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Research article

H_∞ observer-based event-triggered sliding mode control for a class of discrete-time nonlinear networked systems with quantizations

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ABSTRACT

This paper investigates the problem of H_∞ observer-based event-triggered sliding mode control (SMC) for a class of uncertain discrete-time Lipschitz nonlinear networked systems with quantizations occurring in both input and output channels. The event-triggered strategy is used to save the limited network bandwidth. Then, based on the zero-order-hold (ZOH) measurement, a state observer is designed to reconstruct the system state, which facilitates the design of the discrete-time sliding surface. Considering the effects of quantizations, networked-induced constraints and event-triggered scheme, the nonlinear state error dynamics and sliding mode dynamics are converted into a unified linear parameter varying (LPV) time-delay system with the aid of a reformulated Lipschitz property. By using the Lyapunov-Krasovskii functional and free weighting matrix, a new sufficient condition is derived to guarantee the robust asymptotic stability of the resulting closed-loop system with prescribed H_∞ performance. And then the observer gain, event-triggering parameter and sliding mode parameter are co-designed. Furthermore, a novel SMC law is synthesized to force the trajectories of the observer system onto a pre-specified sliding mode region in a finite time. Finally, a single-link flexible joint robot example is utilized to demonstrate the effectiveness of the proposed method.

1. Introduction

Recently, networked control systems (NCSs) have attracted a great deal of attention due to their extensive applications in many fields, such as advanced aircraft, unmanned aerial vehicles and remote surgery. Compared with traditional feedback control systems, NCSs offer various features in terms of low cost, ease of installation and maintenance, and high flexibility. However, the insertion of limited-capacity communication channels into control systems introduces many challenging problems including transmission delay, packet dropout, quantization, etc. Much efforts have been made on modeling, stability analysis and controller synthesis for NCSs, see for example [1–4], and the references therein.

In practical applications, the control systems are implemented by the use of digitally sampled measurements. The common approach is to transmit sampled measurements periodically. Although it is preferred for modeling and analyzing the system in period manner, the communication burden is often neglected. Therefore, for systems with limited network resources and heavy communication burdens, it would be necessary to develop an effective approach to reduce the unnecessary utilization of the limited communication resources while maintaining the control performance. Recently, event-triggered mechanism, as an alternative approach to save the limited network resources, has been proposed where the sampling signal is released only if an event-triggering condition related to system state is violated. In contrast to time-triggered scheme, the conspicuous superiority of the event-triggered strategy is that it can largely reduce network energy consumption while maintaining satisfactory control performance. Benefiting from the event-triggered scheme, fruitful outcomes on the research of event-triggered control have been established for several control issues, such as, observer-based control [5,6], H_∞ control [7,8], quantization control [9,10], and sliding mode control [11].

In another active research frontier, SMC, due to its outstanding characteristics such as fast response and the inherent robustness against external disturbances and model uncertainties, has gained considerable attention and been successfully applied in various engineering applications during the past decades [12,13]. The basic SMC thought is to design a predefined sliding surface and then to construct a sliding mode controller to drive the state trajectories of closed-loop system onto the sliding surface in a finite time and stay within it thereafter. Until now, it has been widely investigated in many control systems, such as, singular systems [14,15], Markovian jump systems [16,17], and NCSs [18].

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More recently, SMC in conjunction with event-triggered method has been studied in many systems [11,19–22]. Among them, the problem of event-triggered SMC for stabilization of linear/nonlinear systems was investigated by Behera et al. [19,20]. For uncertain Memristive Chua's systems, the event-triggered SMC scheme was studied by Wen et al. [21]. Observer-based event-triggered SMC problem for stochastic systems with limited communication capacity was studied by Wu et al. [22]. These works have validated the effectiveness of event-triggered SMC method for linear/nonlinear systems with different system constraints.

On the other hand, quantization problems have received much attention in NCSs in recent years, owing to its significant impact on the control system performance [23,24]. In NCSs, the control inputs and measurement outputs are usually quantized before being transmitted. Around this topic, many fundamental results have been investigated by many researchers in terms of linear systems or nonlinear systems. In Ref. [25], the quantized feedback control problem was investigated for MIMO systems by applying a sector bound approach. In Ref. [26], the quantization parameter mismatch problem for linear systems was studied by using SMC approach. To reduce the data transmission and further save the limited network bandwidth, the event-triggered control for continuous-time linear systems with both input and state quantizations was discussed in Ref. [27]. The problem of event-triggered H_∞ control for singular system with quantizations and time-delays was studied in Ref. [28]. In addition, the problem of event-triggered SMC for continuous-time linear systems with state quantization was investigated in Ref. [29]. For output-feedback control, Tanwani et al. [30] studied the observer-based feedback stabilization problem for linear systems with event-triggered sampling and dynamic quantization. It is worth noting that the aforementioned event-triggered quantization problems are considered in linear systems. In practical control systems, almost all dynamic systems are nonlinear systems. It is significant and imperative to studied the problem of event-triggered quantization control for nonlinear networked systems. In Ref. [31], the authors addressed the event-triggered filter design for time-varying discrete nonlinear networked systems with output quantization. However, to the best of our knowledge, there are no results available analyzing the H_∞ observer-based event-triggered SMC for a class of uncertain discrete-time Lipschitz nonlinear networked systems subject to quantizations and network-induced delays, which motivates us to cope with this challenging and meaningful topic.

