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Robust H_∞ dynamic output feedback synchronization for complex dynamical networks with disturbances

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ABSTRACT

In this paper, the robust H_∞ dynamic output feedback synchronization problem for complex dynamical networks with disturbances is studied. A novel decentralized output feedback control scheme is proposed. For each node, a dynamic output feedback controller which is driven by local relative output measurements is constructed. By introducing the spectral decomposition technique, the closed-loop synchronization error system is proved to be robustly stable with an optimal H_∞ disturbance attenuation level. A simulation example of master-slave large scale system verifies the effectiveness of the proposed method.

1. Introduction

During the past few decades, the research of complex dynamical networks (CDNs) has received much attention in various fields [1–5]. CDNs are a class of interconnected systems and are used to describe diverse systems in practice. Examples of CDNs include world wide web, telephone call graphs, neural networks, and smart grids. The survey paper [6] gives the state of art in the area of control techniques for complex networks. As one of the most important collective behavior, the synchronization problem has been investigated by many researchers. The network synchronization is a timekeeping dynamical behavior in which the states of all modes converge towards the same trajectory. So far, various methodologies were proposed to approach the synchronization problem, such as adaptive control [7–11], impulsive control [12–14], pinning control [15,16], sampled-data control [17,18] and sliding mode control [19,20].

The research of performance optimization based methods [24–26] has long been recognized as an important aspect in the field of robust control, recently, the performance optimization based control for CDNs has received considerable attention [27–30]. Specifically, various control schemes based on H_∞ or L_2 performances are proposed. In [21], the global H_∞ pinning synchronization problem for a class of CDNs has been addressed. In [22], based on L_2 performance specification, a robust synchronization control scheme was proposed for CDNs with disturbed sampling couplings. The existing results are mainly based on state feedback control methods, which require the state of each node to be available. Nevertheless, the state information may not be completely obtained in practice. Compared with state feedback control, little literature can be found in output feedback control for complex networks. In [34], two types of adaptive neural network decentralized output feedback controllers are proposed for a class of uncertain nonlinear large-scale systems with unknown time delays and output couplings. An adaptive fuzzy decentralized output feedback control design is presented in [35] for a class of interconnected nonlinear pure-feedback systems with output couplings. In addition, in [23], an adaptive output feedback control method is proposed for the synchronization problem of CDNs with output couplings. It is worth to mention that all the aforementioned methods deal with output couplings. Moreover, the adaptive controller in [23] has a distributed structure, thus it requires the neighboring output information, which sometimes might be difficult or even impossible to get and use in practice since the outputs of each node are internal information and cannot be shared due to communication constraints. Additionally, the disturbances are not considered in [23]. So far, to the best of our knowledge, the problem of decentralized output feedback synchronization for CDNs with state couplings and disturbances has not been well addressed and remains open.

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Motivated by the above reasons, in this paper, a robust H_∞ dynamic output feedback controller scheme is proposed to deal with synchronization problem for CDNs with disturbances and state couplings. Output feedback controllers which are driven by local output tracking errors are designed for each node. By introducing the spectral decomposition technique, the global closed-loop system is transformed into a group of decoupled systems. A local optimization is performed and sufficient conditions for the closed-loop systems to be robustly stable with an optimal H_∞ disturbance attenuation are obtained. The controller gains can be obtained by a two-step optimization procedure. Compared with the existing results, the main contributions are as follows:

(a) For a class of CDNs with disturbances, a novel decentralized dynamic output feedback control scheme is proposed to deal with the synchronization problem. The adaptive controller design in [23] is based on the information of the output couplings, since the information of the considered state coupling cannot be used, the adaptive control method in [23] cannot be extended to deal with the considered problem.
(b) The proposed controllers require only access to local output measurements. In [23], the adaptive controller design has a distributed structure and requires more information, i.e., neighboring output measurements, which may not be available in practice.

The remaining of the paper is organized as follows. In Section 2, the control objectives and preliminary results are presented. In Section 3, the robust H_∞ output feedback control scheme is presented. An example is given in Section 4 before this paper is concluded in Section 5.

Notations: Throughout this paper, the following notations are used, for a matrix A, A^T represents its transpose; $\lambda_{max}(\cdot)$ and $\lambda_{min}(\cdot)$ represent the maximum and minimum eigenvalues of a real symmetric matrix; the symbol $*$ within a matrix represents the symmetric entry; I represents an identity matrix with appropriate dimension; $\otimes$ represents the Kronecker product of two matrices; $diag\{\ldots\}$ represents a diagonal matrix.

