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# An Improved Stability Criterion of Networked Control Systems

Xinxin Zhang, Xiefu Jiang and Qing-Long Han

*Abstract*— **The stability criterion of networked control systems with both the network-induced delays and data packet dropouts is investigated. A Lyapunov-Krasovskii functional candidate, which makes use of the information of the lower, upper bounds and the middle point of the time-varying network-induced delay interval simultaneously, is proposed and a tighter bounding for an integral term of the delay is estimated to drive a less conservative stability condition for networked control systems. No redundant matrix variable is introduced. Finally, two numerical examples are given to show the effectiveness of the proposed stability criterion.**

## I. INTRODUCTION

Networked control systems (NCSs) are feedback control systems wherein the control loops are closed through a real-time network. Recently, great importance has been attached to the study of stability analysis and control design of NCSs due to their low cost, reduced weight and power requirements, simple installation and maintenance, and high reliability. A linear continuous plant and a continuous controller was the concern of [1]. However, the insertion of a real-time network introduces time delays due to time-sharing of the communication media. The existence of a network-induced delay can degrade the performance of an NCS, and can even destabilize the system. Zhang *et al.* studied the stability of an NCS under network-induced delay [2]. One of the important issues is to find a less conservative stability criterion of an NCS.

In recent decade, more and more attention has been paid on stability analysis of time-delay systems with interval time-varying delay [3], [4]. NCSs are typical systems with interval time-varying delay [7], [8]. As for NCSs, Park *et al.* used Moon inequality to calculate the maximum allowable delay bound (MADB) for NCSs [9], [10]. Yue *et al.* presented a new model for an NCS and investigated the $H_\infty$ control problem considering both the network-induced delay and data dropout [5], [7]. Jiang *et al.* [6] proposed a new Lyapunov-Krasovskii functional as follows

$$V_1(t) = x^T(t)Px(t) + \tau_m \int_{-\tau_m}^{0} ds \int_{t+s}^{t} \dot{x}^T(\theta)R_1\dot{x}(\theta)d\theta$$
$$+ \int_{t-\eta}^{t} x^T(s)Q_2x(s)ds + \eta \int_{-\eta}^{0} ds \int_{t+s}^{t} \dot{x}^T(\theta)R_2\dot{x}(\theta)d\theta$$
$$+ \int_{t-\tau_m}^{t} x^T(s)Q_1x(s)ds + \delta \int_{-\eta}^{-\tau_m} ds \int_{t+s}^{t} \dot{x}^T(\theta)S\dot{x}(\theta)d\theta$$

which made use of the information of both the lower and upper bounds of the time-varying network-induced delay to obtain a less conservative stability criterion than existing results, where the definition of $\tau_m$ and $\eta$ can be found in Section II, $P = P^T > 0, Q_1 = Q_1^T > 0, Q_2 = Q_2^T > 0, R_1 = R_1^T > 0, R_2 = R_2^T > 0, S = S^T > 0$ of appropriate dimensions. [11] retained the information [6] had lost when evaluating the bounds of some cross terms to drive a less conservative result than [6]. How to find a less conservative stability condition than some existing ones for an NCS motivate current study.

In this paper, we will use the following Lyapunov-Krasovskii functional

$$V_2(t) = V_1(t) + \int_{t-\tau_a}^{t} x^T(s)Q_3x(s)ds$$
$$+\tau_a \int_{-\tau_a}^{0} ds \int_{t+s}^{t} \dot{x}^T(\theta)R_3\dot{x}(\theta)d\theta \quad (1)$$

which makes use of the information of the lower, upper bounds and the middle point of the time-varying network-induced delay interval simultaneously, to obtain a less conservative condition in terms of a linear matrix inequality for an NCS, no redundant matrix variable will be introduced, where $Q_3 = Q_3^T > 0, R_3 = R_3^T > 0$ of appropriate dimensions, and $\tau_a = \frac{1}{2}(\tau_m + \eta), \tau_m \geq 0, \eta \geq 0$.

