>0$, $Z_1>0$, $Z_2>0$, $H>0$ of appropriate dimensions such that the following linear matrix inequalities hold

$$\Sigma_i = \begin{bmatrix} \Pi+\Pi_i & \Omega^T\varphi \\ * & -\varphi \end{bmatrix} < 0 ,\ (i=1,2) \qquad (7)$$

where $\varphi = \frac{\tau_m}{4}^2 (Z_1+Z_2)+(\tau_M-\tau_m)^2 H$

$\Omega = [A \quad BK \quad 0 \quad 0 \quad 0 \quad 0]$

$$\Pi_1 = -[0 \quad I \quad 0 \quad -I \quad 0 \quad 0]^T H \ [0 \quad I \quad 0 \quad -I \quad 0 \quad 0]$$

$$\Pi_2 = -[0 \quad I \quad 0 \quad 0 \quad 0 \quad -I]^T H \ [0 \quad I \quad 0 \quad 0 \quad 0 \quad -I]$$

and

$$\Pi = \begin{bmatrix} \Pi_{11} & PBK & Z_1 & 0 & 0 & 0 \\ * & \Pi_{22} & 0 & H & 0 & H \\ * & * & \Pi_{33} & Z_2 & 0 & 0 \\ * & * & * & \Pi_{44} & 0 & 0 \\ * & * & * & * & \Pi_{55} & 0 \\ * & * & * & * & * & \Pi_{66} \end{bmatrix}$$

with $\Pi_{11} = PA + A^T P + Q_1 - Z_1$

$\Pi_{22} = -2H$

$\Pi_{33} = -Q_1 + Q_2 - Z_1 - Z_2$

$\Pi_{44} = -Q_2 + R_1 - Z_2 - H$

$\Pi_{55} = -R_1 + R_2$

$\Pi_{66} = -H - R_2$

Proof. Constructing a Lyapunov-Krasovskii functional for the system (5) as

$$\begin{aligned} V(x_t) &= x^T(t)Px(t) \\ &+ \sum_{i=1}^{2}\int_{t-i\frac{\tau_m}{2}}^{t-(i-1)\frac{\tau_m}{2}} x^T(s)Q_i x(s)ds \\ &+ \sum_{i=1}^{2}\int_{t-\tau_m-i\sigma}^{t-\tau_m-(i-1)\sigma} x^T(s)R_i x(s)ds \\ &+ \frac{\tau_m}{2}\sum_{i=1}^{2}\int_{-i\frac{\tau_m}{2}}^{-(i-1)\frac{\tau_m}{2}}\int_{t+\theta}^{t} \dot{x}^T(s)Z_i\dot{x}(s)dsd\theta \\ &+ (\tau_M-\tau_m)\int_{-\tau_M}^{-\tau_m}\int_{t+\theta}^{t} \dot{x}^T(s)H\dot{x}(s)dsd\theta \end{aligned} \qquad (8)$$

where $P>0$, $Q_1>0$, $Q_2>0$, $R_1>0$, $R_2>0$, $Z_1>0$, $Z_2>0$, $H>0$ are real symmetric matrices of appropriate dimensions , $\sigma = \frac{\tau_M - \tau_m}{2}$. Taking the time derivative of $V(x_t)$ with respect to t along the trajectory of system (5), yields

$$\begin{aligned} \dot{V}(x_t) &= 2x^T(t)P[Ax(t)+BKx(t-\tau(t))] \\ &+ \sum_{i=1}^{2} x^T(t-(i-1)\frac{\tau_m}{2})Q_i x(t-(i-1)\frac{\tau_m}{2}) \\ &- \sum_{i=1}^{2} x^T(t-i\frac{\tau_m}{2})Q_i x(t-i\frac{\tau_m}{2}) \\ &+ \sum_{i=1}^{2} x^T(t-\tau_m-(i-1)\sigma)R_i x(t-\tau_m-(i-1)\sigma) \\ &- \sum_{i=1}^{2} x^T(t-\tau_m-i\sigma)R_i x(t-\tau_m-i\sigma) \\ &+ (\frac{\tau_m}{2})^2\sum_{i=1}^{2}\dot{x}^T(t)Z_i\dot{x}(t) \\ &- \frac{\tau_m}{2}\sum_{i=1}^{2}\int_{t-i\frac{\tau_m}{2}}^{t-(i-1)\frac{\tau_m}{2}} \dot{x}^T(s)Z_i\dot{x}(s)ds \\ &+ (\tau_M-\tau_m)^2\dot{x}^T(t)H\dot{x}(t) \\ &- (\tau_M-\tau_m)\int_{t-\tau_M}^{t-\tau_m} \dot{x}^T(s)H\dot{x}(s)ds \end{aligned} \qquad (9)$$

