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Adaptive event-triggered communication scheme for networked control systems with randomly occurring nonlinearities and uncertainties

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ABSTRACT

This paper proposes a novel adaptive event-triggered communication scheme for networked control systems (NCSs) with randomly occurring nonlinearities and uncertainties. Firstly, an adaptive event-triggered communication scheme for NCSs is proposed, which can adaptively adjust the trigger parameter with respect to the dynamic error to save the limited network resources while ensuring the desired control performance. Secondly, an integrated model of the studied system is built under consideration of the network-induced delay, adaptive event-triggered communication scheme and randomly occurring nonlinearities and uncertainties in a unified framework. Then, sufficient stability criterion to judge the mean-square sense asymptotically stable and stabilization criterion to co-design the parameters of the communication scheme and controller are obtained for the system under consideration. Finally, two examples are given to illustrate the effectiveness of the developed method.

1. Introduction

Feedback control systems communicating over a real time network are called networked control systems (NCSs), in which the components, i.e., the sensors, controllers and actuators are distributed and connected to a controlled plant [1]. While NCSs have many advantages, for example low cost, reduced weight and power requirements, and simple installation and maintenance, the insertion of a communication network causes some challenging issues on account of the limited network bandwidth, such as network-induced delays and packet dropouts, which may lead to performance degradation or even instability of an NCS [2–4]. During the past decades, the stability analysis and controller synthesis for NCSs have experienced an increasing attention, see, for example [5–7] and reference therein.

Generally, most of the control tasks are executed periodically in many digital control applications [8,9]. Although periodic executing is preferred from the analysis and control design point of view, it consumes most of the limited communication and computation resources, especially when the system is operating desirably without disturbances [10]. Considering the limited network resources, event-triggered communication scheme has emerged as an effective method to improve the resources utilization while ensuring a satisfactory performance of the closed-loop system [11–14]. In recent years, significant considerations have been focused on the event-triggered control for linear systems [15–17], nonlinear systems [18] as well as multi-agent systems [19–21]. Notice that the aforementioned results are based on a "static" event-triggered communication scheme. For example in [15], the next transmission instant is determined by $t_{k+1}h = t_kh + \min\{ih \,|\, e^T(j_kh)\Phi e(j_kh) \geq \delta x^T(t_kh)\Phi x(t_kh)\}$, where Φ is a symmetric positive definite matrix, $e(j_kh) \triangleq x(j_kh) - x(t_kh)$, $x(j_kh)$, $x(t_kh)$ are the newly sampled and last released data, respectively, $j_kh = t_kh + ih$, $i \in \mathbb{N}$ and δ is a pre-given constant. As the simulation results in [15], the"static" communication scheme can reduce the average transmission frequency while maintaining the desired control performance. However, one thing should be pointed out that the performance of the closed-loop system has been degraded in comparison with those obtained under a periodic communication scheme, since less information of the controlled plant is used for feedback. To the best of authors' knowledge, how to design a novel adaptive event-triggered communication scheme while saving the limited network resources and keeping the desired performance is still open. This is the first motivation of this work.

In a class of complex networks, nonlinear disturbances and parameter uncertainties randomly occur, such as sudden environmental disturbances, network-induced failures and repairs of components [22]. Therefore, nonlinearities and uncertainties may occur in a probabilistic way with a certain type and intensity [23]. So far, there are some valuable works for a system with simultaneous

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consideration of randomly occurring nonlinearities and uncertainties. In [24], a state estimator is used to estimate the true states of the proposed dynamic system under consideration of the randomly occurring nonlinearities. Considering the effect of the randomly occurring uncertainties, nonlinearities and time delays, sufficient conditions are established to ensure the synchronization criteria for an array of coupled complex discrete-time networks in [25]. Up to now, few works have been found in the literature on an adaptive event-triggered control method for NCSs with simultaneous consideration of randomly occurring nonlinearities and uncertainties. This is the second motivation of this work.

In this paper, we will develop a novel adaptive event-triggered communication scheme for a class of NCSs involving the phenomena of the randomly occurring nonlinearities and uncertainties. Then the studied system is modeled as an error dynamic system, under consideration of the network-induced delay and the randomly occurring nonlinearities and uncertainties in a unified framework. By employing a discontinuous Lyapunov–Krasovskii functional candidate, two criteria are established for the asymptotical mean-square stability analysis and control synthesis in terms of matrix inequalities. The main contributions of this paper can be highlighted as:

(1) A novel adaptive event-triggered communication scheme for NCSs with randomly occurring nonlinearities and uncertainties is proposed. Compared with the existing time-invariant communication scheme in the literature, the proposed scheme achieves a better performance while reducing the frequency of data transmission.
(2) An integrated model is built under consideration of the adaptive event-triggered communication scheme, the randomly occurring nonlinearities and uncertainties in a unified framework, which includes some existing models as special cases.
(3) Less conservative results are obtained with less number of scalar decision variables, by view of a constructed discontinuous Lyapunov–Krasovskii functional.

This paper is organized as follows. Section 2 proposes a novel adaptive event-triggered communication scheme to trigger the transmission event and an integrated model to couple the considered system and the communication scheme in a unified framework. Section 3 investigates the stability and stabilization criteria for the studied system. Two numerical examples are given in Section 4 to illustrate the effectiveness of the proposed method. Finally, Section 5 concludes this paper.