Motivated by the aforementioned analysis, the purpose of this paper is to investigate the problem of H_∞ observer-based SMC for a class of uncertain discrete-time Lipschitz nonlinear networked systems with event-triggered sampling and quantizations. The main contributions could be summarized as follows [1]: By employing a reformulated Lipschitz property [32], the closed-loop system subject to event-triggering condition, network-induced delays, and input and output quantizations is modeled as a unified LPV system with time-varying delays [2]. By use of the Lyapunov-Kraovskii functional approach and free weighting matrix, a sufficient condition is proposed to illustrate the robust asymptotic stability of the resulting closed-loop system with a prescribed H_∞ disturbance attenuation level, and then the co-design algorithm is derived to obtain the event-triggering parameter, observer gain and sliding mode parameter, simultaneously [3]. A novel SMC law for reaching motion is synthesized to ensure the reachability of the sliding mode dynamics in a finite time in spite of input quantization constraints.

The rest of this work is organized as follows. Section 2 provides the descriptions of quantized event-triggered NCS, and some preliminaries. Section 3 details the main results on the event-triggered SMC for uncertain discrete-time Lipschitz nonlinear networked systems under quantization constraints. An example is present in Section 4 to demonstrate the effectiveness of the proposed design method. Finally, this paper is concluded in Section 5.

Notations: For a matrix A, A^{-1} and A^T denote the inverse and transpose of matrix A, respectively, and sym$\{A\}$ stands for the expression $A + A^T$. $\mathbb{R}^n$ stands for the n-dimensional Euclidean space and $\mathbb{R}^{n\times m}$ is the set of $n \times m$ real matrices. $\mathbb{S}^n$ denotes the set of $n \times n$ real symmetric positive definite matrices. Moreover, diag$\{\cdots\}$ represents a block-diagonal matrix, and the symbol * stands for the symmetric term in a symmetric block matrix. The notation $P > 0$ $(P < 0)$ means that P is a positive (or negative) definite matrix. $\|\cdot\|$ is Euclidean norm of a vector and its induced norm of a matrix. For $w(k) \in \mathscr{L}_2[0, \infty)$, its norm is given by $\|w(k)\|_2 = (\sum_{k=0}^{\infty} \|w(k)\|^2)^{\frac{1}{2}}$. $e_s(i) = \Big(\underbrace{0, \ldots, 0, \overbrace{1}^{ith}, 0, \ldots, 0}_{s\ components}\Big)^T \in \mathbb{R}^s,\ s \geq 1$ is a vector of the canonical basis of $\mathbb{R}^s$.

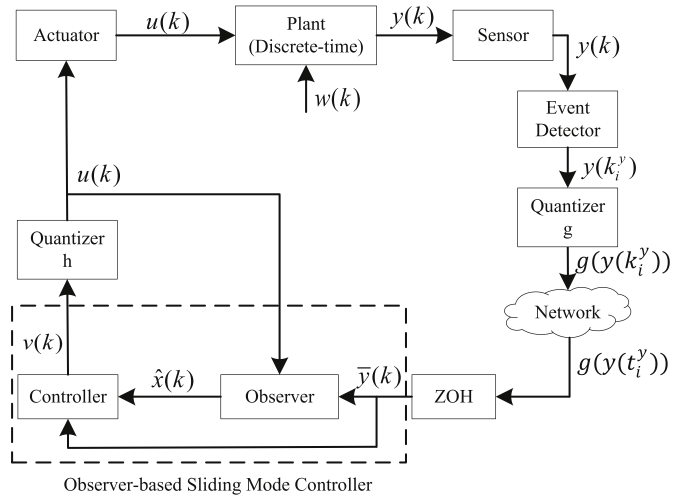

Fig. 1. Event-triggered networked control system structure.

2. Preliminaries

In this paper, the problem of H_∞ observer-based event-triggered SMC subject to quantizations and time-delay is considered. As shown in Fig. 1, the system measurement output is determined by an event detector and then quantized before being transmitted through a network, which can reduce the utilization of the network bandwidth. Furthermore, the control input is also quantized before being transmitted to the plant. The configuration of this architecture is stated as follows.

2.1. Plant

Consider the uncertain discrete-time Lipschitz nonlinear system described by

$$\begin{cases} x(k+1) = (A + \Delta A(k))x(k) + Bu(k) + f(x(k)) + Dw(k), \\ y(k) = Cx(k), \\ x(0) = x_0 \end{cases} \tag{1}$$

where $x(k) \in \mathbb{R}^n$, $u(k) \in \mathbb{R}^m$ and $y(k) \in \mathbb{R}^p$ are the system state, control input and measurement output, respectively. $f(x(k))$ is a known nonlinear function, $w(k) \in \mathbb{R}^q$ is the external disturbance belonging to $\mathscr{L}_2[0, \infty)$. $x_0 \in \mathbb{R}^n$ is the initial condition. A, B, C and D are known real matrices with appropriate dimensions and rank $(B) = m$. $\Delta A(k)$ is an unknown matrix representing time-varying uncertainty which has the form of

$$\Delta A(k) = F_A \Delta_A(k) M_A, \tag{2}$$

where $F_A \in \mathbb{R}^{n\times r}$ and $M_A \in \mathbb{R}^{h\times n}$ are known real matrices, and $\Delta_A(k)$ is an unknown time-varying function satisfying

$$\Delta_A^T(k)\Delta_A(k) \leq I, \quad \forall\ k \geq 0. \tag{3}$$