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Brief paper

Event-driven observer-based output feedback control for linear systems[☆]

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ABSTRACT

This paper concerns the problem of event-driven observer-based output feedback control of linear systems. Contrary to normal sampled-data control systems, where the controller is updated periodically, in event-driven systems, it is updated only when an "event" happens, and a typical event is defined as some error signals exceeding a given threshold. Both continuous- and discrete-time event detector cases are considered. It is shown that even with the significantly reduced sampling frequency, the global uniform ultimate boundedness of the event-driven closed-loop systems can also be guaranteed. A numerical example is finally used to illustrate the effectiveness and advantages of the proposed approaches.

1. Introduction

In sampled-data systems, digital controllers are often used to control continuous-time physical plants, and both continuous-time and discrete-time signals are involved in control systems. Analysis and synthesis of sampled-data control systems have been a subject of many researches in recent years (Chen & Francis, 1995; Fridman, 2010; Fridman, Seuret, & Richard, 2004; Gao, Wu, & Shi, 2009; Hu, Bai, Shi, & Wu, 2007; Shi, 1998). In the traditional sampled-data control framework, the sensor and controller are updated uniformly in time with a constant sampling period T, which is termed as time-driven sampling. Although periodical sampling simplifies design and analysis, it may lead to higher system costs, since sampling happens at a fixed rate regardless whether it is really necessary or not. Especially, in networked control systems (NCSs) (Xia, Fu, & Liu, 2011; Zhang, 2001), sensors communicate frequency with controllers through a load or bandwidth limited network, and in such a case, communication between sensors and controllers should be as small as possible to avoid congestion or packet dropouts.

To cope with the problem, event-driven control, also called event-triggered control or event-based control in the literature, has been proposed as a means to reduce the sampling or frequency of communication between the components of the networked control systems. In event-driven control framework, the necessary sampling or communication is determined by the occurrence of an "event" rather than "time". Since the early works on event-driven control (Arzen, 1999; Åström, 2008; Åström & Bernhardsson, 2002; Heemels et al., 1999), several different event-driven mechanisms and control strategies are proposed, and a detailed analysis of event-driven control systems is presented in Heemels, Sandee, and van Den Bosch (2008). In Arzen (1999), a simple event-driven PID controller is presented, and the PID controller calculates the control signal only when the change of the measurement signal is sufficiently large. In Durand and Marchand (2009), some improvements of the event-driven PID controller introduced in Arzen (1999) have been proposed. In Åström (2008) and Åström and Bernhardsson (2002), some analytical results on comparing the performance of event-driven and sampled-data control are obtained for a first-order system, and the concept of a control signal generator is introduced to generate the control signal between samples. In Lunze and Lehmann (2010), event-driven state-feedback control is considered for linear systems with bounded disturbances, and the results are extended to event-driven control with communication

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delays and packet losses in Lehmann and Lunze (2012). An approach to design of asymptotically stable event-driven implementations of linear and nonlinear controllers is proposed in Tabuada (2007), and the event is generated when the input-to-state stability of the closed-loop system with respect to measurement errors is violated. This idea has been extended to the exponential input-to-state stability case in Mazo, Anta, and Tabuada (2010). In Wang and Lemmon (2009), a self-triggered scheme is presented for linear time-invariant systems with disturbance whose magnitude is bounded by a linear function of the norm of the system state, and the finite-gain $\mathcal{L}_2$ stability of the resulting self-triggered feedback control systems is guaranteed. In Wang and Lemmon (2010), the same authors further investigate the $\mathcal{L}_2$ stability of the self-triggered feedback systems with state-independent disturbances. In Peng and Yang (2013), an event-driven communication scheme and an H_∞ control co-design method for networked control systems (NCSs) with communication delay and packet loss have been proposed, and the maximum allowable number of successive packet losses is established in terms of the parameters in the event threshold condition. It is worth noting that the aforementioned results are based on state-feedback controllers, which assumes that all states of the plant are available. Nevertheless, in many control applications, the full state information is not available, so it is important to investigate output feedback based event-driven control strategies. In Donkers and Heemels (2012), the stability and $\mathcal{L}_\infty$-performance of event-driven control systems with dynamical output feedback controllers are studied with decentralized event-driven mechanisms. In Lehmann and Lunze (2011), the event-driven state-feedback control approach developed in Lunze and Lehmann (2010) is extended to event-based output feedback control, where a state observer is incorporated to generate the control inputs. In Li and Lemmon (2010), event-driven finite-horizon output-feedback problems of discrete-time linear systems are considered, and a computationally tractable approach to determining suboptimal event-triggers is presented. In Trimpe and D'Andrea (2011b), event-driven strategies are used to deal with the state estimation problem in a networked control system. The basic idea is that a sensor measurement is transmitted and used to update the Kalman filter if its associated prediction variance exceeds a certain tolerable bound. In Trimpe and D'Andrea (2011a), a constant threshold on the difference of an actual measurement and its prediction by the estimator is used as the condition to define an event. By using a similar event-driven estimator to obtain a state estimate, where the estimation error is then transformed into explicit polytopic uncertainties, a robust MPC algorithm is proposed in Sijs, Lazar, and Heemels (2010). More recently, the authors in Heemels and Donkers (2013) investigates the observer-based control problem for discrete-time linear systems, where some elegant and important event-triggering mechanisms are proposed, and two general modeling and analysis frameworks based on perturbed linear (PL) systems and piecewise linear (PWL) systems are established.