In [6], by using

$$\begin{aligned} & -\delta \int_{t-\eta}^{t-\tau_m} \dot{x}^T(s)S\dot{x}(s)ds \\ = & -\delta \int_{t-\eta}^{i_k h} \dot{x}^T(s)S\dot{x}(s)ds - \delta \int_{i_k h}^{t-\tau_m} \dot{x}^T(s)S\dot{x}(s)ds \\ \leq & -(i_k h - t + \eta) \int_{t-\eta}^{i_k h} \dot{x}^T(s)S\dot{x}(s)ds \\ & -(t - \tau_m - i_k h) \int_{i_k h}^{t-\tau_m} \dot{x}^T(s)S\dot{x}(s)ds \end{aligned}$$

a stability condition has been derived based on an inequality from Lemma 1, where $\delta = \eta - \tau_m$. In order to obtain a tighter bounding for this term, $\tau_a$ will be introduced to bisect the time-varying network-induced delay interval as $[\tau_m, \tau_a]$ and $[\tau_a, \eta]$, the conservatism of evaluating the bounds of some weighted cross terms will be reduced. Therefore a less conservative result will be obtained. Numerical examples will

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X. Zhang is with the School of Automation, Hangzhou Dianzi University, Hangzhou 310018, China stars108197@yahoo.com.cn

X. Jiang is with the School of Automation, Hangzhou Dianzi University, Hangzhou 310018, China jiangxf@hdu.edu.cn

Q.-L. Han is with the School of Computing Sciences, Central Queensland University, Rockhampton, Qld 4702, Australia, q.han@cqu.edu.au

be given to show the effectiveness of the proposed stability criterion.

Notation: For symmetric matrices $X$ and $Y$, the notation $X \leq Y$ (respectively $X < Y$) means that $X - Y$ is negative semidefinite (respectively, negative definite). The term $R^n$ denotes the $n$-dimensional Euclidean space. The term $R^{m\times n}$ denotes the set of all the real $m\times n$ matrices. I is the identity matrix of appropriate dimensions.

## II. PROBLEM STATEMENT

We consider the following system controlled through a network

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) \\ x(t_0) = x_0 \end{cases} \quad (2)$$

where $x(t) \in R^n$ is the state vector, $u(t) \in R^n$ is the input vector, $A$ and $B$ are known parameter matrices of appropriate dimensions, $x_0$ is the initial condition.

First, since there exist communication delay $\tau^{sc}$ between the sensor and the controller and computational delay $\tau^c$ in the controller, the following control law is employed for the system (2)

$$u(t^+) = Kx(t - \tau_k^{sc} - \tau_k^c), t \in \{kh + \tau_k^{sc} + \tau_k^c\}, k = 1, 2, \dots \quad (3)$$

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

Second, substituting (3) into (2) yields

$$\begin{aligned} &\dot{x}(t) = Ax(t) + BKx(kh), \\ &t \in [kh + \tau_k, (k+1)h + \tau_{k+1}), k = 1, 2, \dots \end{aligned} \quad (4)$$

where the communication delay $\tau^{ca}$ between the controller and the actuator is considered, and the time-delay $\tau_k = \tau_k^{sc} + \tau_k^c + \tau_k^{ca}$ denotes the time from the instant $kh$ when sensor nodes sample sensor data from a plant to the instant when actuators transfer data to the plant. Also considering the data packet dropout, the closed-loop system (4) can be modified as [5]

$$\begin{aligned} &\dot{x}(t) = Ax(t) + BKx(i_k h), \\ &t \in [i_k h + \tau_k, i_{k+1} h + \tau_{k+1}), k = 1, 2, \dots \end{aligned} \quad (5)$$

where $i_k, k = 1, 2, ...$ are some integers and $\{i_1, i_2, i_3, ...\} \subset \{0, 1, 2, ...\}$. Obviously, $\cup_{k=1}^{\infty}[i_k h + \tau_k, i_{k+1}h + \tau_{k+1}) = [t_0, \infty), t_0 \geq 0$. In this paper, $u(t) = 0$ is assumed before the first control signal reaches the plant. If $i_{k+1} < i_k$, then the new data packet reaches the plant before the old one. At this time, the old data packet should be discarded and its successive data packet used instead. Therefore, it is necessary to find an appropriate network scheduling method that can discard the old data packet when the new one reaches the plant before the old one. In the following discussion, we assume that $i_{k+1} > i_k, k = 1, 2, 3, ....$

Throughout this paper, the following assumptions and lemma are needed.

