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Research article

Improved results on state feedback stabilization for a networked control system with additive time-varying delay components' controller

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ABSTRACT

This paper investigates the problems of stability and stabilization for a networked control system (NCS) with additive time-varying delay components' controller. Firstly, stability of a NCS with additive time-varying delays is investigated. A novel approach with free parameters is proposed. By constructing a new Lyapunov-Krasovskii functional (LKF) with two free parameters, stability criteria are obtained. The obtained stability criteria depend not only on upper bounds of delays but also free parameters. In addition, input-output method is extended to study the stability problem for the NCS. Compared with other approaches such as input-output method, the free-parameter approach is more flexible and effective in reducing the conservatism. Then, based on the stability results, a state feedback controller is designed to guarantee the asymptotically stable of the closed-loop systems. Finally, numerical examples are provided to show the effectiveness and less conservatism of the proposed results.

1. Introduction

Control systems with different components such as sensors, controllers and actuators connected via communication networks are called networked control systems (NCSs) [1]. Compared with traditional control systems, NCSs have been increasing research interests due to their advantages in low cost, reduced weight, high reliability and wide applications in science and engineering. Meanwhile, time delays exist commonly in the implementation of NCSs due to the finite switching speeds of amplifiers and traffic congestions in signal transmission processes. Since the existence of time delays may cause instability, oscillation or divergence to deteriorate system performance, stability control for NCSs with time delays have significantly theoretical and practical values. As is known to all, stability and stabilization are central issues to study the behavior of a system, which have attracted wide attention of researchers in different fields and fruitful results have been obtained [1–12]. Therefore, the stability and stabilization for NCSs with time delays have become hot research topics [13–20].

Stability criteria are used to check whether the NCSs are stable. Therefore, stability criteria play important roles in stability analysis of NCSs with time delays. According to whether stability criteria include the information of time delays, they are classified into delay-independent stability criteria and delay-dependent ones. Since the time delays encountered in NCSs are usually not very big, delay-dependent stability criteria are less conservative. Hence, much attention has been paid to delay-dependent stability criteria [21–36].

In most of the reported results on stability criteria for NCSs with time delays, time delays have been taken in a singular or simple form in the state variable. However, signals transmitted from one point to another may experience a few segments of networks, which can possibly induce successive delays with different properties due to the variable network transmission condition [24,25]. One useful example is shown in Fig. 1, which can easily explain the concept of additive time delays. In Fig. 1, it can be seen that there are basically two kinds of delays, where $d_1(t)$ is the time delay induced from sensor to controller and $d_2(t)$ is the time delay induced from controller to the actuator. On the other hand, when $d_1(t)+d_2(t)$ reaches its maximum, we do not necessarily have both $d_1(t)$ and $d_2(t)$ reach their maxima at the same time. So it is not rational to lump $d_1(t)$ and $d_2(t)$ into one state delay.

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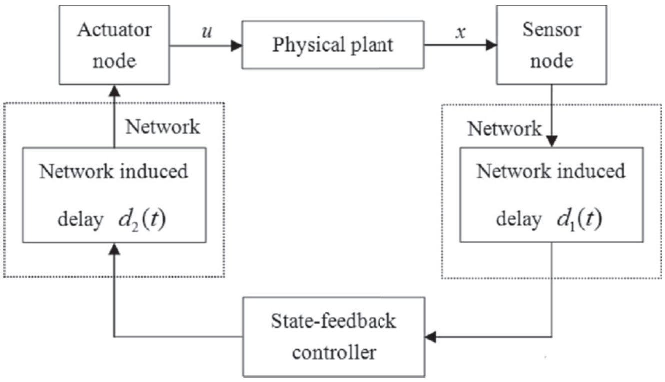

Fig. 1. Networked control system.

Recently, to reflect more realistic dynamical behaviors, a new type of NCSs with additive time-varying delays have attracted much attention [14–18]. System with additive time-varying delays was initially conducted in Ref. [14], and a delay-dependent stability criterion was obtained by exploiting a new LKF. A following up investigation was given in Ref. [15]. Recently, further researches have been done in Refs. [16–18]. In Ref. [17], less conservative results than [14,15] were obtained by constructing a LKF and using integral inequality approach. In Ref. [18], an improved stability result was derived by employing a new integral inequality. In Ref. [16], delay-dependent state feedback stabilization for a NCS with two additive time-varying delays was studied by splitting the whole delay interval into two subintervals according to the delays. Unfortunately, to date, the obtained stability criteria for NCSs with two additive time-varying delays in most existing papers were still conservative despite their practical importance. Thus, it is still an important and challenging problem to further improve current results affected by time delays.

Input-output technique is one of the most effective ways to deal with time delay and has been increasing research interests [34,35,37,38]. In Ref. [34], by applying an input-output approach and a two-term approximation method, filter design of T-S fuzzy discrete-time systems with time-varying delay has been investigated. In Ref. [37], the stability and stabilization of uncertain T-S fuzzy systems with time-varying delay have been considered by the input-output approach. In Ref. [35], an output feedback controller has been designed for discrete-time Takagi-Sugeno fuzzy systems with time-varying delays via the input-output approach. Hence, it is a challenging problem to extend input-output approach to study the stability analysis for NCSs with additive time-varying delays. In addition, most of the approaches such as free-weighting matrix [14,15,17] and slack matrix method [16,18,21,22] are involved in the employment of the constructed LKFs, which are more or less conservative techniques. Hence, it is theoretically and practically significant to hunt for an effective approach to further reduce conservatism for NCSs with additive time-varying delays.