Notation: Throughout this paper, $\mathbb{N}$ stands for the set of positive integers, $\mathbb{R}^n$ denotes the n-dimensional Euclidean space, $\mathbb{R}^{m\times n}$ is the set of $m\times n$ real matrices. For $X\in\mathbb{R}^{n\times n}$, the notation $X>0$ (respectively, $X\geq 0$) means that the matrix X is a real symmetric positive definite (positive semi-definite). In symmetric block matrices, '$*$' is used as ellipsis for terms induced by symmetric, $diag\{\cdots\}$ denotes the block-diagonal matrix.

2. System framework

Consider a system described by

$$\dot{x}(t)=(A_0+\alpha(t)\Delta A(t))x(t)+(B_0+\beta(t)\Delta B(t))u(t)+\gamma(t)h(t,x(t)) \tag{1}$$

where $x(t)\in\mathbb{R}^n$ and $u(t)\in\mathbb{R}^m$ are the system state vector and control input vector, respectively; A_0 and B_0 are constant matrices with appropriate dimensions; $\Delta A(t)$ and $\Delta B(t)$ denote the parameter uncertainties satisfying

$$[\Delta A(t)\ \Delta B(t)]=GF(t)[E_a\ E_b] \tag{2}$$

where G, E_a and E_b are constant matrices with appropriate dimensions and $F(t)$ is an unknown time-varying matrix satisfying $\|F^T(t)F(t)\|\leq I$. The function $h(t,x(t)):\mathbb{R}\times\mathbb{R}^n\to\mathbb{R}^n$ is assumed to be a piecewise-continuous nonlinear function in both arguments t and x, and satisfies

$$h^T(t,x(t))h(t,x(t))\leq\kappa^2x^T(t)H^THx(t) \tag{3}$$

where $\kappa>0$ is the bounding parameter on the uncertain function $h(t,x(t))$, H is a constant matrix and $h(t,0)=0$. The stochastic variables $\alpha(t)$, $\beta(t)$ and $\gamma(t)$ are Bernoulli-distributed white sequences, and take values on either 0 or 1 with

$$\begin{aligned}&\Pr\{\alpha(t)=1\}=\alpha,\quad \Pr\{\alpha(t)=0\}=1-\alpha\\&\Pr\{\beta(t)=1\}=\beta,\quad \Pr\{\beta(t)=0\}=1-\beta\\&\Pr\{\gamma(t)=1\}=\gamma,\quad \Pr\{\gamma(t)=0\}=1-\gamma\end{aligned}$$

where $\alpha\in[0,1]$, $\beta\in[0,1]$ and $\gamma\in[0,1]$ represent known constants.

Remark 1. Notice that the stochastic variables $\alpha(t)$, $\beta(t)$ and $\gamma(t)$ are introduced to characterize the phenomena of the randomly occurring nonlinearities and uncertainties, respectively. Particularly when $\alpha=0$, $\beta=0$ and $\gamma=1$, the system model (1) shrinks to the studied systems in [26,27]. Therefore, one can conclude that the system models in [26,27] are special cases of the model in this work.

Throughout this paper, we assume that the system (1) is controlled through a network. Before further proceeding, the following assumptions are made, which are common in NCSs research in the literature.

Assumption 1. The sensor is clock-driven, while the controller and actuator are event-driven. The signal in a communication network is transmitted with a single packet.

Assumption 2. Communication delays from the sensor to the controller and from the controller to the actuator, and the computational and waiting delays are lumped together as $\eta_k\in[\eta_m,\eta_M]$, where η_m and η_M are the lower and upper bounds of η_k, respectively.

2.1. An adaptive event-triggered communication scheme

Considering the limited bandwidth of the communication network, we propose an adaptive event-triggered communication (AETC) scheme for the system (1), which is utilized to determine whether or not the current sampled data should be transmitted to the controller. More specifically, let $\{t_0h,t_1h,t_2h,\ldots\}$ denote the transmitted instants, where $t_0h=0$ is the first triggering time. When the latest transmitted data is $x(t_kh)$, the next transmission instant $t_{k+1}h$ can be determined by

$$t_{k+1}h=t_kh+\min\{nh\,|\,e^T(i_kh)\Phi e(i_kh)>\sigma(i_kh)x^T(t_kh)\Phi x(t_kh)\} \tag{4}$$

where $\Phi>0$ is a weighting matrix. The threshold error between the current sampled data and the latest transmission one is defined as

$$e(i_kh)\triangleq x(i_kh)-x(t_kh) \tag{5}$$

where $i_kh=t_kh+nh$, $n\in\mathbb{N}$, h is the sampling period of the sensor, t_k $(k=0,1,2,\ldots)$ are some integers such that $\{t_0,t_1,t_2,\ldots\}\subset\{0,1,2,\ldots\}$. Considering the time delay in the communication, the corresponding transmitted signals arrive at the actuator at instants $t_0h+\eta_0,t_1h+\eta_1,t_2h+\eta_2,\ldots$, respectively, where $\eta_0=0$. Then, it is clear that $t_0h+\eta_0<t_1h+\eta_1<t_2h+\eta_2<\cdots$ with the assumption that packet dropouts and packet disorders do not occur. From (4), it can be seen that the next transmission instant $t_{k+1}h$ depends not only on the error $e(i_kh)$, but also on the latest transmitted state vector $x(t_kh)$. Moreover, in (4), the trigger