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Brief paper

Delay-independent stabilization of a class of time-delay systems via periodically intermittent control☆

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The problem of delay-independently periodically intermittent stabilization for a class of time-delay systems is examined. First, the stability of the considered periodically intermittently controlled time-delay systems is analyzed by using the piecewise switching-time-dependent Lyapunov function/functional. The introduced Lyapunov function/functional is nonincreasing at switching instants, which can guarantee the exponential stability of the considered systems irrespective of the sizes of the state delays. Next, based on the newly established stability criteria, sufficient conditions for the existence of delay-independently periodically intermittent state-feedback controllers are derived. Finally, two illustrative examples are presented to show the validity of the obtained results.

1. Introduction

The last decades have witnessed an increasing interest in intermittent control due to its potential applications in various fields such as civil/structural engineering, chemical engineering, psychology, and communication. Intermittent control is a discontinuous feedback control, which fills the gap between the two extremes of continuous and impulsive control in that the control signal is implemented intermittently. Compared with continuous control, intermittent control can efficiently save energy and give more flexibility to the designer. On the other hand, compared with impulsive control, intermittent control has the advantage of easy implementation in engineering practice because it does not have to change the state instantaneously. Therefore, the intermittent control scheme integrates the merits of continuous and impulsive control. According to the way that the controller is activated, the intermittent control can be categorized into event-driven intermittent control and time-driven intermittent control. For the former, the control action is activated only when a pre-given event occurs (Gawthrop, Neild, & Wagg, 2012; Gawthrop & Wang, 2009a,b; Zochowski, 2000), while for the latter, the controller is activated at a sequence of fixed finite time intervals. Several types of time-driven intermittent control have been considered in the literature. For example, there are intermittent predictive control (Ronco, Arsan, & Gawthrop, 1999), delayed feedback control with controller failure (Sun, Liu, Rees, & Wang, 2008), intermittent feedback for model-based networked control systems (Estrada & Antsaklis, 2010; Garcia & Antsaklis, 2013), sampled-data control with control packet loss (Chen & Zheng, 2012; Zhang & Yu, 2010), intermittent impulsive control (Liu, Shen, & Zhang, 2011), distributed consensus of multi-agent systems with intermittent communications (Wen, Duan, Ren, & Chen, 2014), and periodically intermittent feedback control (Chen, Zhong, Jiang, & Lu, 2014; Hu, Yu, Jiang, & Teng, 2010; Huang, Li, & Han, 2009; Huang, Li, & Liu, 2008; Huang, Li, Yu, & Chen, 2009; Li, Liao, & Huang, 2007; Song & Huang, 2015; Wang, Hao, & Zuo, 2010; Xing, Jiang, & Hu, 2013; Yang & Cao, 2009; Yu, Hu, Jiang, & Teng, 2011).

In the framework of periodically intermittent feedback, two distinct modes of operation are involved: the closed-loop mode for the time intervals $[k\omega, k\omega + \delta)$, and the open-loop mode for the time intervals $[k\omega + \delta, (k + 1)\omega)$, where the parameters ω and δ denote the control period and the control width, respectively. So the periodically intermittently controlled system can be viewed as a switched system in which the closed-loop mode and the open-loop mode operate in alternating manner. Correspondingly, the

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stability analysis of a periodically intermittently controlled system boils down to the stability analysis of a time-driven switching system consisting a stable subsystem and an unstable subsystem. In the previous results (Hu et al., 2010; Huang, Li, & Han, 2009; Huang et al., 2008; Huang, Li, Yu et al., 2009; Li et al., 2007; Wang et al., 2010; Xing et al., 2013; Yang & Cao, 2009; Yu et al., 2011), the stability of periodically intermittently controlled delayed neural networks was studied. The stability analysis was carried out by applying common Lyapunov function/functional based techniques in which two distinct modes share the same Lyapunov function/functional. The basic idea is to obtain the decay rate estimate of the closed-loop mode and the increase rate estimate of the open-loop mode with the aid of delay differential inequalities. Then by suppressing the increase rate of the open-loop mode using the decay rate of the closed-loop mode, the stability criteria are established. It is well-known that the existence of a common Lyapunov function is too rigorous to stability analysis of many switched systems (Chen & Zheng, 2010; Sun, Zhao, & Hill, 2006; Zhao & Hill, 2008). So these results may be conservative. Recently, Chen et al. (2014) proposed the piecewise Lyapunov function/functional based approaches for stability analysis and synthesis of periodically intermittently controlled time-delay systems. These approaches can make good use of mode information and reduce the conservatism inherent in the common Lyapunov function/functional based methods. However, like the results given in Huang et al. (2008), Huang, Li, and Han (2009); Huang, Li, Yu et al. (2009), Li et al. (2007), Wang et al. (2010) and Yang and Cao (2009), the stability criteria derived in Chen et al. (2014) also require that the control width should be strictly larger than the size of the state delay. Although the theoretical results presented in Hu et al. (2010), Xing et al. (2013) and Yu et al. (2011) removed this constraint, their stability conditions still depend upon the delay bounds. This means that all the existing stability results for periodically intermittently controlled time-delay systems are only suitable to the case where the delay bounds are known even if the original time-delay systems can be delay-independently stabilizable. These observations motivate the study of the following question: for a delay-independently stabilizable time-delay system, what conditions can guarantee the existence of delay-independently periodically intermittently state-feedback controllers? It should be pointed out that this question cannot be solved by the existing exponent estimation based methods. This is because the exponential decay/increase rate of a time-delay system usually depends on the delay bounds.

