Nonlinear Analysis: Hybrid Systems 26 (2017) 307–318

Contents lists available at ScienceDirect

Nonlinear Analysis: Hybrid Systems

journal homepage: www.elsevier.com/locate/nahs

Pinning impulsive synchronization of complex dynamical networks with various time-varying delay sizes

Xin Wang [a,b,*], Xinzhi Liu [b], Kun She [a], Shouming Zhong [c]

[a] School of Information and Software Engineering, University of Electronic Science and Technology of China, Chengdu Sichuan 610054, PR China

[b] Department of Applied Mathematics, University of Waterloo, Waterloo, Ontario, Canada N2L 3G1

[c] School of Mathematical Sciences, University of Electronic Science and Technology of China, Chengdu Sichuan 611731, PR China

ARTICLE INFO

Article history:
Received 10 August 2016
Accepted 13 June 2017

Keywords:
Synchronization
Complex dynamical networks
Pinning impulsive control
Time-varying delay

ABSTRACT

This paper studies the pinning impulsive synchronization problem for a class of complex dynamical networks with time-varying delay. By applying the Lyapunov stability theory and mathematical analysis technique, sufficient verifiable criterion for the synchronization of delayed complex dynamical networks with small delay is derived analytically. It is shown that synchronization can be achieved by only impulsively controlling a small fraction of network nodes. Moreover, a novel sufficient condition is constructed to relax the restrictions on the size of time-delay and guarantee the synchronization of concerned networks with large delay. Two numerical examples are presented to illustrate the effectiveness of the obtained results.

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1. Introduction

During the last decade, the study of complex networks has become a focal research topic in various fields, e.g., mathematics, biology, physics, sociology and so on [1,2]. A complex network usually consists of a large of set of coupled interconnected nodes, in which each node is a dynamical system. Synchronization of the interconnected nodes is an interesting phenomenon and has been intensively studied in recent years [3–5]. However, due to the complexities of node dynamics and topological structure of a network, all the nodes cannot achieve synchronization by themselves. Thus, proper external controllers are required for achieving this goal. After scholars' long-term exploration and unremitting efforts, various types of conventional and novel control methods have been successfully applied to achieve network synchronization, including adaptive control [6,7], intermittent control [8], impulsive control [9], non-fragile control [10], sampled control [11] and so forth.

Among these synchronization methods, impulsive control is a kind of discontinuous control, the controllers are applied onto systems only at some discrete instants. Besides, impulsive controllers are also easy to implement and lower-cost because they have a relatively simple structure. In many systems such as signal processing systems, computer networks, automatic control systems, flying object motions and telecommunications, impulsive effects are common phenomena characterized by abrupt changes at certain moments. Owing to these effectiveness, robustness and low cost of impulsive control strategies, results [12–16] have been reported to design appropriate impulsive control instants and suitable impulsive control gains to achieve the synchronization for various kinds of complex dynamical networks. On the other

* Corresponding author at: School of Information and Software Engineering, University of Electronic Science and Technology of China, Chengdu Sichuan 610054, PR China.

E-mail address: xinwang201314@126.com (X. Wang).

http://dx.doi.org/10.1016/j.nahs.2017.06.005
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hand, the traditional method to synchronize a complex dynamical network is to add a controller to each of the network nodes to tame the node dynamics to approach a desired synchronization trajectory. However, a complex dynamical network is normally composed of a large of number of nodes, and it is expensive and infeasible to control all nodes. Motivated by this practical consideration, the idea of controlling a small portion of nodes, named pinning control, was introduced in [17], and many pinning algorithms have been reported for the synchronization of complex dynamical networks [18–23]. Obviously, the pinning control method reduces the control cost to a certain extent by reducing the amount of controllers added to the nodes. It is worth noting that the cost of control can be further reduced by combining pinning and impulsive controls, i.e., adding the impulsive controllers to a small fraction of network nodes. In this regard, recently, by combining the advantages of pinning control and impulsive control, the authors in [24,25] have simulated many interesting pinning impulsive control strategies on the synchronization of complex dynamical networks.

