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Event-triggered network-based synchronization of delayed neural networks ☆

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ABSTRACT

This paper is concerned with the problem of event-triggered network-based synchronization for a class of delayed neural networks. By introducing an event generator in the control loop, the model of event-triggered master–slave synchronization frame is constructed. Considering the effect of the communication network including transmission delay and stochastic fluctuation, an event-triggered error system of master system and slave system is formulated. By using the Lyapunov functional method, some delay-dependent synchronization criteria in terms of linear matrix inequality are proposed to ensure the mean square synchronization between the master system and the slave system. A singular value decomposition lemma is introduced to solve the control design problem for the case of the lower bound of neuron activation function is nonzero, which is different from the previous literature. Two illustrative examples are provided to demonstrate the limited network bandwidth could be saved by using the proposed design scheme.

1. Introduction

In recent years, chaotic synchronization has been extensively studied due to its strong potential applications in engineering, such as secure communication, robot queue, and chemical reaction. Chaos is a complex nonlinear behavior that can be observed in some dynamic systems, in which different initial values or random disturbances often lead to different dynamic behaviors. Since Pecora and Carroll's pioneer work in [1], chaos synchronization has been attracting much attention of researchers. As a result, lots of control methods have emerged, such as variable structure control, sampled-data feedback control, and adaptive control method (see e.g., [2–7] and the references therein). Neural networks usually show complex dynamic behavior, and easy to achieve in hardware. Therefore, more and more researchers devoted to the research of neural networks and its synchronization problems. Reference [8] has investigated the master–slave synchronization for neural networks with distributed delays and variable sampling which is bounded by a known value. Based on the stochastic analysis theory and adaptive feedback control technique, an adaptive feedback controller was proposed in [9] for the synchronization of neural networks with stochastic perturbation and parameter uncertainties. By combining a Jensen integral inequality and a convex combination technique, the network-based synchronization of delayed neural networks was investigated in [10].

On the other hand, networked control systems (NCSs) have become popular in the past few years due to the extensively strong applications. In NCSs, the control performance is always affected by communication imperfections introduced by the network, for instance, network-induced delay, packet dropout, and data rate constraints. To reduce the influence of the communication networks, a large of researchers attempt to find appropriate control laws, and has yielded some results (see e.g., [11–15] and references therein). Specifically, in [12] an observer-based method was proposed to design the controller for networked systems including both random measurement and actuation delays. By making full use of the delay information in the model, it can obtain a less conservative result. A time-varying controller was provided in [14], in which a predictive control scheme was used to compensate for the communication delay.

It should be noted that most of the aforementioned results are based on a time-triggered scheme. In this kind of scheme, the data packets are transmitted periodically, which may lead to a result that the "unnecessary" data are sent frequently, which causes the excessive use of network bandwidth, especially in the NCSs where the network bandwidth is limited. Recently, an event-triggered scheme has been proposed for controller design (see e.g., [16–30]

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and the references therein). Event-trigging scheme provides a useful way to determine when the packet should be transmitted. In [17], a kind of event generator like which depends on the continuous supervision of the system state was constructed. And a self-triggered scheme was presented in [19,20], where the implementation of the event generator only need monitor the system state in discrete instants. Compared with the event-triggered scheme in [17], it could save network resources better. Similar to the self-triggered method in [19,20], an event-triggering was proposed in [22], and different from [19,20], it provided a method for co-designing both the controller and the trigger parameters. Based on the T–S fuzzy model and time-delay systems method, reference [23] proposed a discrete event-triggered $[x(k)-x(k_s)]^T W[x(k)-x(k_s)] \le \sigma x^T(k)Wx(k)+\varepsilon$, where parameter k_s is the triggering instant, $\sigma \in [0,1), \varepsilon \ge 0$, $W>0$ is a weighting matrix, and addressed the event-triggered fuzzy control for a class of nonlinear networked control systems with time-varyingdelay. Compared with the existing results, the event-triggered scheme proposed in [23] is more general. An event-triggered H_∞ controller design problem for nonlinear networked control systems with time delay and uncertainties is investigated in [31]. By introducing some free weighting matrices to deal with the integral items and converting the coupling time-varying matrix inequalities into a group of decoupling matrix inequalities, some control synthesis for the event-triggered networked T–S fuzzy systems are established in terms of matrix inequalities in [31]. A pinning exponential synchronization of complex networks via event-triggered communication is investigated in [32].

In some practical applications, network synchronization control has great potential values such as secure communication in wireless networks [33]. As the signal in wireless network is very easy to be caught, long network-induced delay-high packet loss rate and susceptible to interference, the existing security technology based on the chaotic synchronization does not apply to wireless network. In other applications such as reliable multiple robots formulation [34], multi-robot distributed queue control and high-speed long distance communication, the networked-based synchronization shows great application values. Therefore, the research on network-based synchronization has a certain theoretical significance and practical value.

