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Singular reduced-order observer-based synchronization for uncertain chaotic systems subject to channel disturbance and chaos-based secure communication

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ABSTRACT

This paper deals with the issues of chaotic synchronization and chaos-based secure communication for chaotic systems subject to uncertain parameters and channel disturbance. First, an augmented singular system is constructed by introducing an augmented vector which consists of both the state and channel disturbance vectors of original drive system, and a singular reduced-order observer which can not only synchronize the drive system but also reconstruct channel disturbance is developed for the augmented singular system. Second, a second-order sliding mode observer is considered to get the exact estimates of output derivatives in a finite time. Based on the estimates of states and output derivatives, a kind of algebraic unknown information recovery method which can recover information signal injected into the drive system and estimate parameter disturbance is proposed. Finally, a numerical simulation example is given to illustrate the effectiveness of the proposed methods.

1. Introduction

The issues of chaotic synchronization and chaos-based secure communication have received more and more attentions. Pecora and Carroll address well-known derive-response configuration for chaotic synchronization in [1]. A comprehensive framework for synchronization is discussed based on the observer design theory in [2]. Recently, many synchronization schemes, such as exponential synchronization [3–6], adaptive synchronization [7–16], robust synchronization [17–21], projective synchronization [22,23], finite-time synchronization [24,25], impulsive synchronization [26–28] and lag synchronization [29], have been developed. For instance, from a control theoretic point of view, the global exponential synchronization via a scalar communication signal is suggested in [3]. The adaptive synchronization between two novel different hyperchaotic systems with partly uncertain parameters is investigated in [11]. Based on Lyapunov stability theory and linear matrix inequality approach, an adaptive synchronization scheme for chaotic systems with unknown parameters and external disturbance is proposed in [12]. Paper [14] develops a robust adaptive control method for synchronization of uncertain chaotic neural networks with mixed delays. In [19], based on Lyapunov stability theory and the dead-zone algorithm, a robust synchronization scheme is developed for two different chaotic systems which are exposed to a bounded noise. Paper [22] applies the active sliding mode control technique to realize the modified projective synchronization of chaotic systems, and the sufficient conditions for synchronization are presented. The problem of finite-time synchronization

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between two different chaotic systems with unknown parameters is investigated in [24]. Based on the theory of impulsive functional differential equations, sufficient conditions for impulsive synchronization with a bound on the synchronization error are derived in [28].

In the chaos-based secure communication schemes, the drive system is regarded as the transmitter where the information signal is injected into drive system, and the transmitted chaotic signal is generated by the transmitter and is then transmitted to the receiver end. The receiver can not only synchronize the drive chaotic system but also recover the information signal. Some recent works of chaos-based secure communication can be found in [19,30–35]. For example, an approach for chaotic synchronization and private communication is proposed by adopting the singular system observer approach in [31]. The problems of chaos synchronization and secure communication for a class of uncertain chaotic systems are discussed based on full-order and reduced-order output-affine observers in [32]. The issues of the chaos synchronization and chaos-based secure communication are also considered when the observer matching condition is not satisfied in [34]. Based on high-gain sliding mode unknown input observers, the problems of chaos synchronization and secure communication are considered in [35]. In existing literatures, most works deal with the problems of chaos synchronization and secure communication without considering channel noise [30–35] or parameter disturbance [31,33]. However, up to date and to the best of our knowledge, the problems of both chaotic synchronization and chaos-based secure communication for a class of chaotic systems subject to simultaneous uncertain parameter and channel disturbance have not yet been fully investigated and this will be the goal of this paper. The proposed methods in this paper can not only synchronize drive system but also recover the injected information signal, while the uncertain parameter and channel disturbance can also be reconstructed simultaneously.

In this paper, a singular reduced-order observer which can synchronize derive system and reconstruct channel disturbance is developed based on the transformed singular augmented drive system, and a kind of algebraic unknown information reconstruction method which can recover the injected information signal and estimate the parameter disturbance is proposed. The derivative information of output is not directly used since the second-order sliding mode observer exactly provides the estimation of it.

The paper is organized as follows. In Section 2, the model of chaotic systems subject to channel disturbance and uncertain parameter is given, and problem statement is presented. In Section 3, a singular reduced-order observer which can not only synchronize the drive system but also estimate channel disturbance is developed. In Section 4, an information signal recovery method is proposed, and the chaos-based secure communication mechanism is discussed. A numerical simulation example is given to illustrate the effectiveness of the proposed methods in Section 5. Some conclusions are given in Section 6.

2. Model description and problem statement

Consider a class of uncertain chaotic systems subject to channel disturbance described by the following equations

$$\begin{cases} \dot{x} = Ax + Gf(x,t) + Gs + D\eta \\ y = Cx + Fd \\ y' = Cx, \end{cases} \tag{1}$$

where $x \in \mathbb{R}^n$ and $y' \in \mathbb{R}^p$ are the state and measurement output vectors, respectively. $y \in \mathbb{R}^p$ is the drive signal and should be received in receiver end. $\eta(t) \in \mathbb{R}^k$ stands for parameter uncertainty, and $d(t) \in \mathbb{R}^h$ is the channel disturbance. $s \in \mathbb{R}^l$ is the information signal which will be recovered in the receiver end. The nonlinear function $f(x,t) : \mathbb{R}^n \times \mathbb{R}^+ \to \mathbb{R}^l$ is a real-valued vector function. A, C, D, G and F are all known constant matrices with appropriate dimensions. We assume that $\text{rank}C = p$, $\text{rank}F = h$, $\text{rank}\bar{D} = k + l$, where $\bar{D} = [G \quad D]$ and $p \geqslant l + k + h$.

Assumption 1. The invariant zeros of the system (1) are all in the open left-hand complex plant, i.e.,

$$\text{rank}\begin{bmatrix} s'I_n - A & 0 & \bar{D} \\ C & F & 0 \end{bmatrix} = n + l + k + h, \tag{2}$$

holds for all complex number s' with $\text{Re}(s') \geqslant 0$.

Assumption 2. The system state $x(t)$, parameter disturbance $\eta(t)$, information signal $s(t)$, channel disturbance $d(t)$ and their derivatives, are all bounded in norm by some unknown constants.

If we introduce a new augmented state vector $\bar{x} = \begin{bmatrix} x^T & d^T \end{bmatrix}^T$, then system (1) can be rewritten as the following singular augmented drive system

$$\begin{cases} E\dot{\bar{x}} = \bar{A}\bar{x} + Gf(E\bar{x},t) + \bar{D}\varphi \\ y = \bar{C}\bar{x} \end{cases} \tag{3}$$

where $\bar{A} = [A \quad 0_{n\times h}]$, $E = [I_n \quad 0_{n\times h}]$, $\bar{C} = [C \quad F]$ and $\varphi = \begin{bmatrix} s^T & \eta^T \end{bmatrix}^T$. By Smith orthogonal procedure, there is an invertible matrix $S \in \mathbb{R}^{p\times p}$ such that $\bar{C} = S\hat{\bar{C}}$, where $\hat{\bar{C}} \in \mathbb{R}^{p\times(n+h)}$ and $\hat{\bar{C}}\hat{\bar{C}}^T = I_p$. We extend the matrix $\hat{\bar{C}}$ to an $(n+h)\times(n+h)$ orthogonal