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Novel delay-dependent master-slave synchronization criteria of chaotic Lur'e systems with time-varying-delay feedback control[☆]

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ABSTRACT

This paper is concerned with the issue of master-slave synchronization for chaotic Lur'e systems (CLSs) with time-varying-delay feedback control. A novel integral inequality is developed by employing two adjustable parameters, which encompasses the celebrated Wirtinger's integral inequality and Jensen's inequality as two special cases. By constructing an augmented Lyapunov–Krasovskii functional (LKF) taking fully the information time-varying-delay range into account, less conservative delay-dependent synchronization criteria are established in the form of linear matrix inequalities (LIMs). Besides, the desired controller gain can be achieved by introducing new nonlinear function conditions, which have not been proposed so far. Finally, a numerical example of typical Chua's circuit is presented to show the improvements over the existing criteria and the effectiveness of the design approach.

1. Introduction

During the past few decades, the investigation for synchronization problem has attracted increasing attention in a variety of fields. This is due to the fact that synchronization problem has extensive applications and great potential for secure communication [1], chaotic systems [2], networks control [3–5], information science [6], PD control [7], adaptive control [8], and other scientific areas [9–11]. As is well-known that many nonlinear systems may be modeled in the form of Lur'e control systems, such as Chua's circuit, hyper chaotic attractors and n-scroll attractor, which consist of a feedback connection

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of a linear system and a nonlinear element satisfying the sector condition [12–14]. Therefore, the synchronization problem of CLSs has been an important research topic [15–19].

It is well-known that time delay is unavoidable in a large amount of dynamical systems because of the finite speed of information processing, which often leads to one of the main factors of poor performance or even instability [20–25]. Meanwhile, a great deal of attention and interest has been focus on the study of time-delay dynamical systems for their wide applications in both engineering and science, for instance, neural networks [20,21], genetic regulatory network [22], H_∞ tracking [23], and other dynamical systems [24,25]. Thus, the effect of delay on master-slave synchronization of CLSs has been investigated broadly, and many important control methods have been utilized [26–36].

More recently, the sampled-data control and feedback control approaches have been applied successfully to the synchronization scheme of CLSs. In [26], sufficient conditions for asymptotic synchronization of CLSs have been acquired by using the free-weighting matrix method in [31]. In order to reduce further the conservatism of the stability results proposed in [26], an augmented LKF including some useful system information has been constructed in [27]. By taking full advantage of the information about sample-induced delay, the synchronization problem with quantized sampled-data controller has been first achieved for CLSs, and a new controller design method has been established in [28]. Several delay-independent and delay-dependent synchronization criteria have been obtained by constructing a new LKF in [29]. The authors in [30] have studied the master-slave synchronization problem of LSs with time delay by employing the integral inequality method. Based on a delay-partition approach in [32,35,36], several delay-dependent synchronization criteria have been established and formulated in the form of LMIs. The author in [33] has dealt with the synchronization issue for a class of general LSs via a general Lur'e–Postnikov Lyapunov functional. By choosing a suitable LKF including the information of time-varying delay range, less conservative delay-range-dependent synchronization criterion of LSs have been derived in [34]. However, in order to obtain sufficient conditions for master-slave synchronization, the authors in [29] have employed model transformation which results in some conservatism for inducing additional terms. Besides, it is noted that only constant delay is considered in [29–33,35,36]. In practice, it is known that the range of delay with non-zero lower bound are often encountered, and such systems are referred to as interval time-delay systems. Hence, it is interesting and valuable issue to search a more effective approach to obtain a larger delay threshold under which synchronization can be ensured theoretically.

