ARTICLE IN PRESS

ISA Transactions ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

ISA Transactions

journal homepage: www.elsevier.com/locate/isatrans

Research article

Non-fragile sampled-data robust synchronization of uncertain delayed chaotic Lurie systems with randomly occurring controller gain fluctuation ☆

Kaibo Shi [a,b,*], Yuanyan Tang [b], Xinzhi Liu [c], Shouming Zhong [d]

[a] School of Information Science and Engineering, Chengdu University, Chengdu 610106, China
[b] Department of Computer and Information Science, Faculty of Science and Technology, University of Macau, Taipa 853, Macau, China
[c] Department of Applied Mathematics, University of Waterloo, Waterloo, Ontario, Canada N2L 3G1
[d] School of Mathematical Sciences, University of Electronic Science and Technology of China, Chengdu 611731, China

ARTICLE INFO

Article history:
Received 17 July 2016
Received in revised form
17 October 2016
Accepted 4 November 2016

Keywords:
Chaotic Lurie system
Neural networks
Robust synchronization
Non-fragile sampled-data control
Randomly occurring controller gain fluctuation

ABSTRACT

This paper proposes a new non-fragile stochastic control method to investigate the robust sampled-data synchronization problem for uncertain chaotic Lurie systems (CLSs) with time-varying delays. The controller gain fluctuation and time-varying uncertain parameters are supposed to be random and satisfy certain Bernoulli distributed white noise sequences. Moreover, by choosing an appropriate Lyapunov-Krasovskii functional (LKF), which takes full advantage of the available information about the actual sampling pattern and the nonlinear condition, a novel synchronization criterion is developed for analyzing the corresponding synchronization error system. Furthermore, based on the most powerful free-matrix-based integral inequality (FMBII), the desired non-fragile sampled-data estimator controller is obtained in terms of the solution of linear matrix inequalities. Finally, three numerical simulation examples of Chua's circuit and neural network are provided to show the effectiveness and superiorities of the proposed theoretical results.

1. Introduction

During the past decades, numerously fast-growing interest has been focused on the investigation on synchronization of chaotic systems [1–10]. Because chaotic synchronization (CS) has great potential and extensive applications in practical systems, such as secure communication, chaos generator design, information science, biological systems and network systems. Therefore, many important and interesting results have been proposed for CS schemes. To date, a large amount of energy and attention have been devoted to the research of synchronization of chaotic systems since the pioneering work [1]. In order to achieve this goal, all kinds of control methods have been developed for the synchronization issue of chaotic systems. For example, adaptive control [2], H_∞ tracking control [3], PD control [4], sampled-data control [5–10], impulsive control [11,12], fuzzy control [13,51,52], feedback control [14,53], pining control [54], and robust adaptive control [15].

On the other hand, it is well-known that various chaotic systems can be modeled precisely in the form of Lurie systems, such as Chua's circuit, network systems and hyper chaotic attractors, which all include a feedback connection of a linear system and a nonlinear element satisfying the sector condition [16–19]. In addition, time delay is inevitable in dynamical systems because it is an inherent feature of many physical processes. However, it often leads to undesirable dynamical behaviors such as oscillation, divergence or even instability [20,21]. Thus, it is necessary to study the synchronization of chaotic Lurie systems (CLSs) with time delay [16–19,22–24]. A major objective of synchronization for CLSs is to design the controller which minimizes an error signal that means a difference between master and slave signal. Whereupon, a number of methods have been proposed on this scheme. For instance, by applying delayed error feedback control, the problem of master-slave synchronization of two delayed CLSs in the presence of parameter mismatches has been investigated in [16]. By introducing the delay-partition approach, the synchronization problem of CLSs with only constant time delay is considered in [17]. In order to obtain less conservative stability results, the designing time-varying delay feedback controllers for synchronization of CLSs has been addressed by employing Lyapunov-

☆This work was supported by the Research Grants of MYRG2015-00049-FST, MYRG2015-00050-FST, RDG009/FST-TYY/2012, FDCT 100-2012-A3, 026-2013-A, 008-2014-AMJ from Macau, and the National Natural Science Foundation of China 61273244 and 61273015, National Basic Research Program of China (Grant no. 61503064 and 51502338).