Applying lemma1, the following inequalities hold:

$$-\frac{\tau_m}{2}\sum_{i=1}^{2}\int_{t-i\frac{\tau_m}{2}}^{t-(i-1)\frac{\tau_m}{2}} \dot{x}^T(s)Z_i\dot{x}(s)ds \le \sum_{i=1}^{2}\begin{bmatrix} x(t-(i-1)\frac{\tau_m}{2}) \\ x(t-i\frac{\tau_m}{2}) \end{bmatrix}^T \begin{bmatrix} -Z_i & Z_i \\ * & -Z_i \end{bmatrix} \begin{bmatrix} x(t-(i-1)\frac{\tau_m}{2}) \\ x(t-i\frac{\tau_m}{2}) \end{bmatrix} \qquad (10)$$

Using the similar method as [9], the following equality is obtained

$$\begin{aligned} -(\tau_M-\tau_m)&\int_{t-\tau_M}^{t-\tau_m} \dot{x}^T(s)H\dot{x}(s)ds \\ &= -(\tau_M-\tau(t))\int_{t-\tau_M}^{t-\tau(t)} \dot{x}^T(s)H\dot{x}(s)ds \\ &\quad -(\tau(t)-\tau_m)\int_{t-\tau(t)}^{t-\tau_m} \dot{x}^T(s)H\dot{x}(s)ds \\ &\quad -(\tau_M-\tau(t))\int_{t-\tau(t)}^{t-\tau_m} \dot{x}^T(s)H\dot{x}(s)ds \\ &\quad -(\tau(t)-\tau_m)\int_{t-\tau_M}^{t-\tau(t)} \dot{x}^T(s)H\dot{x}(s)ds \end{aligned} \qquad (11)$$

Applying lemma1, yields

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$$-(\tau_M-\tau(t))\int_{t-\tau_M}^{t-\tau(t)}\dot{x}^T(s)H\dot{x}(s)ds\le \begin{bmatrix}x(t-\tau(t))\\ x(t-\tau_M)\end{bmatrix}^T\begin{bmatrix}-H & H\\ * & -H\end{bmatrix}\begin{bmatrix}x(t-\tau(t))\\ x(t-\tau_M)\end{bmatrix} \quad (12)$$

and

$$-(\tau(t)-\tau_m)\int_{t-\tau(t)}^{t-\tau_m}\dot{x}^T(s)H\dot{x}(s)ds\le \begin{bmatrix}x(t-\tau_m)\\ x(t-\tau(t))\end{bmatrix}^T\begin{bmatrix}-H & H\\ * & -H\end{bmatrix}\begin{bmatrix}x(t-\tau_m)\\ x(t-\tau(t))\end{bmatrix} \quad (13)$$

Since $\tau(t)-\tau_m\le\tau_M-\tau_m$, the following inequality holds:

$$\begin{aligned}&-(\tau_M-\tau(t))\int_{t-\tau(t)}^{t-\tau_m}\dot{x}^T(s)H\dot{x}(s)ds\\ &=-\frac{\tau_M-\tau(t)}{\tau_M-\tau_m}\int_{t-\tau(t)}^{t-\tau_m}(\tau_M-\tau_m)\dot{x}^T(s)H\dot{x}(s)ds\\ &\le-\frac{\tau_M-\tau(t)}{\tau_M-\tau_m}\int_{t-\tau(t)}^{t-\tau_m}(\tau(t)-\tau_m)\dot{x}^T(s)H\dot{x}(s)ds\\ &\le\frac{\tau_M-\tau(t)}{\tau_M-\tau_m}\begin{bmatrix}x(t-\tau_m)\\ x(t-\tau(t))\end{bmatrix}^T\begin{bmatrix}-H & H\\ * & -H\end{bmatrix}\begin{bmatrix}x(t-\tau_m)\\ x(t-\tau(t))\end{bmatrix}\end{aligned} \quad (14)$$

similarly,

$$\begin{aligned}&-(\tau(t)-\tau_m)\int_{t-\tau_M}^{t-\tau(t)}\dot{x}^T(s)H\dot{x}(s)ds\\ &\le\frac{\tau(t)-\tau_m}{\tau_M-\tau_m}\begin{bmatrix}x(t-\tau(t))\\ x(t-\tau_M)\end{bmatrix}^T\begin{bmatrix}-H & H\\ * & -H\end{bmatrix}\begin{bmatrix}x(t-\tau(t))\\ x(t-\tau_M)\end{bmatrix}\end{aligned} \quad (15)$$

Now, define an augmented state vector

$$\xi(t)=[\,x(t)\;\;x(t-\tau(t))\;\;x(t-\frac{\tau_m}{2})\;\;x(t-\tau_m)\;\;x(t-\tau_m-\sigma)\;\;x(t-\tau_M)\,].$$

Considering (14)-(15), the time derivative $\dot{V}(x_t)$ can be expressed as follows:

$$\dot{V}(x_t)\le\xi(t)(\Pi+\Omega^T\varphi\Omega+\frac{\tau_M-\tau(t)}{\tau_M-\tau_m}\Pi_1+\frac{\tau(t)-\tau_m}{\tau_M-\tau_m}\Pi_2)\xi(t) \quad (16)$$

Applying Lyapunov stability theory, if $\dot{V}(x_t)<0$, then the system(5) is asymptotically stable.

