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Stochastic sampled-data control for synchronization of complex dynamical networks with control packet loss and additive time-varying delays

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ABSTRACT

This study examines the exponential synchronization of complex dynamical networks with control packet loss and additive time-varying delays. Additionally, sampled-data controller with time-varying sampling period is considered and is assumed to switch between m different values in a random way with given probability. Then, a novel Lyapunov–Krasovskii functional (LKF) with triple integral terms is constructed and by using Jensen's inequality and reciprocally convex approach, sufficient conditions under which the dynamical network is exponentially mean-square stable are derived. When applying Jensen's inequality to partition double integral terms in the derivation of linear matrix inequality (LMI) conditions, a new kind of linear combination of positive functions weighted by the inverses of squared convex parameters appears. In order to handle such a combination, an effective method is introduced by extending the lower bound lemma. To design the sampled-data controller, the synchronization error system is represented as a switched system. Based on the derived LMI conditions and average dwell-time method, sufficient conditions for the synchronization of switched error system are derived in terms of LMIs. Finally, numerical example is employed to show the effectiveness of the proposed methods.

1. Introduction

During the past few years, complex dynamical networks (CDNs) have become an interesting research topic and appeal to have more attention in different fields from mathematics, biology, engineering sciences, etc. (Boccaletti, Latora, Marenu, Chavez, and Huang, 2006, Newman, 2003, Wang and Chen, 2003). A complex network is a large set of interconnected nodes, where the nodes and connections can be anything, examples are Internet, Transportation networks, coupled biological and chemical engineering systems, neural networks in human brains and so on. The synchronization is one of the most important dynamical properties of complex networks, number of real world complex networks frequently display the synchronization behaviors among their components, such as the synchronous occurrence on the Internet, synchronous transfer of digital or analog signals in communication networks and biological neural networks are also relating with synchronization. Therefore the synchronization problem for CDNs has received increasing research attention and a number of results have been made available in the literature (Cao and Li, 2009, Gao, Lam, and Chen, 2006, Li and Chen, 2004, Lu and Ho, 2008, Zhou and Chen, 2006). Li and Chen (2004) established the synchronization criteria for CDN models with coupling delays for both continuous and discrete-time cases. Zhou and Chen (2006) analyzed the synchronization dynamics of a general model of complex delayed networks with time delays. Gao et al. (2006) discussed the new delay-dependent conditions for a general CDN model with coupling delays, which guarantee the synchronized states to be asymptotically stable. Lu and Ho (2008) investigated local and global synchronization of CDNs with coupling delay and some criteria ensuring delay-independent and delay-dependent synchronization have been derived in terms of linear matrix inequalities.

Time delay is an elementary realism in physical systems. In practice, time delays occur naturally due to the finite speed of signal transmission, which may reduce the synchronization perfor-

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mance of the network (Kinzel, Englert, Reents, Zigzag, and Kanter, 2009, Liang, Wang, Liu, and Liberzon, 2008). The typical time-delayed coupling is very common in biological and physical systems. Some of the time delays are trivial and so can be untrained, while some others cannot be disregard such as in long distance communication, traffic congestions and so on. A great number of synchronization results for CDNs with time delays have been reported in the literature, see Li, Guan, Gong, and Lai (2008), Xu and Yang (2009), Yue and Li (2009), Zhou, Wang, Wang and Kong (2013), Ji, Lee, Koo, Won, Lee and Park (2011). Xu and Yang (2009), studied the synchronization problem for a class of CDNs with time delay. Yue and Li (2009) investigated the synchronization problem for continuous/discrete general CDNs with time-varying delays and the delays are assumed to vary in an interval where the lower and upper bounds are known. Zhou et al. (2013) examined the synchronization problem for CDNs with interval time-varying coupling delays Ji et al. (2011) investigated the synchronization problem for a class of neutral CDNs with coupling time-varying delays. The stability analysis for neural networks with two additive time-varying delay components has been carried out in Cheng, Zhu, Zhong, Zhang and Zeng (2014), Liu (2014), Shao and Han (2011, 2012), Xiao and Jia (2013), Zhu, Wang and Du (2014). Shao and Han (2012), derived delay-dependent stability criteria for neural networks with two additive time-varying delay components. Zhu et al. (2014), analyzed the stability of continuous-time systems with additive delay components. Xiao and Jia (2013) investigated the stability problem for neural networks with additive time-varying delay components and some stability criteria have been obtained by considering the relationship between time-varying delays and their upper bounds. Liu (2014) proposed new conditions for the delay-range-dependent stability analysis of time-varying delay systems by using Lyapunov–Krasovskii framework. Chen et al. (2014) derived the delay-dependent stability criteria for continuous system with two additive time-varying delay components.