In this paper, we aim at addressing the observer-based event-driven control problem for continuous-time linear systems, and both continuous- and discrete-time event detector cases are considered, where the updating of the controller is determined by an "event" which is defined as some error signals exceeding a given threshold, and the state observer is implemented in a smart sensor to generate the state estimates, and the event-driven condition is designed based on the state estimates. The main contributions of this paper lie in:

(i) For the continuous-time event detector case, different from the event-driven control approaches with constant event threshold (Lehmann & Lunze, 2011; Lunze & Lehmann, 2010), the sampling instants are defined by using an exponentially decreasing event threshold condition, and then, the global uniform ultimate boundedness of the closed-loop system is established. Moreover, the analysis on the minimum inter-event interval is also performed, and the lower bound of the minimum inter-event interval is presented.

(ii) For the discrete-time event detector case, the event-driven condition is monitored periodically with period T, and the closed-loop system is modeled as a time-delay system. With the aid of the exponentially decreasing event threshold condition, the sampling instants are determined explicitly in terms of the parameter T, and the global uniform ultimate boundedness of the resulting closed loop control system is established.

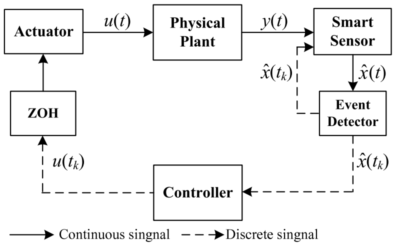

Fig. 1. Event-driven control system.

Finally, a numerical example is given to show the effectiveness and potential of the proposed approaches.

2. Problem statement

As shown in Fig. 1, the event-driven control system considered in this paper can be grouped into the following three modules: (1) the physical plant and smart sensor; (2) the event detector; (3) the event-driven controller.

2.1. Physical plant and smart sensor

The physical plant is given by the following continuous-time linear system:

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) \\ y(t) &= Cx(t) \end{aligned} \tag{1}$$

where $x \in \mathbb{R}^n$ represents the system state vector, $u \in \mathbb{R}^m$ denotes the control input vector, and $y \in \mathbb{R}^q$ is the output vector, and A, B, C are system matrices with appropriate dimensions. It is assumed that the pairs (A, B) and (C, A) are controllable and observable, respectively.

Here, we assume that the sensor has necessary computation capability, and it can pre-process measurements $y(t)$ to obtain the state estimate $\hat{x}(t)$ according to the following state observer:

$$\dot{\hat{x}}(t) = A\hat{x}(t) + Bu(t) + L(y(t) - C\hat{x}(t)), \tag{2}$$

where $\hat{x} \in \mathbb{R}^n$ is the observer state, L is the observer gain appropriately designed.

2.2. Event detector

In this paper, we consider two kinds of event detectors, continuous- and discrete-time event detectors.

2.2.1. Continuous-time event detectors

The event detector monitors the event-driven condition continuously to determine whether an "event" is generated or not. Once