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Event-triggered control of discrete-time switched linear systems with packet losses

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ABSTRACT

The event-triggered control problem for discrete-time switched linear systems with packet losses is addressed in this paper. It is assumed that, at each event-triggered instant transmitted successfully, the controller can only access the transmitted information of system state and mode. In both cases of packet losses and no packet losses, mode dependent event-triggered transmission schemes are proposed. And the closed-loop system is modeled as a switched system with augmented switching signal. Then, based on the multiple Lyapunov function method, in the case of packet losses, exponential stability conditions are given with constraint of the maximum allowable number of successive packet losses, and design methods for state feedback controller gains and mode dependent event-triggered parameters are obtained. Finally, the effectiveness and improvement of the proposed approach are illustrated by a numerical example.

1. Introduction

As a subclass of hybrid systems, switched systems with complicated switching law have gained considerable attention during the last decades [1,2]. A switched system consists of the multiple subsystems and various types of switching signals that determine, at a certain time interval, which subsystem is active. In addition, switched systems have strong practical application background in many fields, such as power electronics, chemical processes, mechanical systems, automotive industry, aircraft and air traffic control and so on [3]. Therefore, a great number of efficient methods have been proposed to solve the stability and stabilization problems for switched systems in the past few decades, see the survey paper [2], and Refs. [3–11].

On the other hand, due to the unreliability of the network links, packet losses often happen when data is transmitted over a limited capacity communication channel. Moreover, packet losses would degrade the performance of the system or even destabilizing the system [12–15]. Furthermore, in the control of switched systems, the asynchronous switching between the controller and subsystems maybe occur when only the information of the system measurement and switching signal is transmitted successfully. Therefore, the asynchronous control problem of a switched system with packet losses will be resulted due to the complexity of mode switching and the limitation of channel capacity, which makes the system analysis more complicated and meanwhile brings many new challenges.

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In addition, a time-triggered communication scheme, which most data transmission via networks currently is based on, can lead to a good system performance. However, when the communication network cannot provide enough bandwidth, that all data packets are transmitted may cause network congestion. Furthermore, releasing all data packets into the communication network will lead to inefficient utilization of scarce computation and network resources. To mitigate the unnecessary data transmission, when the controller and the system are connected via a limited capacity communication channel, the event-triggered scheme was proposed in networked control and estimation [16–19] for non-switched systems. In comparison to conventional time-triggered schemes, event-triggering schemes can maintain the expected performance while reducing the waste of network resources, which also shown its advantage in many areas, such as the consensus and synchronization problems [20–23]. Therefore, event-triggered control problem for switched systems is also an interesting topic and worthy of in-depth study. Furthermore, it is worth mentioning that it is very challenging to consider packet losses in the event-triggered control problem compared with the time-triggered case [24]. However, to the best of our knowledge, there is no work on the event-triggered control problem for discrete-time switched systems with packet losses reported yet. Therefore, this paper devotes to finding a suitable event-triggered scheme and designing a controller such that discrete-time switched closed-loop systems are exponentially stable in the case of packet losses, meanwhile, the quantitative relation between the maximum number of successive packet losses and the event-triggered parameters is established.

The contributions of this paper can be described as follows. The mode dependent event-triggered mechanism with the constraint of the dwell time is proposed and the asynchronous switching control caused by the event-triggered condition is addressed for discrete-time switched linear systems. Based on the proposed event-triggered mechanism, the closed-loop system is modeled as a switched system with augmented switching signal. Then, according to a multiple Lyapunov function and average dwell time methods, sufficient exponential stability conditions are obtained with the constraint of the maximum allowable number of successive packet losses in the case of packet losses. At the same time, state feedback controller gains and mode dependent event-triggered parameters are designed based on matrix inequalities. The proposed method extends the result in [17,18] to the case of discrete-time switched systems. It is expected that the proposed approach leads an important step to study the event-triggered control for the discrete-time switched system, which may also have its potential applications in many areas, such as vaccinating behavior and disease dynamics [25], multi-switching synchronization of multiple chaotic systems [26].