In recent years, use of sampled-data control scheme has been increasing as the digital hardware and communication technologies are quickly developing. Most of the controllers are digital controller or networked to the system and these control systems can be modeled by sampled-data systems whose control signals are kept constant during the sampling period and are allowed to change only at the sampling instant. Due to this reason, the control signals have discontinuous form and may cause extremity to control or analyze the system. It is worth pointing out that in Fridman, Seuret, and Richard (2004), Fridman, Shaked, and Suplin (2005), a new approach called the input delay approach has been introduced to deal with the sampled-data control problems. In sampled-data controllers selecting proper sampling interval is important to design suitable controllers. Traditionally, many researchers have analyzed sampled-data control systems with constant sampling period. Therefore the necessity of the controller with varying sampling interval has been discussed in Ozdemir and Townley (1988), Hu and Michel (2000), Li, Zhang, Hu, and Nie (2011), Lee, Park, Lee and Kwon (2014), Wu, Park, Su, Song, and Chu (2012), Wu, Shi, Su, and Chu (2013). Lee, Wu, and Park (2012) analyzed the synchronization of CDNs with coupling time-varying delays via sampled-data controller. Further, Wu et al. (2012), proposed the exponential synchronization problem for CDNs with time-varying coupling delay via a sampled-data controller with variable sampling. Recently, Wu et al. (2013) studied the problem of sampled-data exponential synchronization of CDNs with time-varying coupling delay. Apart from these facts, taking into account the random change in sampling intervals, a further extension of time-varying case called the stochastically varying sampling intervals has been considered in the literature and the results have been discussed in Astrom and Wittenmark (1989), Gao, Meng and Chen (2008), Gao, Wu, and Shi (2009), Kim, Park, and Jeong (2010), Lee, Park, Kwon, and Lee (2013), Lee, Park, Lee, and Kwon (2013), Li, Zhang, and Jing (2009), Mikheev, Sobolev and Fridman (1988), Shen, Wang, and Liu (2012), Wen and Zeng (2013). Gao et al. (2009) investigated the robust H_∞ control problem for sampled-data with stochastic sampling. Lee, Park, kwon et al. (2013) discussed the synchronization of chaotic system with randomly occurring uncertainties using stochastic sampled-data control. Lee, Park, Lee et al. (2013) introduced the stochastic sampled-data control for state estimation of time-varying delayed neural networks and a delay-dependent stability criteria has been derived.

It is usually assumed that the control packet from the controller to the actuator is transmitted in a perfect way, that is, there is no loss in the control data. However, in practical systems, the control packet can be lost due to several factors, for instance, actuator failures, actuator suspensions for power saving, communication interference or congestion and so on. When the control packet from the controller to the actuator is lost, the actuator input to the plant may set to zero. The linear sampled-data system in the presence of ineffective sampling can be viewed as a switched system consisting of stable sampled-data subsystem with control packet loss or otherwise an unstable linear subsystem. It is clear that frequent control packet loss will inevitably lead to instability and poor performance of systems and it is therefore necessary and important to consider the effect of control packet loss in the sampled-data control systems. Zhang and Yu (2010) used the switched system approach for the stabilization of sampled-data control systems with control inputs missing has been employed and sufficient conditions for the existence of exponential stabilizing state feedback controllers have been derived. Recently, Chen and Zheng (2012) established an improved stabilization method for sampled-data control systems with control packet loss has been developed and the obtained results are proven to be theoretically less conservative than existing ones.

Moreover, stability and synchronization analysis of networks using reciprocal convex technique have been discussed in the literature, see Jiang and Li (2012), Lee and Park (2014), Li, Wang, Yang, and Fei (2012), Park, Ko, and Jeong (2011), Wang, Li, Yang, and Fei (2012), Zhang, Wang, Li, and Fei (2012). Park et al. (2011) introduced reciprocally convex approach to study the stability of systems with time-varying delays. Jiang and Li (2012) analyzed the synchronization of CDNs with interval time-varying delay via pinning control approach and less conservative criteria have been established based on reciprocal convex technique. Zhang et al. (2012) investigated the exponential synchronization in arrays of coupled delayed chaotic neural networks with nonlinear hybrid coupling. Lee and Park (2014) focused on the stability analysis of systems with interval time-varying delays by using second-order reciprocally convex approach, where some triple integral terms in the LKF have been considered. To the best of authors' knowledge, stochastic sampled-data synchronization control problem for CDNs with control packet loss and additive time-varying delays has not yet been studied in the literature.

Motivated by the above discussion, in this paper, a design problem for stochastic sampled-data synchronization of complex dynamical networks with control packet loss and additive time-varying delays is investigated. Unlike, the other studies, the proposed CDNs are studied using the sampled-data controller with stochastic sampling. By constructing a new LKF and by using reciprocal convex technique and free-weighting matrix method, delay-dependent conditions under which the complex networks can achieve desired synchronization are derived. Finally, a numerical example and its simulation results are given to illustrate the effectiveness and reduced conservatism of the proposed results.

Notations: $\mathbb{R}^n$ denotes the n-dimensional Euclidean space and $\mathbb{R}^{n\times m}$ be the set of all $n \times m$ real matrices. For real symmetric matrices