Applying lemma2, we can see the following matrix inequality holds,

$$\xi(t)(\Pi+\Omega^T\varphi\Omega+\frac{\tau_M-\tau(t)}{\tau_M-\tau_m}\Pi_1+\frac{\tau(t)-\tau_m}{\tau_M-\tau_m}\Pi_2)\xi(t)<0 \quad (17)$$

if and only if inequalities(18) hold.

$$\Pi+\Pi_i+\Omega^T\varphi\Omega<0\quad(i=1,2) \quad (18)$$

Using Schur complement, the above matrix inequalities are equivalent to the matrix inequalities (7) in Theorem1.

Theorem1 is proofed.

Consider the following class of norm-bounded uncertain linear time-varying delay system:

$$\begin{cases}\dot{x}(t)=(A+\ \ A)x(t)+(B+\ \ B)Kx(t-\tau(t))\\ x(t)=\phi(t), \qquad t\in[-\tau_M,-\tau_m]\end{cases} \quad (19)$$

where, we suppose A and B have parameter perturbations as A and B which are in the form of

$$[\ \ A\quad\ \ B]=DF(t)\left[E_A\quad E_B\right] \quad (20)$$

where D, E_A, E_B are constant matrices of appropriate dimensions and $F(t)\in\mathrm{R}^{i\times j}$ is an unknown time-varying matrix function satisfying $F^T(t)F(t)\le I,\ \ \forall t$. It is assumed that all the elements of $F(t)$ are Lebesgue measurable.

Theorem 2 The uncertain system (19) subject to the linear fractional norm-bounded uncertainty (20)for given constants $0\le\tau_m\le\tau_M$ is asymptotically stable, if there exist real symmetric matrices $P>0$, $Q_1>0$, $Q_2>0$, $R_1>0$, $R_2>0$, $Z_1>0$, $Z_2>0$, $H>0$ of appropriate dimensions and constants $\varepsilon_i>0$ ($i=1,2$)such that the following linear matrix inequalities hold

$$\begin{bmatrix}\Sigma_i & \varepsilon_i M & E^T\\ * & -\varepsilon_i I & 0\\ * & * & -\varepsilon_i I\end{bmatrix}<0\qquad(i=1,2) \quad (21)$$

where Σ_i is defined in (7),

$$M=\left[D^TP\quad 0\quad 0\quad 0\quad 0\quad 0\quad D^T\varphi\right]^T$$

$$E=\left[E_1\quad E_2K\quad 0\quad 0\quad 0\quad 0\quad 0\right]$$

Proof. In LMI (8), replace the system matrices A and B with $A+DF(t)E_A$, $B+DF(t)E_B$.

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Applying the Lyapunov stability theory, if the following matrix inequalities hold,

$$\Sigma_i + MF(t)E + E^T F^T(t) M^T < 0 \ \ (i = 1,2) \quad (22)$$

the uncertain closed-loop system(19) is asymptotically stable. Applying lemma 3, the above matrix inequalities hold，if and only if there exist constants $\varepsilon_i > 0$ such that the following inequalities hold:

$$\Sigma_i + \varepsilon_i MM^T + \varepsilon_i^{-1} E^T E < 0 \ \ (i = 1,2) \quad (23)$$

Applying Schur complement, the above matrix inequalities are equivalent to the linear matrix inequalities (21). This completes the proof.

4. NUMERICAL EXAMPLE

In this section, we use an example to show our stability criteria which have fewer matrix variables, is less conservative.

Let us consider the system (5) as follows

$$A = \begin{bmatrix} 0 & 1 \\ 0 & -0.1 \end{bmatrix}, \ B = \begin{bmatrix} 0 \\ 0.1 \end{bmatrix}$$

The network-based controller is designed with $K = [-3.75 \ -11.5]$.This example is discussed in [2, 4-6]. Table1 and Table2 list the maximum allowable time bound τ_M for various τ_m. It is clear that Theorem1 is less conservative than others.

Table 1: MADB τ_M for $\tau_m = 0$

[2]	[4]	[5]	[6]	Theorem1
0.0538	0.8871	1.0081	1.0239	1.0240

Table 2: MADB τ_M for different τ_m

method \ τ_m	0.05	0.10	0.15	0.20
[5]	1.0105	1.0132	1.0161	1.0193
[6]	1.0274	1.0274	1.0292	1.0310
Theorem1	1.0314	1.0378	1.0431	1.0475

5. CONCLUSION

The stability problem has been investigated for NCSs with both network-induced delay and data packet dropouts. A new delay-dependent stability criteria has been derived, which improves some previous ones in that it has fewer matrix variables and less conservatism. Then a numerical example has been provided to demonstrate the effectiveness of the proposed method.

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