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On designing stochastic sampled-data controller for master–slave synchronization of chaotic Lur'e system via a novel integral inequality☆

Kaibo Shi[a,b,*], Xinzhi Liu[b,c], Hong Zhu[a], Shouming Zhong[d,e]

[a] School of Automation Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China
[b] Department of Applied Mathematics, University of Waterloo, Waterloo, Ontario, Canada N2L 3G1, Canada
[c] Department of Civil and Environmental Engineering, University of Waterloo, Waterloo, Ontario, Canada N2L 3G1, Canada
[d] School of Mathematical Sciences, University of Electronic Science and Technology of China, Chengdu 611731, China
[e] Key Laboratory for Neuroinformation of Ministry of Education, University of Electronic Science and Technology of China, Chengdu 611731, China

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ABSTRACT

This study investigates the problem of designing stochastic sampled-data controller for master–slave synchronization of chaotic Lur'e systems (CLSs) via a novel approach. Specially, first, we assume that the occurrence probabilities of the sampling intervals are fixed constants and satisfy a Bernoulli distribution. In order to take full advantage of the sawtooth structure characteristics of the sampling input delay, we construct a newly augmented Lyapunov–Krasovskii functional (LKF) based on the extended Wirtinger inequality. Second, by using a novel free-matrix-based integral inequality (FMBII) including well-known integral inequalities as special cases, an exponentially mean-square synchronization criterion is proposed for analyzing the corresponding synchronization error system. Third, the desired estimator gain can be designed in terms of the solution to linear matrix inequalities (LMIs) which can be solved effectively by using available software. Finally, three numerical simulation examples of Chua's circuit and neural network are given to illustrate the effectiveness and superiorities of the proposed method.

1. Introduction

Since the pioneering work of Pecora and Carroll [1], synchronization of chaotic systems has attracted numerously fast-growing interest and attention [2–4]. Many scientists and engineers have proposed a variety of alternative schemes for ensuring the control and synchronization of chaotic systems due to its potential applications in practical systems, for instance, biology, engineering, chaos generator design, secure communication, network systems and some other nonlinear fields [5–8].

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* Corresponding author at: School of Automation Engineering, University of Electronic Science and Technology of China, Chengdu, 611731, China. Tel: +86 28 61831540; fax: +86 28 61831113.

E-mail addresses: skbs111@163.com (K. Shi), xzliu@uwaterloo.ca (X. Liu), zhuhong@uestc.edu.cn (H. Zhu), zhongsm@uestc.edu.cn (S. Zhong).

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It should be pointed out that dynamical behavior of chaotic systems is highly sensitive to small changes of initial values, and the trajectories in phase space are bounded due to the presence of nonlinearity. In addition, as is well-known that a lot of nonlinear chaotic systems can be presented in the form of Lur'e systems, such as Chua's circuit, network systems and hyper chaotic attractors, which include a feedback connection of a linear system and a nonlinear element satisfying the sector condition [9–13]. Up to now, a large amount of energy and attention has been devoted to the study of synchronization of CLSs. However, how to design a suitable controller to guarantee the desired performance of CLSs is still an important issue at present. Therefore, the synchronization of CLSs has been one of the focal points in many research and application fields.

From the control strategy point of view, various control approaches have been proposed in the field of the synchronization of CLSs. These approaches can be divided into two classes in general. The first one is based on the continuous updating feedback signals and is usually achieved by analog circuits, such as time-delay feedback control [14,15], adaptive control [16], nonlinear feedback control [17], PD control [18], H_∞ tracking control [19]. The other one is based on the discrete signals updated at instant times, for instance, impulsive control [20,21], fuzzy control [22], sampled-data control [23–28].

