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Delay-dependent $\mathcal{H}_\infty$ filtering for complex dynamical networks with time-varying delays in nonlinear function and network couplings

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ABSTRACT

This paper investigates the $\mathcal{H}_\infty$ filtering problem for a class of continuous-time complex dynamical networks with time-varying delays in nonlinear function and network couplings. The aim of the addressed problem is to design a $\mathcal{H}_\infty$ filter against the exogenous disturbances, such that the filtering error system of complex dynamical networks is asymptotically stable and guarantees the desired $\mathcal{H}_\infty$ performance attenuation level. Based on the Lyapunov stability theory, suitable Lyapunov–Krasovskii functional is constructed in terms of Kronecker product, furthermore, new delay-dependent sufficient stability conditions are derived in terms of linear matrix inequalities by using reciprocal convex combination approach to obtain less conservative results. Finally, numerical examples are exploited to demonstrate the effectiveness of the proposed theoretical results.

1. Introduction

The study of complex networks handles with the network whose structure is irregular, complex and networks with highly interconnected nodes, which evolves dynamically with respect to time [1]. Nowadays, extensive research work is focused on complex dynamical networks (CDNs) due to its wider applications in airport networks [2], computer networks [3], biological networks [4], communication networks [5], etc. These systems exhibit complicated dynamics which are represented by a set of interconnected nodes, edges and coupling strength. Therefore, researchers have paid great attention to analyze the dynamical behavior of CDNs. The techniques of synchronization and state estimation for CDNs can be found in [6–9]. For singular CDNs both synchronization and state estimation problem have been investigated in [10]. Recently, authors in [11] have derived the sufficient conditions for adaptive synchronization of CDNs with non-delay and variable delay couplings via pinning control to achieve minimum number of pinning nodes. Robust exponential stabilization and adaptive synchronization for uncertain CDNs with time-delay in the coupling nodes have been discussed in [12,13]. Synchronization happening between two or more coupled networks is known as “outer synchronization”. Generalized outer synchronization between two uncertain networks with or without time delay has been proposed in [14].

In real complex network systems, such as in the progress of brain nervous activity, time delay occurs during the information transmission between nerve cells because of the limited speed of signal transmission as well as in the network traffic congestion systems. Thus, the

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presence of time delays (coupling delays) in CDNs is unavoidable. It leads often as a source of instability and poor performance of system behaviors, for instance, see [15–18]. The dynamical behavior of CDNs with non-identical nodes are much more complicated than with identical nodes. To deal with different dimensional nodes, authors in [19] have studied the synchronization criteria for time-delayed coupling CDNs with different dimensional nodes by using the decentralized dynamic compensation controllers.

Nowadays, various control methods such as adaptive control, sample data control, impulsive control, and $\mathcal{H}_\infty$ control have been explored to realize the synchronization phenomena of CDNs, for details see [11,13,19] and references therein. The sample data controller has been applied in [20,21] to synchronize the CDNs with Markovian jump parameters by considering the time-varying delays in the network. Impulsive control technology introduced in [22,23] is an efficient method to deal with dynamical systems which cannot ensure continuous disturbance. Very recently, the problem of impulsive control and synchronization of CDNs have been investigated in [24]. By using single impulsive controller, sufficient conditions have been obtained in [25] for pinning synchronization of delayed undirected CDNs. Observer based controller design for complex systems has been an interesting topic in control theory. In practical, a non-fragile observer based robust controller for fractional order CDNs has been designed in [26] by using indirect Lyapunov approach. By introducing fractional-order Lyapunov stability theorem, pinning controller for synchronization of the directed and undirected complex networks has been reported in [27].