*Assumption* 1: The sensor is clock-driven; the controller and actuator are event-driven.

*Assumption* 2: There exist two constants $\tau_m \geq 0$ and $\eta \geq 0$ such that

$$(i_{k+1} - i_k)h + \tau_{k+1} \leq \eta, \tau_k \geq \tau_m, k = 1, 2, ... \quad (6)$$

*Remark 1:* since $x(i_k h) = x(t - (t - i_k h))$, defining $\tau(t) = t - i_k h, t \in [i_k h + \tau_k, i_{k+1}h + \tau_{k+1}), k = 1, 2, ...,$ rewrite (5) as

$$\dot{x}(t) = Ax(t) + BKx(t - \tau(t)) \quad (7)$$

where $\tau(t)$ is piecewise linear with derivative $\dot{\tau}(t) = 1$ for $t \neq i_k h + \tau_k$ and $\tau(t)$ is discontinuous at the points $t = i_k h + \tau_k$ , $k = 1, 2, ....$ It is clear that $\tau_k \leq \tau(t) \leq (i_{k+1} - i_k)h + \tau_{k+1} \leq \eta$ for $t \in [i_k h + \tau_k, i_{k+1}h + \tau_{k+1}), k = 1, 2, ....$

Thus, the system (5) is equivalent to the linear system (7) with interval time-varying time-delay. Therefore, an approach to stability analysis and design for time-delay systems can be extended to handle the same issues for NCSs, which was also confirmed by [12].

To end this section, we introduce the following lemma which is useful in deriving a stability criterion for system (5).

*Lemma 1:* [13] For any constant matrix $W \in R^{n\times n}, W = W^T > 0$, scalar $\gamma > 0$, and vector function $\dot{x} : [-\gamma, 0] \longrightarrow R^n$ such that the following integration is well defined, then

$$\begin{aligned} &-\gamma \int_{t-\gamma}^{t} \dot{x}^T(\xi) W \dot{x}(\xi) d\xi \\ &\leq \begin{bmatrix} x(t) \\ x(t-\gamma) \end{bmatrix}^T \begin{bmatrix} -W & W \\ W & -W \end{bmatrix} \begin{bmatrix} x(t) \\ x(t-\gamma) \end{bmatrix} \end{aligned}$$

## III. NEW STABILITY CRITERIA

We consider asymptotic stability for system (5). Using Lyapunov-Krasovskii functional (1), we have the following result.

*Proposition 1:* For some given scalars $\tau_m$ and $\eta$, the closed-loop system (5) is asymptotically stable, if there exist symmetric positive-definite matrices $P > 0, Q_i > 0, R_i > 0 (i = 1, 2, 3)$ and $S > 0$ of appropriate dimensions such that

$$\Psi_1 \triangleq \Phi + \Gamma_1^T S \Gamma_1 < 0, \quad (8)$$

and

$$\Psi_2 \triangleq \Phi + \Gamma_2^T S \Gamma_2 < 0 \quad (9)$$

where

$$\begin{aligned} \Phi &= \begin{bmatrix} \Phi_{11} & \Phi_{12} & R_1 & R_2 & R_3 \\ \Phi_{12}^T & \Phi_{22} & S & S & 3S \\ R_1 & S & \Phi_{33} & S & S \\ R_2 & S & S & \Phi_{44} & S \\ R_3 & 3S & S & S & \Phi_{55} \end{bmatrix} \\ \delta &= \eta - \tau_m, \tau_a = \frac{1}{2}(\tau_m + \eta), \\ \Theta &= \tau_m^2 R_1 + \eta^2 R_2 + \tau_a^2 R_3 + \delta^2 S, \\ \Phi_{11} &= PA + A^T P + \sum_{i=1}^{3} Q_i - \sum_{i=1}^{3} R_i + A^T \Theta A, \\ \Phi_{12} &= PBK + A^T \Theta BK, \Phi_{22} = (BK)^T \Theta BK - 5S, \\ \Phi_{33} &= -Q_1 - R_1 - 3S, \Phi_{44} = -Q_2 - R_2 - 3S, \end{aligned}$$

