



H_∞ synchronization for complex dynamical networks with coupling delays using distributed impulsive control



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ABSTRACT

The H_∞ synchronization problem for complex dynamical networks with coupling delays and external disturbance via distributed impulsive control is studied. Two types of time-varying coupling delays are considered: the delays without any restriction on the delay derivatives, and the delays whose derivatives are strictly less than 1. A time-varying Lyapunov function/functional approach is applied to L_2 -gain analysis of the synchronization error systems. H_∞ synchronization criteria are established to guarantee the synchronization to be robust with respect to disturbance in the sense that the L_2 -gain from the disturbance to the control output is satisfactorily small. For each type of coupling delays, an algorithm involving convex optimization is proposed to design distributed impulsive controllers achieving a suboptimal value of the sum of coupling strengths for a prescribed L_2 -gain. Two numerical examples illustrate the efficiency of the theoretical results.

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1. Introduction

During the last decade, complex dynamical networks (CDNs) have received considerable attention from various scientific communities, due to their broad applications in many fields including secure communication, information science, sociology, biological science, etc. A CDN is a set of many interconnected nodes that interact in different ways. Many dynamical systems in nature, society, and engineering can be described by the models of CDNs, such as biological networks, neural networks, social networks, electricity distribution networks and so on [1–3]. Synchronization is a kind of typical collective behaviors exhibited in CDNs, and has been observed in many examples of CDNs [4,5]. It is worth mentioning that some synchronization phenomena are useful for many applications, such as the synchronous transfer of digital or analog signals in communication network [6]. Local and global synchronization of CDNs has been intensively investigated in the literature [7–14]. However, for many CDNs in real world, the synchronization property cannot be achieved by their local connections. In this situation, certain controllers are needed to force the trajectories of all nodes to the synchronization manifold. In recent years, various control techniques, including adaptive control [15–17], pinning control [18–20], sampled-data control [21,22], impulsive control [23,24], intermittent control [25,26], and output synchronization [27], have been developed to synchronize CDNs. In [28–31], the problems of stability and synchronization of coupled reaction–diffusion networks were investigated.

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Impulsive control method has been widely used in many areas, such as ecosystem management, epidemiology, financial systems, mechanical systems with impacts, secure communication, and orbital transfer of satellites. The main feature of impulsive control method is that the control action is exerted on a plant only at some discrete instants [32–35]. This feature leads to the reduced amount of information to be transmitted, a decreased bandwidth usage, and an increase of robustness against the disturbance. Furthermore, with the rapid development of digital technology, impulsive control method becomes more practical because the impulsive control signals can be generated by digital devices. Two kinds of impulsive control schemes have been studied in the impulsive synchronization problem of CDNs: the decentralized and distributed impulsive control schemes. In the decentralized impulsive control scheme, each node is controlled by a local impulsive control law in which only local state information of the node is utilized. In [36], a decentralized hybrid impulsive control strategy was applied for synchronizing all nodes of the CDN to a desired goal trajectory. In [37], a similar impulsive control scheme was used to solve the synchronization problem of coupled dynamical networks with nonidentical Duffing oscillators. The impulsive synchronization criteria derived in [36,37] were established via the time-invariant Lyapunov function/functional based methods. Due to the conservatism of the time-invariant Lyapunov function based method, the synthesis problem of decentralized impulsive controllers was not solved therein. To overcome the shortcoming of the time-invariant Lyapunov function method, the authors of [38] developed a time-varying Lyapunov function/functional method to establish less conservative stability results of the synchronization error systems. Based on the new stability results, decentralized impulsive controllers can be designed by solving a set of linear matrix inequalities (LMIs).