It is important to note that the external disturbances are ubiquitous in nature as well as in complex networks. In this case, the notion of $\mathcal{H}_\infty$ theory has been determined to reduce the effect of exogenous disturbances and to quantify them within the prescribed level [28,29]. Based on decentralized observer, the problem of robust $\mathcal{H}_\infty$ observer-based control for synchronization of a class of CDNs has been investigated in [30]. The novel concept of $\mathcal{H}_\infty$ synchronization and state estimation for CDNs with mixed delays have been introduced in [31,32] to quantify against the exogenous disturbance of the complex networks. The problem of filtering or state estimation has been widely applied in the fields of signal processing, image processing and control applications. Among various filtering methods, Kalman filtering deals with minimizing the variance of the state estimation error for a given measurement noise. However, in most practical applications, the statistical assumptions on the external noise signals cannot be known exactly. To overcome this limitation, $\mathcal{H}_\infty$ filtering technique has been introduced to deal with unavoidable parameter shifts and external disturbances [33,34]. Nowadays, the $\mathcal{H}_\infty$ filtering technology has been applied recently to various dynamical time-delay systems such as networked control systems [23,35], neutral systems [36], singular systems [37], and T–S fuzzy systems [38,39]. Meantime, the delay-dependent filtering analysis for neural networks has been investigated in [40,41] by employing some inequality techniques to reduce the conservatism.

In the literature discussions above, most of the results have been concerned with synchronization and state estimation of CDNs. However, CDNs have its wider applications in science and engineering. Up to now, only limited works have been done with respect to $\mathcal{H}_\infty$ filter design for CDNs. Recently, the robust $\mathcal{H}_\infty$ filtering design has been investigated in [42] for a class of discrete-time complex networks which has stochastic packet dropouts and time delays combined with disturbance inputs. The lack of research analysis is probably due to difficulty in designing suitable filter parameters. In order to shorten such a gap, in this paper, suitable full-order filter is designed for continuous-time CDNs with time-varying delays.

On the other hand, it has been well known that there exist various approaches to reduce the conservatism of delay-dependent stability results for time-delay systems. The reduction of conservatism means that to increase the feasibility region. In this paper, we have utilized the reciprocal convex combination approach [43] to derive the sufficient conditions for the problem of delay-dependent $\mathcal{H}_\infty$ filtering for CDNs. To the best of authors knowledge, $\mathcal{H}_\infty$ filtering analysis for CDNs by using reciprocal convex approach has not been investigated yet.

Motivated by the above discussions, this paper is aimed to study the problem of $\mathcal{H}_\infty$ filtering for continuous-time CDNs with time-varying delays in the coupling nodes. By constructing suitable Lyapunov–Krasovskii functional in terms of Kronecker product, sufficient stability conditions are derived in terms of linear matrix inequalities (LMIs) to guarantee the existence of the designed $\mathcal{H}_\infty$ filters. The main contributions of this paper lie in the following aspects: (i) *For the first time, suitable full-order $\mathcal{H}_\infty$ filters are designed for each node for continuous-time CDNs with time-varying delays in nonlinear function and network couplings.* (ii) *The properties of Kronecker product are employed to derive the stability conditions in a more compact form.* (iii) *In order to reduce the possible conservatism of the result, reciprocal convex combination approach is utilized.* (iv) *To illustrate the applicability of the proposed results, Barabasi–Albert (BA) scale-free network model is considered.*

The rest of this paper is organized as follows. A class of continuous-time delayed CDNs consisting of N coupled nodes is presented and some necessary definition and lemmas are provided in Section 2. In Section 3, sufficient conditions are obtained in the form of LMIs and then the $\mathcal{H}_\infty$ filters are designed. Numerical simulations are given in Section 4, to verify the effectiveness of the designed $\mathcal{H}_\infty$ filters. Finally, in Section 5 conclusions and future research interests are given.

Notation: Throughout this paper, $\mathbb{R}^n$ denotes the n dimensional Euclidean space and $\mathbb{R}^{m\times n}$ is the space of $m\times n$ real matrices. $L_2[0,\infty)$ represents the space of square integrable vector functions over $[0,\infty)$. The Kronecker product of matrices $Q\in\mathbb{R}^{m\times n}$ and $R\in\mathbb{R}^{p\times q}$ is a matrix in $\mathbb{R}^{mp\times nq}$ and denoted as $Q\otimes R$. We use diag $\{\cdots\}$ as a block-diagonal matrix. $A>0\,(<0)$ means A is a symmetric positive (negative) definite matrix, A^{-1} denotes the inverse of matrix A. A^T denotes the transpose of matrix A and I is the identity matrix with compatible dimension.