However, it should be mentioned that all the results mentioned earlier on the synchronization of complex networks with pinning and impulsive controls did not take into account the time-delay. Actually, the reason that time-delay is significant to the investigation of complex networks due to the finite switching speed of amplifiers and the inherent communication time between nodes. For example, in the communication network, we contact our family, friends or others by telephone, WeChat and so on, the information received would be affected by time delay. Therefore, it is crucial to consider the time delay in studies of complex network synchronization. Recently, some research efforts have been devoted to the area of synchronization of delayed complex networks with pinning and impulsive controls. For instance, in [26], Tang et al. investigated the pinning impulsive synchronization problem for stochastic delayed coupled networks, and a hybrid adaptive controller, consisting of a pinning adaptive controller and an impulsive controller, was designed to achieve network synchronization. In [27], a new pinning impulsive control algorithm was introduced to stabilize a class of nonlinear dynamical networks with time-varying delay. Furthermore, in [28,29], the authors addressed the pinning impulsive synchronization issue of complex dynamical networks, while the nodes to be controlled are fixed at all impulsive instants. Meanwhile, most existing results [30,31] focused mainly on pinning impulsive synchronization for undirected complex dynamical networks, i.e., the configuration matrix is symmetric. However, directed networks commonly exist in a wide variety of natural and synthetic systems, e.g., telecommunication network, interpersonal relationship network, and social and economic networks.

In order to fill the research gap discussed above, this paper studies the issue of pinning impulsive synchronization for complex dynamical networks with time-varying delay. There are several difficulties to conduct this research. First, to apply pinning impulsive control method, it is necessary and difficult to select appropriate nodes to control at each impulsive instant. Second, for networks with delay, it is practically needed to establish sufficient criteria to guarantee the synchronization of the complex networks with various delay sizes. Third, the nodes of the network to be controlled are fixed at all impulsive instants, which is not consistent with the realistic network. Moreover, the impulsive constant control was usually used in the previously known results. Thus, how do we translate it into a variable control? Which is another interesting problem. In this paper, we introduce a type of pinning combining with impulsive control scheme to overcome the above difficulties, and sufficient verifiable conditions for the synchronization of complex dynamical network with small and large time-delay are derived, respectively. Finally, two numerical examples are given to illustrate the effectiveness and correctness of the derived theoretical results.

The remainder of this paper is arranged as follows: Preliminaries and the pinning algorithm on selecting nodes to add the impulsive controllers are presented in Section 2. Sufficient criterion of synchronization with small delay is given in Section 3. Sufficient condition of synchronization with large delay is obtained in Section 4. Numerical examples and further discussions are presented to verify the effectiveness of the derived results in Section 5. The conclusions are given in Section 6.

Notations: The standard notations will be used throughout this paper. The notation $P > (\geq, <, \leq) 0$ is used to denote a real symmetric positive-definite (respectively, positive-semidefinite, negative, and negative-semidefinite) matrix. I_n represents the identity matrix with dimension n. $\lambda_{min}(\cdot)$ and $\lambda_{max}(\cdot)$ represent the minimum and the maximum eigenvalue of the corresponding matrix, respectively. $\Re^n$ denotes the n dimensional Euclidean space. $\Re^{n\times n}$ denotes the $n \times n$ real matrices. The notation T denotes the transpose of a matrix or a vector. The vector norm is defined as $\|x\| = \sqrt{x^T x}$. For matrix $A \in \Re^{n\times n}$, $\|A\| = \sqrt{\lambda_{max}(A^T A)}$. $\#D$ denotes the number of elements of a finite set D. Matrices, if not explicitly stated, are assumed to have compatible dimensions.

2. Problem statement and preliminaries

In this section, we consider the following linearly diffusive coupled complex dynamical network with N identical time-delayed nodes:

$$\dot{x}_i(t) = f(x_i(t), x_i(t-\tau(t))) + c\sum_{j=1}^{N} b_{ij}\Gamma x_j(t) + \tilde{c}\sum_{j=1}^{N} g_{ij}\Gamma x_j(t-\tau(t)), \quad i = 1, 2, \ldots, N, \tag{1}$$

where $x_i(t) = [x_{i1}(t), x_{i2}(t), \ldots, x_{in}(t)]^T \in \Re^n$ is the state variable of the ith node, $f : \Re^n \times \Re^n \to \Re^n$ is a nonlinear vector valued function describing the dynamics of nodes. c and $\tilde{c}$ are two parameters of non-delayed and time-varying delayed coupling strengthen. $\Gamma = (\gamma_{ij}) \in \Re^{n\times n}$ is an inner-coupling matrix. $\tau(t)$ is the time-varying coupling delay satisfying $0 \leq \tau(t) \leq \tau$, $\dot{\tau}(t) \leq \mu < 1$ for some positive scalars τ and μ. The matrices $B = (b_{ij}) \in \Re^{N\times N}$ and $G = (g_{ij}) \in \Re^{N\times N}$

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