Motivated by the issues discussed above, the delay-dependent master-slave synchronization problem of CLSs with time-varying-delay feedback control is investigated in this paper. The main contributions of this paper are listed as follows. First, by making full use of the information of time-varying-delay range and nonlinear term of the error system, novel delay-dependent synchronization criteria are established in terms of LIMs. Second, a creative integral inequality is originally modified, which includes Wirtinger's integral inequality and Jensen's inequality and is more tighter to estimate the bounds of integral terms than existing ones. Third, a new bounding-partitioning method of nonlinear function is developed via a tuning parameter δ. Finally, a numerical example of noted Chua's circuit is given to illustrate the effectiveness and advantages of synchronization criteria and the design method.

Notation: Notations used in this paper are fairly standard: $\mathbb{R}^n$ denotes the n-dimensional Euclidean space, $\mathbb{R}^{n\times m}$ the set of all $n \times m$ dimensional matrices; $\mathbf{I}$ the identity matrix of appropriate dimensions, $\mathbf{A}^T$ the matrix transposition of the matrix $\mathbf{A}$. By $\mathbf{X} > 0$ (respectively $\mathbf{X} \geq 0$), for $\mathbf{X} \in \mathbb{R}^{n\times n}$, we mean that the matrix $\mathbf{X}$ is real symmetric positive definite (respectively, positive semi-definite); $diag\{r_1, \dots, r_n\}$ denotes block diagonal matrix with diagonal elements $r_i, i = 1, 2, \dots, n$, the symbol $*$ represents the elements below the main diagonal of a symmetric matrix, $\mathbf{A}\otimes\mathbf{B}$ the Kronecker product of the matrices $\mathbf{A}$ and $\mathbf{B}$, $Sym\{\mathbf{M}\}$ is defined as $Sym\{\mathbf{M}\} = \frac{1}{2}(\mathbf{M} + \mathbf{M}^T)$.

2. Preliminaries

Consider the following master-slave synchronization of CLSs with time-varying-delay feedback control:

$$\mathcal{M}: \begin{cases} \dot{\mathbf{x}}(t) = \mathcal{A}\mathbf{x}(t) + \mathcal{W}\varphi(\mathcal{D}\mathbf{x}(t)), \\ \chi(t) = \mathcal{B}\mathbf{x}(t), \end{cases} \tag{1}$$

$$\mathfrak{S}: \begin{cases} \dot{\mathbf{y}}(t) = \mathcal{A}\mathbf{y}(t) + \mathcal{W}\varphi(\mathcal{D}\mathbf{y}(t)) + \mathbf{u}(t), \\ \psi(t) = \mathcal{B}\mathbf{y}(t), \end{cases} \tag{2}$$

$$\mathcal{C}: \mathbf{u}(t) = \mathcal{K}(\chi(t - h(t)) - \psi(t - h(t))), \tag{3}$$

which consists of master system $\mathcal{M}$, slave system $\mathfrak{S}$ and controller $\mathcal{C}$. $\mathcal{M}$ and $\mathfrak{S}$ with $\mathbf{u}(t) = 0$ are identical CLSs with state vectors $\mathbf{x}(t)$, $\mathbf{y}(t) \in \mathbb{R}^n$, outputs of subsystems are $\chi(t)$ and $\psi(t) \in \mathbb{R}^l$, respectively, $\mathbf{u}(t) \in \mathbb{R}^n$ is the slave system control input, $\mathcal{A} \in \mathbb{R}^{n\times n}$, $\mathcal{W} \in \mathbb{R}^{n\times n_d}$, $\mathcal{D} \in \mathbb{R}^{n_d\times n}$ and $\mathcal{B} \in \mathbb{R}^{l\times n}$ are known real matrices, $\mathcal{K} \in \mathbb{R}^{n\times l}$ is the time-varying-delay controller gain matrix to be designed. It is assumed that $\varphi(\cdot)$ is the nonlinear function in the feedback path. Fig. 1 illustrates expressly the feedback control process for the master-slave synchronization scheme described by (1)–(3).

Assumption A. Time-varying delay $h(t)$ is differential function and satisfies the following condition:

$$0 < h_L \leq h(t) \leq h_U, \quad \dot{h}(t) \leq \mu < 1, \tag{4}$$

where h_L, h_U and μ are constants.