Inspired by the aforementioned discussion, in this paper, we discuss the delay-dependent stability and stabilization problem for a NCS with additive time-varying delay components' controller. The main contributions of this paper are summarized as follows.

1) A new LKF with two free parameters is constructed for NCSs with additive time-varying delays. Specially, two free parameters $\tau_1 \in (0, h_1)$, $\tau_2 \in (h_1, h)$ are introduced in $V_3(t)$, $V_4(t)$, and $V_5(t)$, which can fully capture the information of the time-varying delays. Thus, compared with existing results in Refs. [1,14–18,39], our results are more flexible and less conservative.
2) Input-output method is extended to study the delay-dependent stability problem of NCSs. Further, the comparison on the effectiveness in reducing conservatism has been made between the input-output method and the free-parameter approach.

Notations: Throughout this paper, the superscript T stands for matrix transposition. $\mathbb{R}^n$ denotes the n-dimensional Euclidean space, $\mathbb{R}^{n\times m}$ is the set of all $n\times m$ real matrices. I_n, 0_n, and $0_{n,m}$ stand for $n\times n$ identity matrix, $n\times n$, and $n\times m$ zero matrices, respectively. $e_i = [0_{n,(i-1)n}\ I_n\ 0_{n,(13-i)n}]$ $(i = 1, 2, \dots, 13)$, $e_{i,j} = e_i - e_j$, $\bar{e}_i = [0_{n,(i-1)n}\ I_n\ 0_{n,(9-i)n}]$ $(i = 1, 2, \dots, 9)$, $\bar{e}_{i,j} = \bar{e}_i - \bar{e}_j$, $\widetilde{e}_i = [0_{n,(i-1)n}\ I_n\ 0_{n,(11-i)n}]$ $(i = 1, 2, \dots, 11)$, $\widetilde{e}_{i,j} = \widetilde{e}_i - \widetilde{e}_j$, $\breve{e}_i = [0_{n,(i-1)n}\ I_n\ 0_{n,(10-i)n}]$ $(i = 1, 2, \dots, 10)$, $\breve{e}_{i,j} = \breve{e}_i - \breve{e}_j$. For real symmetric matrices, X and Y, the notation $X > Y$ means that the matrix $X - Y$ is positive define. The symmetric term in a matrix is denoted by $*$, diag$\{\dots\}$ stands for a block-diagonal matrix. $G_1 \circ G_2$ represents the series connection of mapping G_1 and G_2. $\|G\|_\infty$ denotes the l_2-induced norm of a transfer function matrix or a general operator.

2. Problem description and preliminaries

A typical NCS configuration is illustrated in Fig. 1, where all control information is transmitted via network. The physical plant is described by

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

where $x(t) \in \mathbb{R}^n$ and $u(t) \in \mathbb{R}^{m\times n}$ are state and control input vectors, respectively. $A \in \mathbb{R}^{n\times n}$ and $B \in \mathbb{R}^{n\times m}$ are known real constant matrices. The state feedback controller is designed as follows:

$$u(t) = Kx(t - d_1(t) - d_2(t)), \tag{2}$$

where K is the state feedback gain matrix. $d_1(t)$ is the input delay induced from sensor to controller and $d_2(t)$ is the input delay induced from controller to the actuator, which satisfy

$$\begin{aligned} &0 \le d_1(t) \le h_1, \quad \dot{d}_1(t) \le \mu_1, \\ &0 \le d_2(t) \le h_2, \quad \dot{d}_2(t) \le \mu_2, \end{aligned} \tag{3}$$

and $d(t) \triangleq d_1(t) + d_2(t)$, $\mu \triangleq \mu_1 + \mu_2$, $h \triangleq h_1 + h_2$. Substituting (2) into (1), we have the following NCS with two additive input delays:

$$\dot{x}(t) = Ax(t) + BKx(t - d_1(t) - d_2(t)). \tag{4}$$

Remark 1. The state feedback controller can timely feedback and adjust the current performance status of the NCS, which has been widely investigated in Refs. [1,2,15,16,37,39]. On the other hand, NCSs with time delays may introduce instability, oscillation, and poor performance. However, stability is the precondition for a NCS to work. Hence, it is necessary to design a desired state feedback controller to guarantee the asymptotically stable of the NCS.

Lemma 1. [19]. For any constant matrix $W \in \mathrm{R}^{n\times n}$, $W = W^T > 0$, a scalar function $h := h(t) > 0$, and a vector-valued function $\dot{x} : [-h, 0] \to \mathbb{R}^n$, such that the following integrations are well defined, then

$$-h\int_{t-h}^{t} \dot{x}^T(s)W\dot{x}(s)ds \le \zeta_1^T(t)\begin{bmatrix} -W & W \\ * & -W \end{bmatrix}\zeta_1(t),$$

$$-\frac{h^2}{2}\int_{-h}^{0}\int_{t+\theta}^{t} \dot{x}^T(s)W\dot{x}(s)dsd\theta \le \zeta_2^T(t)\begin{bmatrix} -W & W \\ * & -W \end{bmatrix}\zeta_2(t),$$