The purpose of this paper is to study the problem of delay-independent stabilization of a class of time-delay systems via periodically intermittently control. Piecewise switching-time-dependent Lyapunov functions/functionals are introduced to analyze the stability of the periodically intermittently controlled time-delay systems. An important feature of the introduced Lyapunov functions/functionals is the nonincreasing property at the switching instants. Such feature makes the stability analysis of the periodically intermittently controlled time-delay system like the stability analysis for a time-delay system without switching. As a result, delay-independent stability criteria are obtained for the periodically intermittently controlled time-delay systems. Then using the linear matrix inequalities (LMIs) techniques, sufficient conditions for the existence of delay-independently periodically intermittent state-feedback controllers are established.

The rest of the paper is organized as follows. In Section 2, some basic definitions and preliminaries are presented. In Section 3, stability criteria for the considered systems are developed by using the piecewise switching-time-dependent Lyapunov function/functional based methods. Section 4 provides sufficient conditions on the existence of delay-independently periodically intermittent state-feedback controllers. In Section 5, two numerical examples are given to demonstrate the efficiency of the proposed methods. Finally, some concluding remarks are made in Section 6.

2. System description and preliminaries

In the sequel, if not explicitly, matrices are assumed to have compatible dimensions. The notation $M > (\geq, <, \leq) 0$ is used to denote a symmetric positive-definite (positive-semidefinite, negative, negative-semidefinite) matrix. I stands for an identity matrix of suitable dimension. $\|\cdot\|$ refers to the Euclidean vector norm. $\mathbb{N}$ represents the set of nonnegative integers, that is, $\mathbb{N} = \{0, 1, 2, \ldots\}$. For $\tau > 0$, let $C([-\tau, 0], \mathbb{R}^n)$ denote the space of bounded, continuous functions $x : [-\tau, 0] \mapsto \mathbb{R}^n$ with norm $\|x\|_\tau = \max_{-\tau\leq\theta\leq 0} \|x(t+\theta)\|$. If $y \in C([-\tau, \alpha], \mathbb{R}^n)$ with $\alpha > 0$ and $t \in [0, \alpha)$, then $y_t \in C([-\tau, 0], \mathbb{R}^n)$ is defined by $y_t(\theta) = y(t+\theta)$, $\theta \in [-\tau, 0]$.

Consider a class of time-delay systems of the form

$$\begin{aligned} \dot{x}(t) &= \sum_{l=0}^{1} \left[C_l x(t-\tau_{lt}) + A_l f(x(t-\tau_{lt})) \right] \\ &\quad + Bu(t), \quad t > 0, \\ x(t) &= \phi(t), \qquad -\bar{\tau} \leq t \leq 0, \end{aligned} \tag{1}$$

where $x(t) \in \mathbb{R}^n$ and $u(t) \in \mathbb{R}^m$ denote the vectors of the system state and the input at time t; C_l, $A_l \in \mathbb{R}^{n\times n}$, $l = 0, 1$, are constant matrices; $f(x) = \left(f_1(x_1), f_2(x_2), \ldots, f_n(x_n)\right)^{\mathrm{T}}$ is a continuous map from $\mathbb{R}^n$ to $\mathbb{R}^n$; $\tau_{0t} = 0$, and $\tau_{1t} = \tau(t)$, where $\tau(t)$ is a time-varying function satisfying $0 \leq \tau(t) \leq \bar{\tau}$; $\phi \in C([-\bar{\tau}, 0]; \mathbb{R}^n)$ is the initial function. Throughout this paper, assume that the continuous map $f(\cdot)$ satisfies the following condition.

Assumption (**A1**) There exist scalars κ_i^- and κ_i^+ such that for any $s_1, s_2 \in \mathbb{R}$, $s_1 \neq s_2$,

$$\kappa_i^- \leq \frac{f_i(s_1) - f_i(s_2)}{s_1 - s_2} \leq \kappa_i^+, \quad i = 1, 2, \ldots, n.$$

Moreover, we consider the following two cases for the time-varying delay $\tau(t)$.

Case 1: $\tau(t)$ is a bounded continuous function satisfying

$$0 \leq \tau(t) \leq \bar{\tau}, \quad \forall t \geq 0,$$

where $\bar{\tau}$ is a scalar representing the upper bound of the time delay.

Case 2: $\tau(t)$ is a bounded differentiable function satisfying

$$0 \leq \tau(t) \leq \bar{\tau}, \qquad \dot{\tau}(t) \leq r < 1, \quad \forall t \geq 0,$$

where r is a nonnegative scalar.

For system (1), the following assumption is made throughout the paper.

Assumption (**A2**): System (1) with $u = 0$ is unstable.

The periodically intermittent linear state-feedback control law takes the following form

$$u(t) = K(t)x(t) \tag{2}$$

with

$$K(t) = \begin{cases} K, & t \in \Delta_{1k} \triangleq [k\omega, k\omega + \delta), \\ 0, & t \in \Delta_{2k} \triangleq [k\omega + \delta, \ (k+1)\omega), \end{cases}$$

where $K \in \mathbb{R}^{m\times n}$ is the control gain matrix to be designed.

Remark 1. The structure of the intermittent controller (2) implies that $u(t) = 0$ for all $t \in \Delta_{2k}$, $k \in \mathbb{N}$. This assumption makes sense as it provides a good representation of certain events. For example, it can model the controller failure or the purposeful suspension of controllers for equipment maintenance or a decreased bandwidth usage.