* Corresponding author at: School of Information Science and Engineering, Chengdu University, Chengdu 610106, China.
E-mail address: skbs111@163.com (K. Shi).

http://dx.doi.org/10.1016/j.isatra.2016.11.002
0019-0578/© 2016 ISA. Published by Elsevier Ltd. All rights reserved.

Krasovskii functional (LKF) approach in [18]. It should be noted that two cases of time-varying delays are fully considered in [18]. So the synchronization criteria derived here are more general and resultful than the ones in [16,17]. The proposed methods in [18] have been applied successfully to fault-tolerant synchronization for CLSs in [19].

However, in order to take the advantage of modern high-speed, high-quality computers and communication networks, the digital controllers replace gradually analog circuits [25–32]. Because this control method only needs the samples of the state variables of the master-slave chaotic systems 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 an important tool in the study of the synchronization of CLSs. Based on the input delay approach proposed in [33], the sampled-data synchronization schemes have been a hot research topic and studied extensively in the recent [34–45]. How to choose the suitable sampling period is an important issue to be considered. It is clear that a bigger sampling period will lead to lower communication channel occupying, fewer actuation of the controller, and less signal transmission. Therefore, it is a key objective to design a desired sampled-data controller which can achieve the master-slave synchronization under a bigger sampling period. Seuret et al. [34] has proposed a novel framework for the stability analysis of linear sampled-data systems using the discrete-time Lyapunov theorem. The problem of stabilization for sampled-data fuzzy systems under variable sampling has been investigated well in [35]. The sampled-data control problem for the master-slave synchronization are studied extensively by introducing a discontinuous LKF in [36,37,40]. The stochastic synchronization issue has been discussed for markovian jump neural networks with time-varying delay under variable samplings in [38]. The master-slave synchronization problem of Lurie systems with probabilistic sampled-data control has been studied via a input-delay approach in [39]. In order to obtain a longer sampling period, a piecewise differentiable LKF is constructed in [23,24,42]. Unlike those in [23,24,42], the proposed LKF in [22] is positive definite at sampling times but not necessarily positive definite inside the sampling interval. In addition, in the real-world situation, the designed controllers often cannot be achieved exactly because of the existence of some unavoidable uncertainty in its coefficients such as actuator degradation, roundoff errors in numerical computation, aging of components, and requirement for parameters're-adjustment during the process. As a result, non-fragile control schemes are proposed to deal with the controller gain fluctuation issues, which can guarantee availably the randomly occurring controller gain fluctuations in synchronization problem [46,47,55–57]. However, there still exists room improving existing results, because some important and useful information of estimating the upper bound of the derivative of the LKF and nonlinear functions have not been well utilized in [22–24,44,45], which may lead to more conservative results. Moreover, the sampled-data synchronization for CLSs with or without constant time delay has been taken into account in [22–24,44,45]. The uncertain variations maybe subject to random changes because of environment circumstance in the process of controller implementation among networks. In this case, the uncertain variations maybe presented in a probabilistic way with certain types and intensity. It is therefore worth taking randomly occurring uncertain variations into account in control design [57]. To the best of our knowledge, the robust non-fragile sampled-data synchronization problem for a class of time-varying uncertain CLSs with randomly occurring controller gain fluctuation has not been well addressed.

Motivated by the proceeding discussion, the aim of this paper is to investigate the robust sampled-data synchronization issue for time-varying uncertain CLSs via a novel non-fragile stochastic control method. The main contribution of this paper lies in the following three aspects. In the first place, compared with traditional chaotic Lurie systems [22–24,44,45], we model a new class of time-varying uncertain CLSs by taking full account of randomly occurring uncertain variations, where the uncertain variations appear in a random way based on a certain kind of probabilistic law. In the second place, we construct a new form of LKF by introducing two novel alterable parameters and making full use of the available information about the actual sampling pattern. In the third place, in order to obtain new results, an effective free-matrix-based integral inequality containing the existing inequalities [22–24,44,45,48] as special cases is employed, which can provide great room in reducing the conservatism of proposed results. Based on the derived condition, the desired non-fragile sampled-data controller can be achieved by solving a set of LMIs under a longer sampling period. Finally, three numerical simulations of Chua's circuit and neural network are given to demonstrate the effectiveness and advantages of the developed 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; $\mathcal{I}$ denotes the identity matrix of appropriate dimensions, T stands for matrix transposition, the natation $\mathcal{X}>0$ (respectively $\mathcal{X}\geq 0$), for $\mathcal{X}\in\mathbb{R}^{n\times n}$ means that the matrix is real symmetric positive definite(respectively,positive semi-definite); $diag\{\mathfrak{r}_1, \mathfrak{r}_2, \ldots, \mathfrak{r}_n\}$ denotes block diagonal matrix with diagonal elements $\mathfrak{r}_i$, $i=1, 2, \ldots, n$, the symbol $*$ represents the elements below the main diagonal of a symmetric matrix, $Sym(\mathcal{A})$ is defined as $Sym(\mathcal{A})=\mathcal{A}+\mathcal{A}^T$.

