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Observer-based state estimation and unknown input reconstruction for nonlinear complex dynamical systems

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ABSTRACT

This paper considers the issues of both state estimation and unknown information reconstruction for a class of uncertain complex dynamical networks subject to unknown inputs. First, a robust adaptive sliding mode observer which can be used to estimate the states of complex networks through available measurement outputs is developed by employing both adaptive technique and sliding mode control approach. Second, a high-gain second-order sliding mode observer is considered to exactly estimate the derivatives of the output vectors in a finite time. Third, by using the estimates of the states and output derivatives, a kind of algebraic unknown input reconstruction method is proposed. Finally, some numerical simulation examples are given to illustrate the effectiveness of the proposed methods.

1. Introduction

Complex dynamical networks which consist of a large number of highly interconnected dynamical units and therefore exhibit very complicate dynamics have received increasing attention in various fields of the real world, such as biology, sociology, World Wide Web, electrical power grids, and so on. Most of attention has been focused on the problems of synchronization, stabilization and control problems with extensive and satisfactory results [1–18]. The issue of synchronization has been already studied by other authors using different kinds of approaches [1–15]. For example, the locally and globally adaptive synchronization of uncertain complex dynamical network is investigated, and several network synchronization criteria are deduced in [1]. Based on pinning control technique, some synchronization criterions for different complex networks are proposed in [6–8]. The synchronization criterions for both continuous-time and discrete-time complex dynamical networks with general time delay are obtained in [6]. For the complex networks with coupling delay, some approaches are developed to realize synchronization [9–15], such as exponential synchronization [9], finite-time synchronization [10], adaptive lag synchronization [11], linear approximation synchronization [12], and function projective synchronization [13]. The stabilization and control problems of complex dynamical networks are widely concerned [16–18]. For instance, the problems of robust H_∞ control are also investigated for uncertain complex delayed dynamical networks and impulsive switched complex delayed networks in [17,18], respectively.

Recently, for the purpose of better understanding the complex networks and making use of key network nodes in practice, it becomes necessary to estimate the states of nodes through available measurements, the state and parameter

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estimation problems of complex networks are investigated in [19–22]. In [19], the state estimation problem is studied by designing a state estimator to estimate the states of complex networks through available measurement outputs such that the dynamics of the estimation error is guaranteed to be asymptotically stable. The state estimation issue is also discussed for a class of complex dynamical networks with mixed time delays, and a sufficient condition under which the filtering error satisfies the performance constraint is obtained in [20]. The identification problem of unknown system parameter is considered for uncertain complex networks with fractional-order node dynamics in [21]. For singular complex dynamical networks with time-varying delays, a state estimator is designed to estimate the network states and a delay-dependent asymptotically stability condition is established for the system of the estimation error [22]. In addition, the unknown input identification techniques are widely applied to solve control problems of systems with disturbances, and it is with great significance for fault tolerant control, synchronization of complex networks and multichannel communication in complex networks [23]. The reconstructed unknown input information can help us make better measures for realizing synchronization, stabilization control and fault-tolerant. To the best of our knowledge, the issues of simultaneous state estimation and unknown input reconstruction for uncertain complex networks have received very little research attention despite its significance in practice, and are still open and challenging in the field of complex networks.

In this paper, it is the first time that the problems of both state estimation and unknown input reconstruction for uncertain complex networks are simultaneously discussed. A robust adaptive sliding mode observer with a sliding mode control law and an adaptive law is developed to estimate the states of complex networks. A kind of method for unknown information reconstruction is proposed based on a high-gain second-order robust sliding mode observer. We do not use any derivative information of measurement output directly when we reconstruct unknown inputs since the high-gain robust sliding mode observer provides the exact estimation of it.

The paper is organized as follows. In Section 2, an uncertain complex dynamical system and some preliminaries are given. In Section 3, an adaptive robust sliding mode observer is designed to reach the purpose of state estimation. A high-gain second-order sliding mode observer is considered to exactly estimate the derivatives of the measurement outputs, and a kind of algebraic unknown input reconstruction is developed in Section 4. In Section 5, some numerical simulation examples are given to illustrate the effectiveness of the proposed methods, and some conclusions are summarized in Section 6.

Notation: The notation used throughout the paper is fair standard. $\mathbb{R}^n$ denotes the n-dimensional Euclidean space, $\mathbb{R}^{n\times m}$ is the set of real $n \times m$ matrices. For $X \in \mathbb{R}^{n\times n}$, the notation $X > 0$ ($X < 0$) means that the matrix X is a real symmetric positive definite (negative definite). The Kronecker product of matrices M and N is denoted as $M \otimes N$.

2. The model description and preliminaries

Consider the following uncertain complex dynamical system consisting of N coupled nodes

$$\begin{cases} \dot{x}_i(t) = Ax_i(t) + Bf(x_i(t)) + c\sum_{j=1}^{N} H_{ij}\Gamma x_j(t) + D_i\eta_i, \\ y_i(t) = Cx_i(t), \end{cases} \tag{1}$$

where $x_i(t) = [x_{i1}(t) \quad x_{i2}(t) \quad \cdots \quad x_{in}(t)]^T \in \mathbb{R}^n$ and $y_i(t) = [y_{i1}(t) \quad y_{i2}(t) \quad \cdots \quad y_{ip}(t)]^T \in \mathbb{R}^p$ are the state vector and output vector of the ith node, respectively. $f(x_i(t)) \in \mathbb{R}^m$ are nonlinear vector-valued functions satisfying certain conditions given later, $\eta_i \in \mathbb{R}^k$ stands for the model uncertainty, parameter perturbation or external disturbance and is regarded as the unknown input vector of ith node. Positive constant $c > 0$ represents coupling strength, and $\Gamma = diag\{\gamma_1 \quad \gamma_2 \quad \cdots \quad \gamma_n\} \in \mathbb{R}^{n\times n}$ is an inner-coupling matrix. $H = (H_{ij})_{N\times N}$ denotes the coupling configuration matrix. If there is a connection between node i and j ($i \neq j$), then $H_{ij} = H_{ji} = 1$, otherwise $H_{ij} = H_{ji} = 0$, the diagonal elements of matrix H are defined by $H_{ii} = -\sum_{j=1, j\neq i}^{N} H_{ij}$ ($i = 1, 2, \ldots, N$). $A \in \mathbb{R}^{n\times n}$, $B \in \mathbb{R}^{n\times m}$, $C \in \mathbb{R}^{p\times n}$ and $D_i \in \mathbb{R}^{n\times k}$ are all known constant matrices with corresponding dimension. We assume that $\text{rank}C = p$, $\text{rank}(CB_i) = \text{rank}B_i = m + k$ and $n \geqslant p \geqslant m + k$, where $B_i = [B \quad D_i]$.

For the convenient of description, we omit the time variable t in the following section.

Assumption 1. The state vector x_i, the unknown input η_i and their derivatives are bounded in norm by some unknown constants. Specifically, there exist positive numbers ρ_i such that $\|\eta_i\| \leqslant \rho_i$ holds.

Assumption 2. The nonlinear function $f(\cdot)$ satisfies the Lipschitz condition, i.e.,

$$\|f(x_i) - f(\hat{x}_i)\| \leqslant L_{fi}\|x_i - \hat{x}_i\|, \quad \forall x, \hat{x} \in \mathbb{R}^n, \tag{2}$$

where $L_{fi} > 0$ are some Lipschitz constants.

Assumption 3. The system $\{A, C, B_i\}$ is minimum phase, i.e. the invariant zeros of the triple $\{A, C, B_i\}$ are all in the open left-hand complex plant, or