Inspired by the event-triggering scheme for NCSs and the theorem of matrix singular value decomposition, we propose a network-based synchronization method for the delayed neural networks through an event-triggered controller. In the framework under consideration, an event generator is introduced into the synchronization control loop. The sampled data packets from master system and slave system are sent to the event-generator, which induces network delays and stochastic fluctuations. A judgement mechanism is constructed to determine when the control signal is sent to a zero-order hold (ZOH). We formulate the error system model and use a Brownian motion to describe the stochastic fluctuations. By using the Lyapunov functional method, a delay-dependent synchronization criterion of global asymptotic stability in the mean square sense is derived. By introducing the singular value decomposition lemma, a controller designing method based on linear matrix inequalities is presented. Two simulation examples are given to illustrate the effectiveness of the proposed design methods.

Notation: $\mathbb{R}^n$ denotes the n-dimensional Euclidean space; $\mathbb{R}^{n\times m}$ is the set of real $n \times m$ matrices; and $\mathbb{Z}_+$ denotes the set of non-negative integers. I is the identity matrix of appropriate dimensions. $\|\cdot\|$ stands for the Euclidean vector norm or spectral norm as appropriate. diag $\{\cdots\}$ denotes a block-diagonal matrix; and col $\{\cdots\}$ stands for a matrix column with blocks given by the matrices in $\{\cdots\}$. The notation $X>0$ (respectively, $X<0$) for $X \in \mathbb{R}^{n\times n}$ means that the matrix X is real symmetric positive definite (respectively, negative definite). The asterisk $*$ in a matrix is used to denote term that is induced by symmetry. $\lambda_{\min}(P)$ and $\lambda_{\max}(P)$ denote the minimum and maximum eigenvalues of a real symmetric matrix P, respectively. $\mathbb{E}\{\cdot\}$ denotes the expectation. $(\Omega, \mathcal{F}, \mathcal{P})$ is a probability space, where Ω is the sample space, $\mathcal{F}$ is the δ-algebra of subsets of the sample space and $\mathcal{P}$ is the probability measure on $\mathcal{F}$. $\mathcal{C}([a,b];\mathbb{R})$ denotes the set of all continuous functions from $[a,b]$ to $\mathbb{R}$.

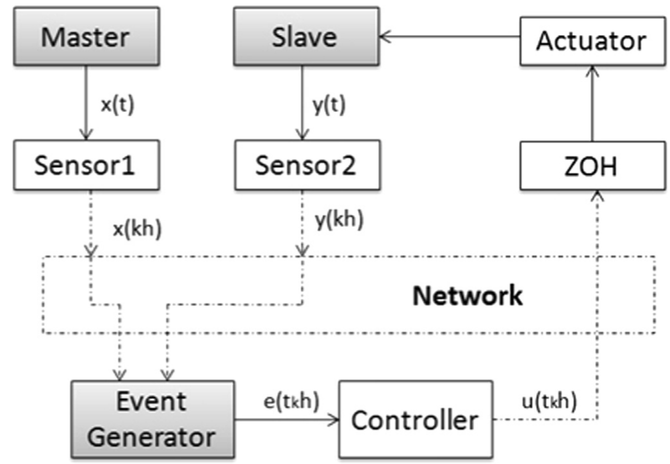

Fig. 1. The model of synchronization system.

2. Problem formulation

In this section, the model of network-based master–slave synchronization of delayed neural networks is constructed. As shown in Fig. 1, the Master and the Slave sample their states simultaneously and with the same period. The sampled states are sent to an Event-generator through a communication network. After some selections and computations, the control signals are sent to the ZOH. We assume that all the state vectors of the Master and the Slave are measurable. And the Event-generator, Controller and Actuator are event-driven.

We consider the dynamic behaviors of the master system could be described by the following neural network:

$$\dot{x}(t) = -Ax(t)+Bg(x(t))+Wg(x(t-d(t))) \tag{1}$$

where $x(t) = \mathrm{col}\{x_1(t), x_2(t), \ldots, x_n(t)\} \in \mathbb{R}^n$ is the state vector; $g(x(t)) = \mathrm{col}\{g_1(x_1(t)), g_2(x_2(t)), \ldots, g_n(x_n(t))\}$ represents the neural activation function; $A = \mathrm{diag}\{a_1, a_2, \ldots, a_n\}$ is a diagonal matrix with $a_i > 0$, and B, W are the connection weight matrices. The time delay $d(t)$ is bounded as $0 < d(t) \le d$, $\dot{d}(t) \le \mu < 1$, where d and μ are known constants.

The slave system is expressed by

$$\dot{y}(t) = -Ay(t)+Bg(y(t))+Wg(y(t-d(t)))+Du(t) \tag{2}$$

where $y(t) = \mathrm{col}\{y_1(t), y_2(t), \ldots, y_n(t)\} \in \mathbb{R}^n$ is the state vector, and A, B, W are the same matrices as those described in (1). D is a known constant matrix, and $u(t)$ is the control input.

Let $e(t) = y(t) - x(t)$ be the error state. The purpose of this paper is to design a controller $u(t) = Ke(t)$, such that the slave system (2) synchronizes with the master system (1), and K is the controller gain to be determined. The problem of network-based synchronization has been investigated in [10] through a remote controller. However, how to save the network resources was not considered in [10]. In this section, we introduce an event generator in the controller node by using the following judgement algorithm:

$$[e((k+j)h)-e(kh)]^T\phi[e((k+j)h)-e(kh)] \le \sigma e^T((k+j)h)\phi e((k+j)h) \tag{3}$$