$$\Phi_{55} = -Q_3 - R_3 - 5S,$$
$$\Gamma_1 = \begin{bmatrix} 0 & I & I & -I & -I \end{bmatrix},$$
$$\Gamma_2 = \begin{bmatrix} 0 & I & -I & I & -I \end{bmatrix}.$$

**Proof.** Taking the derivative of $V_2(t)$ with respect to $t$ along the trajectory of (5) yields

$$\begin{aligned}
&\dot{V}_2(t) = x^T(t)(PA + A^TP)x(t) + 2x^T(t)PBKx(i_kh) \\
&+x^T(t)Q_1x(t) - x^T(t-\tau_m)Q_1x(t-\tau_m) \\
&+x^T(t)Q_2x(t) - x^T(t-\eta)Q_2x(t-\eta) \\
&+x^T(t)Q_3x(t) - x^T(t-\tau_a)Q_3x(t-\tau_a) \\
&+\dot{x}^T(t)(\tau_m^2R_1 + \eta^2R_2 + \tau_a^2R_3 + \delta^2S)\dot{x}(t) \\
&-\tau_m\int_{t-\tau_m}^{t}\dot{x}^T(s)R_1\dot{x}(s)ds - \eta\int_{t-\eta}^{t}\dot{x}^T(s)R_2\dot{x}(s)ds \\
&-\tau_a\int_{t-\tau_a}^{t}\dot{x}^T(s)R_3\dot{x}(s)ds - \delta\int_{t-\eta}^{t-\tau_m}\dot{x}^T(s)S\dot{x}(s)ds
\end{aligned}$$

for $t \in [i_kh + \tau_k, i_{k+1}h + \tau_{k+1}), k = 1, 2, ....$ Use Lemma 1 to obtain

$$\begin{aligned}
&-\tau_m\int_{t-\tau_m}^{t}\dot{x}^T(s)R_1\dot{x}(s)ds \\
&\leq \begin{bmatrix} x(t) \\ x(t-\tau_m) \end{bmatrix}^T \begin{bmatrix} -R_1 & R_1 \\ R_1 & -R_1 \end{bmatrix} \begin{bmatrix} x(t) \\ x(t-\tau_m) \end{bmatrix}, \\
&-\eta\int_{t-\eta}^{t}\dot{x}^T(s)R_2\dot{x}(s)ds \\
&\leq \begin{bmatrix} x(t) \\ x(t-\eta) \end{bmatrix}^T \begin{bmatrix} -R_2 & R_2 \\ R_2 & -R_2 \end{bmatrix} \begin{bmatrix} x(t) \\ x(t-\eta) \end{bmatrix}, \\
&-\tau_a\int_{t-\tau_a}^{t}\dot{x}^T(s)R_3\dot{x}(s)ds \\
&\leq \begin{bmatrix} x(t) \\ x(t-\tau_a) \end{bmatrix}^T \begin{bmatrix} -R_3 & R_3 \\ R_3 & -R_3 \end{bmatrix} \begin{bmatrix} x(t) \\ x(t-\tau_a) \end{bmatrix}
\end{aligned}$$