2. Preliminaries

Consider the following robust non-fragile sampled-data synchronization of time-varying uncertain CLSs with randomly occurring controller gain fluctuation:

$$\mathfrak{M}:\begin{cases}\dot{x}(t)=(\mathcal{A}+\beta(t)\triangle\mathcal{A}(t))x(t)+(\mathcal{B}+\beta(t)\triangle\mathcal{B}(t))\\ \qquad x(t-\tau(t))+(\mathcal{W}+\beta(t)\triangle\mathcal{W}(t))g(\mathcal{D}x(t)),\\ \gamma(t)=\mathcal{C}x(t),\end{cases} \tag{1}$$

$$\mathfrak{S}:\begin{cases}\dot{y}(t)=(\mathcal{A}+\beta(t)\triangle\mathcal{A}(t))y(t)+(\mathcal{B}+\beta(t)\triangle\mathcal{B}(t))\\ \qquad y(t-\tau(t))+(\mathcal{W}+\beta(t)\triangle\mathcal{W}(t))g(\mathcal{D}y(t))+u(t),\\ \lambda(t)=\mathcal{C}y(t),\end{cases} \tag{2}$$

$$\mathfrak{C}:\ u(t)=(\mathcal{K}+\beta(t)\triangle\mathcal{K}(t))(\gamma(t_k)-\lambda(t_k)),\quad t\in[t_k, t_{k+1}), \tag{3}$$

which consists of master system $\mathfrak{M}$, slave system $\mathfrak{S}$ and controller $\mathfrak{C}$. $\mathfrak{M}$ and $\mathfrak{S}$ with $u(t)=0$ are identical time-varying uncertain CLSs with state vectors $x(t)$, $y(t)\in\mathbb{R}^n$, outputs of subsystems are $\gamma(t)$ and $\lambda(t)\in\mathbb{R}^l$, respectively, $u(t)\in\mathbb{R}^n$ is the slave system control input, $\mathcal{A}\in\mathbb{R}^{n\times n}$, $\mathcal{B}\in\mathbb{R}^{n\times n}$, $\mathcal{W}\in\mathbb{R}^{n\times m}$, $\mathcal{D}\in\mathbb{R}^{m\times n}$ and $\mathcal{C}\in\mathbb{R}^{l\times n}$ are known real matrices. $\triangle\mathcal{A}(t)$, $\triangle\mathcal{B}(t)$ and $\triangle\mathcal{W}(t)$ are unknown matrices representing time-varying parameter uncertainties. $\mathcal{K}\in\mathbb{R}^{n\times l}$ is the sampled-data feedback control gain matrix to be designed, real-valued matrix $\triangle\mathcal{K}(t)$ denotes the controller gain fluctuation. In this paper, the time-varying parameter uncertainties are assumed to be of the following form:

$$[\triangle\mathcal{A}(t), \triangle\mathcal{B}(t), \triangle\mathcal{W}(t), \triangle\mathcal{K}(t)]=\mathcal{H}\Upsilon(t)[\mathcal{M}_a, \mathcal{M}_b, \mathcal{M}_w, \mathcal{M}_k], \tag{4}$$

where $\mathcal{H}$, $\mathcal{M}_a$, $\mathcal{M}_b$, $\mathcal{M}_w$ and $\mathcal{M}_k$ are known constant matrices, $\Upsilon(t)$ is an unknown time-varying matrix satisfying