More recently, with rapid development of the digital hardware and communication technologies, the analog signal processing methods are frequently replaced by digital signal processing methods to provide better reliability, accuracy and stable performance. The importance of the sampled-data control scheme has been increasing quickly among many control methods. Because it only needs the samples of the state variables of the master–slave CLSs at discrete time instants, which can reduce fleetly a lot of synchronization information transmitted and enhances the efficiency of bandwidth usage. Hence, the sampled-data control method has become a key tool in the study of the synchronization of CLSs. Based on the input delay approach proposed in [23], the sampled-data synchronization scheme has been a hot research topic and studied extensively in the recent [24–29]. In order to obtain a longer sampling period, a piecewise differentiable LKF is constructed in [25,26], which may make full use of the information in the nonlinear part of the system. Unlike the existing ones in [25,26], the proposed a new LKF in [27] is positive definite at sampling times but not necessarily positive definite inside the sampling interval, which implies that the traditional continuous-time Lyapunov theorem cannot directly result in the desired exponential synchronization criterion. The synchronization problem for CLSs with quantized sampled-data controller is investigated in [28]. The robust synchronization problem of chaotic Lur'e systems with external disturbance is discussed by using H_∞ sampled-data control [29].

Selecting proper sampling period is the most important task in sampled-data control systems for designing desired controllers. Traditionally, many researchers often have focused more on constant sampling. On the other hand, variable sampling periods are applied to various practical systems due to their ability in dealing effectively with all kinds of problems, such as change in network situation, limitation of the calculating speed of hardware and so on. Therefore, the necessity of the controller design problem using sampled-data with the stochastically varying sampling interval has been highlighted and many important results have been reported [30–37]. Unfortunately, although sampled-data control technologies have been developed relatively well in control theory, the particular sampled-data synchronization problem for CLSs has so far received very little attention due mainly to the mathematical complexity. Indeed, there are still some essential difficulties that are need to be solved urgently . For instance, how to actually design a set of easy-to-implement sampled-data controllers to synchronize the CLSs especially when the original CLSs is unstable. To the best of our knowledge, there are a few published papers on sampled-data synchronization for CLSs using sampled-data with a stochastically varying sampling interval. Therefore, it is interesting and challenging issue to study further the sampled-data synchronization for CLSs under a longer sampling interval.

Motivated by the issues discussed above, the master–slave synchronization problem of CLSs with stochastic sampled-data control is investigated in this paper. The sampling period chosen here is assumed to be time-varying that switches between two different values in a random way with a given probability. In addition, this method can be extended further to the multiple stochastic sampling periods. Based on the extended Wirtinger inequality, a time-dependent LKF is proposed by introducing two independent random variable parameters. The advantage of the constructed LKF lies in the fact that it makes the best of the sawtooth structure characteristics of the sampling input delay and nonlinear function condition. In order to obtain a desired estimator gain such that the master and slave system can be exponentially mean-square synchronized, a novel FWBII is employed, which can provide great freedom in reducing the conservativeness of the inequality. Finally, three numerical simulation examples of Chua's circuit and neural network are given to show the effectiveness and the advantage of the proposed main results.

Notation: Notations used in this paper are fairly standard: $\mathbb{R}^n$ denotes the n-dimensional Euclidean space, $\mathbb{R}^{n\times m}$ is the set of all $n \times m$ dimensional matrices; I denotes the identity matrix of appropriate dimensions, T stands for matrix transposition, the natation $X > 0$ (respectively $X \geq 0$), for $X \in \mathbb{R}^{n\times n}$ means that the matrix is real symmetric positive definite(respectively, positive semi-definite); $diag\{r_1, r_2, \ldots, r_n\}$ denotes block diagonal matrix with diagonal elements $r_i, i = 1, 2, \ldots, n,$ the symbol $*$ represents the elements below the main diagonal of a symmetric matrix, $Sym(A)$ is defined as $Sym(A) = A + A^T$. $\mathbb{E}\{x\}$ and $\mathbb{E}\{x|y\}$, respectively, mean the expectation of a stochastic variable x and the expectation of the stochastic variable x conditional on the stochastic variable y. $Pr\{\alpha\}$ is the occurrence probability of an event α.

2. Preliminaries

Consider the following sampled-data synchronization control of CLSs with stochastic sampling:

$$\mathscr{M}: \begin{cases} \dot{x}(t) = \mathscr{A}x(t) + \mathscr{H}\varphi(\mathscr{D}x(t)), \\ p(t) = \mathscr{B}x(t), \end{cases}$$