As for

$$-\delta\int_{t-\eta}^{t-\tau_m}\dot{x}^T(s)S\dot{x}(s)ds$$

Case I: $t - \tau_m \leq i_kh \leq t - \tau_a$,

$$\begin{aligned}
&-\delta\int_{t-\eta}^{t-\tau_m}\dot{x}^T(s)S\dot{x}(s)ds \\
&= -\delta\int_{t-\eta}^{t-\tau_a}\dot{x}^T(s)S\dot{x}(s)ds - \delta\int_{t-\tau_a}^{i_kh}\dot{x}^T(s)S\dot{x}(s)ds \\
&\quad -\delta\int_{i_kh}^{t-\tau_m}\dot{x}^T(s)S\dot{x}(s)ds \\
&\leq 2\begin{bmatrix} x(t-\tau_a) \\ x(t-\eta) \end{bmatrix}^T \begin{bmatrix} -S & S \\ S & -S \end{bmatrix} \begin{bmatrix} x(t-\tau_a) \\ x(t-\eta) \end{bmatrix} \\
&\quad +2\begin{bmatrix} x(i_kh) \\ x(t-\tau_a) \end{bmatrix}^T \begin{bmatrix} -S & S \\ S & -S \end{bmatrix} \begin{bmatrix} x(i_kh) \\ x(t-\tau_a) \end{bmatrix} \\
&\quad +2\begin{bmatrix} x(t-\tau_m) \\ x(i_kh) \end{bmatrix}^T \begin{bmatrix} -S & S \\ S & -S \end{bmatrix} \begin{bmatrix} x(t-\tau_m) \\ x(i_kh) \end{bmatrix}
\end{aligned}$$

then, we have

$$\begin{aligned}
\dot{V}_2(t) &\leq \xi^T(t)\Psi_1\xi(t), \\
t &\in [i_kh + \tau_k, i_{k+1}h + \tau_{k+1}), k = 1, 2, \ldots
\end{aligned}$$

where

$$\begin{aligned}
\xi^T(t) &= \begin{bmatrix} \xi_1^T(t) & \xi_2^T(t) \end{bmatrix}, \\
\xi_1^T(t) &= \begin{bmatrix} x^T(t) & x^T(i_kh) \end{bmatrix}, \\
\xi_2^T(t) &= \begin{bmatrix} x^T(t-\tau_m) & x^T(t-\eta) & x^T(t-\tau_a) \end{bmatrix}
\end{aligned}$$

One can see that if $\Psi_1 < 0$, then there exists some scalar $\lambda_1 > 0$ such that $\dot{V}_2(t) \leq -\lambda_1 x^T(t)x(t)$ for $t \in [i_kh + \tau_k, i_{k+1}h + \tau_{k+1}), k = 1, 2, ....$

Case II: $t - \tau_a < i_kh \leq t - \eta$,

$$\begin{aligned}
&-\delta\int_{t-\eta}^{t-\tau_m}\dot{x}^T(s)S\dot{x}(s)ds \\
&= -\delta\int_{t-\eta}^{i_kh}\dot{x}^T(s)S\dot{x}(s)ds - \delta\int_{i_kh}^{t-\tau_a}\dot{x}^T(s)S\dot{x}(s)ds \\
&\quad -\delta\int_{t-\tau_a}^{t-\tau_m}\dot{x}^T(s)S\dot{x}(s)ds \\
&\leq 2\begin{bmatrix} x(i_kh) \\ x(t-\eta) \end{bmatrix}^T \begin{bmatrix} -S & S \\ S & -S \end{bmatrix} \begin{bmatrix} x(i_kh) \\ x(t-\eta) \end{bmatrix} \\
&\quad +2\begin{bmatrix} x(t-\tau_a) \\ x(i_kh) \end{bmatrix}^T \begin{bmatrix} -S & S \\ S & -S \end{bmatrix} \begin{bmatrix} x(t-\tau_a) \\ x(i_kh) \end{bmatrix} \\
&\quad +2\begin{bmatrix} x(t-\tau_m) \\ x(t-\tau_a) \end{bmatrix}^T \begin{bmatrix} -S & S \\ S & -S \end{bmatrix} \begin{bmatrix} x(t-\tau_m) \\ x(t-\tau_a) \end{bmatrix}
\end{aligned}$$

then, we have

$$\begin{aligned}
\dot{V}_2(t) &\leq \xi^T(t)\Psi_2\xi(t), \\
t &\in [i_kh + \tau_k, i_{k+1}h + \tau_{k+1}), k = 1, 2, \ldots
\end{aligned}$$

One can see that if $\Psi_2 < 0$, then there exists some scalar $\lambda_2 > 0$ such that $\dot{V}_2(t) \leq -\lambda_2 x^T(t)x(t)$ for $t \in [i_kh + \tau_k, i_{k+1}h + \tau_{k+1}), k = 1, 2, ....$ Therefore, if (8) and (9) hold, then there exist some scalar $\lambda = \min(\lambda_1, \lambda_2) > 0$ such that $\dot{V}_2(t) \leq -\lambda x^T(t)x(t)$ for $t \in [i_kh + \tau_k, i_{k+1}h + \tau_{k+1}), k = 1, 2, ....$ Similar to the proof of [14] one can obtain that the system (5) is asymptotically stable. This completes the proof.