Notation: Throughout this paper, $\mathbf{R}^n$ denotes the n-dimensional Euclidean space, $\mathbf{Z}^+$ represents the set of nonnegative integers. I is the appropriately dimensioned identity matrix, W^{-1} denotes inverse of matrix W, W^T denotes transpose of matrix W, $W > 0$ means that W is positive definite. δ_{ij} is the standard Kronecker delta function. Asterisk '*' in a symmetric matrix denotes the entry implied by symmetry. Matrices, if not explicitly stated, are assumed to have compatible dimensions.

2. Problem formulations

In this paper, the following discrete-time switched linear systems are considered:

$$x(k+1) = A_{\sigma(k)}x(k) + B_{\sigma(k)}u(k), \tag{1}$$

where $x(k) \in \mathbf{R}^n$ and $u(k) \in \mathbf{R}^m$ are the system state and control input, respectively. The switching signal $\sigma(k) : \mathbf{Z}^+ \to \mathcal{M} = \{1, 2, \dots, N\}$ is a piecewise constant function of time and N is the number of subsystems. For every $i \in \mathcal{M}$, A_i and B_i are constant real matrices with appropriate dimension. Denote (A_i, B_i) as the ith subsystem.

Firstly, we introduce the necessary definition and assumptions in this paper.

Definition 2.1 [1]**.** Let $N_\sigma(k_0, k)$ be the number of switches of $\sigma(k)$ in the interval (k_0, k).

(1) If there exists a constant $\tau_d > 0$ and $N_\sigma(k_0, k) \le 1$ when $k - k_0 \le \tau_d$, then we call $\sigma(k)$ have a dwell time τ_d.

(2) If there exists a constant $\tau_a > 0$ and positive number N_0 such that $N_\sigma(k_0, k) \le N_0 + \frac{k-k_0}{\tau_a}$, $\forall\ k \ge k_0 \ge 0$, then we call $\sigma(k)$ have an average dwell time τ_a and chatter bound N_0. For simplicity, we denote $\sigma(k) \in \mathcal{S}[\tau_a, N_0]$, where $\mathcal{S}[\tau_a, N_0]$ denotes the set of the switching signals with an average dwell time τ_a and chatter bound N_0.

Assumption 2.1. For each $i \in \mathcal{M}$, the subsystem (A_i, B_i) is stabilizable. Moreover, there exists a state feedback gain matrix K_i such that $A_i + B_iK_i$ is Schur stable.

Assumption 2.2. Assume that $\sigma(k)$ has a dwell time τ_d and $\sigma(k) \in \mathcal{S}[\tau_a, N_0]$.

Remark 2.1. According to Assumption 2.1, exponential stability of the closed-loop system with state feedback controller $u(k) = K_{\sigma(k)}x(k)$ can be guaranteed by slow switching characterized by dwell time or average dwell time.

Fig. 1 shows that the framework for event-triggered control of discrete-time switched system, in which the system mode dependent event-triggered mechanism is proposed to generate the transmission sequence $\{k_s\}_{s\ge 1}$, and signals are transmitted via a limited capacity communication channel, which maybe cause packet losses. In the following, we propose the event-trigged transmission mechanism:

$$k_{s+1} = \min\left\{k'_{s+1}, k_s + \tau_d\right\}, k_0 = 0, \tag{2}$$

where $k'_{s+1} = \min_{k>k_s}\{k|[x(k) - x(k_s)]^T\Phi_{\sigma(k_s)}[x(k) - x(k_s)] \ge \nu x^T(k_s)\Phi_{\sigma(k_s)}x(k_s)\}$, the positive scalar ν and the positive defined matrix Φ_i are event-triggered parameters associated with the ith subsystem (A_i, B_i).