2. Problem statement and preliminaries

2.1. Preliminaries

For matrices M, U, V, W, the following properties of the Kronecker product are used:

$$M \otimes (U+V) = M \otimes U + M \otimes V$$

$$(M \otimes V)(U \otimes W) = MU \otimes VW$$

For the graph $\mathcal{G}$, the adjacency matrix $\mathcal{A}(\mathcal{G}) = [a_{ij}]$ is defined by setting $a_{ij}=1$ if the ith and the jth nodes are adjacent nodes of the graph, and $a_{ij}=0$ otherwise. For an undirected graph, $a_{ij}=a_{ji}$. The symbol $\Delta(\mathcal{G}) = [\delta_{ij}]$ represents the degree matrix and is an $N\times N$ diagonal matrix, otherwise δ_{ii} is the degree of vertex i. The Laplacian of $\mathcal{G}$, $\mathcal{L}(\mathcal{G}) = [\mathcal{L}_{ij}]$, is defined as the difference $\Delta(\mathcal{G}) - \mathcal{A}(\mathcal{G})$. The Laplacian $\mathcal{L}(\mathcal{G})$ is always rank deficient and positive semi-definite.

2.2. Problem statement

Let the dynamics of the ith node of a network of N identical interconnected dynamical systems, indexed as $1,2,\ldots,N$, be described by

$$\dot{x}_i(t) = Ax_i(t) + Bu_i(t) + B_w w_i(t) - \alpha(t)\sum_{j=1}^{N}\mathcal{L}_{ij}\Gamma x_j \tag{1}$$

$$y_i(t) = C_1 x_i(t) + D_{12} w_i(t) \tag{2}$$

where $x_i(t)\in R^n$, $u_i(t)\in R^m$, $w_i(t)\in R^r$, $y_i(t)\in R^p$ represent the state, the control input, the external disturbance, the measured output respectively. A, B, B_w, C_1, and D_{12} are constant matrices of appropriate dimension. $\Gamma\in R^{n\times n}$ is the inner coupling matrix describing the interconnections among components. The scalar $\alpha(t)$ is the time-varying coupling strength. It is assumed that $\alpha(t)\geq 0$ for all $t\in R^+$ and has known upper bound $\overline{\alpha} = \sup_{t\in R^+}\alpha(t)$ and lower bound $\underline{\alpha} = \inf_{t\in R^+}\alpha(t)$.

Assumption 1. The graph associated with the N followers is undirected.

Remark 1. In [23], the synchronization problem of complex networks with output couplings and constant coupling strength via output feedback has been considered. Compared with [23], the considered complex networks with disturbances, state couplings and time-varying coupling strength are much more general.

Remark 2. Similar to [23], we assume that the graph is undirected in Assumption 1, i.e., the associated Laplacian matrix is symmetric, which makes it possible to introduce the spectral decomposition technique in the design of decentralized output feedback controller in the sequel. Moreover, because of the asymmetry of the Laplacian matrices associated with directed graphs, which leads to significant challenges in designing the robust dynamic output feedback controllers, the graph is only assumed to be undirected for simplicity.

Here, define that $x_0\in R^n$ is a given target of states for the networks. Assume that the target is a differential signal satisfying

$$\dot{x}_0(t) = Ax_0(t) \tag{3}$$

$$y_0 = C_1 x_0(t) \tag{4}$$

Now, define the local synchronization error

$$e_i(t) = x_i(t) - x_0(t) \tag{5}$$

$$e_{yi}(t) = y_i(t) - y_0(t) \tag{6}$$

Then, by the Kronecker product, the dynamics of the global synchronization error is described by

$$\dot{e}(t) = (I_N\otimes A)e(t) + (I_N\otimes B)u(t) + (I_N\otimes B_w)w(t) - \alpha(t)(\mathcal{L}\otimes\Gamma)e(t) \tag{7}$$

$$e_y(t) = (I_N\otimes C_1)e(t) + (I_N\otimes D_{12})w(t) \tag{8}$$

$$e_z(t) = (I_N\otimes C_2)e(t) + (I_N\otimes D_{21})u(t) \tag{9}$$

where $e(t) = [e_1^T(t)\ldots e_N^T(t)]^T$, $e_y(t) = [e_{y1}^T(t)\ldots e_{yN}^T(t)]^T$, $e_z(t)\in R^{Nl}$ is the regulated output of the synchronization error system and $e_z(t) = [e_{z1}^T(t)\ldots e_{zN}^T(t)]^T$, C_2 and D_{21} are constant matrices of appropriate dimensions. The graph Laplacian is defined by

$$\mathcal{L}_{ij} = \begin{cases} -\Sigma_{k=1,k\neq i}^{N} a_{ik}, & j\neq i \\ a_{ij}, & j=i \end{cases} \tag{10}$$

Then the control objective of this paper is to construct robust H_∞ output feedback controllers such that the synchronization error system (7)–(9) is robustly stable and its H_∞ disturbance attenuation index is minimized.