The decentralized impulsive control schemes may be more suitable to the CDNs with weak coupling because the local impulsive controller of each node in this scheme neglect the state information of its neighboring nodes. When the inner coupling is not weak, a distributed control approach may be needed. In [39], a distributed impulsive control scheme was proposed to realize synchronization for a class of CDNs with coupling delays. In the impulsive control scheme proposed in [39], all the error information of each node with its neighboring nodes at impulse instants is used as feedback information. Since this scheme uses the information from a wider subset of the network nodes, it may assure synchronization of the CDNs with stronger coupling than decentralized impulsive control. The synchronization criteria in [39] were derived by an analysis method based on an impulsive delay differential inequality. In [40], by utilizing a Razumikhin-type analysis technique, the distributed impulsive synchronization condition is expressed in terms of LMIs. Then, an algorithm was proposed to find a suboptimal distributed impulsive controller in the sense that the sum of coupling strengths of the distributed impulsive control is minimized.

On the other hand, it has been well-known that external disturbance is quite common in real-world systems, as well as CDNs. The presence of external disturbance will degrade the system performance and might even destroy synchronization among the nodes. Thus, it is of significant importance to consider the disturbance rejection problem when a given CDN is subject to external disturbance. For the situation that the disturbance signals are square integrable, the concept of L_2 -gain provides a numerical measure of sensitivity of the L_2 disturbance input signal to the control output signal. Therefore, in the presence of external disturbance, we need to design a so-called H_∞ synchronization controller such that the closed-loop synchronization error system is robust with respect to disturbance in the sense that the L_2 -gain is satisfactorily small. In [41], H_∞ control of CDNs subject to external disturbance was considered, and single controller was constructed for achieving certain prescribed H_∞ performance. In [42], the disturbance rejection problem of linear CDNs perturbed by external disturbances was investigated. It was shown that this problem can be converted into the H_∞ control of a set of independent linear systems. The observer-based H_∞ control for synchronization of a class of CDNs was studied in [43], where a synchronization criterion was obtained under which the controlled CDN can be stabilizable with a guaranteed H_∞ performance. In [44], the robust H_∞ control problem of uncertain delayed CDNs with nonidentical nodes was investigated, and an algorithm for designing dynamic output feedback controllers was proposed. The H_∞ cluster synchronization for CDNs with mixed time delays was studied in [45], and a H_∞ cluster synchronization criterion was obtained in the form of LMIs. However, to the best of the authors' knowledge, so far no attempt has been made to solve the problem of H_∞ synchronization of CDNs via impulsive control, which has motivated the present research.

In this paper, the time-varying Lyapunov function/functional approach is adopted to solve the H_∞ synchronization problem of the CDNs with coupling delays and external disturbance via impulsive control. Two cases of uncertain coupling delays are considered: the delay without any restriction on the delay derivative, and the delay whose derivative is strictly less than 1. For the first case, by using a time-varying Lyapunov function approach combined Razumikhin technique, a delay-dependent H_∞ synchronization criterion is derived such that a prescribed L_2 -gain level is satisfied. For the second case, a time-varying Lyapunov functional approach is applied to L_2 -gain analysis of the synchronization error system. Different from Case 1, the obtained H_∞ synchronization condition is independent of the size of the coupling delay. For each case, based on the H_∞ synchronization criterion, an iterative algorithm is proposed to design a distributed impulsive controller achieving a suboptimal value of the sum of coupling strengths for a prescribed L_2 -gain level.

This paper is organized as follows. In Section 2, the model of CDNs with distributed impulsive control and the problem to be solved are formulated. Main results, including finite L_2 -gain analysis and suboptimal H_∞ controller design, are presented in Section 3. Two numerical examples are given in Section 4 and conclusions follow in Section 5.

Notation. Throughout this paper, $\mathbb{R}^n$ and $\mathbb{R}^{n \times m}$ denote the n -dimensional Euclidean space and the set of all $n \times m$ matrices, respectively. The notation $\|\cdot\|$ refers to the Euclidean vector norm. $\mathbb{R}_+ = [0, +\infty)$, $\mathbb{N} = \{0, 1, 2, \dots\}$. For a real symmetric matrix P , the notation $P > (\geq, <, \leq) 0$ is used to denote a positive definite (positive semidefinite, negative

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