*Remark 2:* Proposition 1 provides a delay-dependent stability criterion for the system (5). In deriving the criterion, we employ $\tau_a$ to bisect the time-varying network-induced delay interval as $[\tau_m, \tau_a]$ and $[\tau_a, \eta]$ which reduce the conservatism of evaluating the bounds of some weighted cross terms.

## IV. NUMERICAL EXAMPLES

In this section, two examples are given to show the effectiveness of the results derived in this paper.

*Example 1:* Consider the following system controlled over a network

$$\dot{x}(t) = \begin{bmatrix} 0 & 1 \\ 0 & -0.1 \end{bmatrix} x(t) + \begin{bmatrix} 0 \\ 0.1 \end{bmatrix} u(t) \quad (10)$$

The network-based controller is designed with $K = \begin{bmatrix} -3.75 & -11.5 \end{bmatrix}$. Using stability criteria in some existing literature and this paper (Proposition 1 for $\tau_m = 0$), the maximum allowable transfer intervals (MATIs) of the delay, that guarantees the asymptotic stability of system (10) controlled over a network are listed in Table I. It is clear to see that for this example, some existing results have been improved.

TABLE I

MATIs BASED ON DIFFERENT METHODS IN SOME EXISTING LITERATURE AND THIS PAPER

| Method | MATI |
|---|---|
| Zhang *et al.* [2] | $4.5 \times 10^{-4}s$ |
| Park *et al.* [9] | $0.0538s$ |
| Kim *et al.* [10] | $0.7805s$ |
| Yue *et al.* [5] | $0.8871s$ |
| Jiang *et al.* [6] | $1.0081s$ |
| Proposition 1 | $1.0239s$ |

TABLE II

MATIs OF THE DELAY IN [4] AND THIS PAPER

| $\tau_m$ | Jiang and Han [4] | This paper |
|---|---|---|
| 0.01s | 1.0086 | 1.0243 |
| 0.05s | 1.0105 | 1.0257 |
| 0.10s | 1.0132 | 1.0274 |
| 0.15s | 1.0161 | 1.0292 |
| 0.20s | 1.0193 | 1.0310 |

Moreover, MATIs that guarantee asymptotic stability of the system (10) controlled over a network is given in Table II for different lower bound of the time-varying network-induced delay by using the method proposed in this paper and Proposition 1 in [4]. One can see that this paper can provide better results than Proposition 1 in [4].

*Example 2:* Consider the following system

$$\dot{x}(t) = \begin{bmatrix} -2 & 0 \\ 0 & -0.9 \end{bmatrix} x(t) + \begin{bmatrix} -1 & 0 \\ -1 & -1 \end{bmatrix} x(t-\tau(t))$$

Table III lists the comparison between the results derived in this paper and those in [11] for different $\tau_m$. From the table, one can see that the stability results obtained in this paper are less conservative than those in Shao [11].

## V. CONCLUSION

In this paper, the problem of stability of networked control systems has been considered. A less conservative condition has been proposed in terms of a linear matrix inequality based on a new Lyapunov-Krasvoskii functional which using the information of the lower, upper bounds and the middle point of the time-varying network-induced delay interval simultaneously. Numerical examples have been given to demonstrate the effectiveness of the proposed stability criterion.

TABLE III

MATIs OF THE DELAY IN [11] AND THIS PAPER

| $\tau_m$ | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Shao [11] | 1.8737 | 2.5049 | 3.2591 | 4.0744 |
| This paper | 1.9177 | 2.5326 | 3.2737 | 4.0787 |

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