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Synchronization of fractional-order colored dynamical networks via open-plus-closed-loop control

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HIGHLIGHTS

- Fractional-order colored complex network model.
- The open-plus-closed-loop strategy is applied for an edge-colored network.
- The synchronization criteria for fractional-order networks are obtained.

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ABSTRACT

In this paper, the synchronization of a fractional-order colored complex dynamical network model is studied for the first time. In this network model, color edges imply that both the outer coupling topology and the inner interactions between any pair of nodes may be different, and color nodes mean that local dynamics may be different. Based on the stability theory of fractional-order systems, the scheme of synchronization for fractional-order colored complex dynamical networks is presented. To achieve the synchronization of a complex fractional-order edge-colored network, the open-plus-closed-loop (OPCL) strategy is adopted and effective controllers for synchronization are designed. The open-plus-closed-loop (OPCL) strategy avoids the need for computation of eigenvalues of a very large matrix. Then, a synchronization method for a class of fractional-order colored complex network, containing both colored edges and colored nodes, is developed and some effective synchronization conditions via close-loop control are presented. Two examples of numerical simulations are presented to show the effectiveness of the proposed control strategies.

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1. Introduction

As it is well known, complex networks permeate every aspect of our daily lives, existing in various fields of the real world, such as social networks, biological networks, organizational networks, neural networks, and many others [1–6]. In fact, most networks can be modeled by complex dynamical networks, in which each node is a nonlinear dynamical system. The connection among the large number of nodes embodies the complexity of a network. This connection includes outer and inner couplings. For any pair of nodes with connections (there exist edges among the pairs of nodes) in a network, it is always assumed that the inter-connections between any connected pairs of nodes are identical, or the inner coupling matrix is usually assumed to be identical in most studies. On the other hand, when the inter-connections between any connected pairs of nodes are not completely identical, it is said that the network has color edges, or it is a color-edged network. From

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the view of application, inner couplings are as important as outer couplings for many realistic systems, such as the social and the traffic networks. Furthermore, when a network possesses nodes with different local dynamics, it is called a node-colored network. That is to say, colored networks may be node-colored and/or edge-colored. The authors of Ref. [7] proposed a new network model referred to as colored networks, which is an ensemble of dynamical nodes interconnected through inner couplings, which consists of both colored nodes and colored edges. The node-colored networks have been discussed in many works [8,7], but the edge-colored networks have been seldom studied.

The synchronization of dynamical networks can explain many natural phenomena [9–11]. Since Barahona and Pecora have presented the synchronization of small-world networks and scale-free networks in Refs. [12,13]. The synchronization phenomena of complex networks has attracted the attention of many researchers, with the expectation of gaining new insights into the interactions taking place in real-world complex systems [14–17].

Fractional calculus is a generalization of integration and differentiation to a non-integer-order integro-differential operator, has attracted lots of attention due to its application in physics and engineering [18,19]. Nowadays, it has been found that many systems in interdisciplinary fields, such as dielectric polarization, viscoelasticity, quantum evolution of complex system, electromagnetic wave, and fractional kinetics, can be described by fractional differential equations [20–23]. These research efforts have shown that fractional derivatives provide an excellent tool for describing the memory and hereditary properties of various materials and processes. Therefore, considering fractional-order systems as nodes in complex networks and studying synchronization of the fractional-order complex dynamical networks have both application background and important theoretical significance.

It is now well known that various control schemes, such as impulsive control [23], adaptive control [24], pinning control [25], open-loop and closed-loop control (OPCL) [26,27] can be used to realize the synchronization of complex networks. The original application of the OPCL method was limited to the integer-order differential systems. In the OPCL technique to the integer-order network systems, the matrix H is an arbitrary constant Hurwitz matrix whose eigenvalues have negative real parts. Moreover, there are few works to realize synchronization of fractional-order dynamical networks via OPCL technique. Thus, we will combine the advantages of closed-loop and open-loop control strategies to design effective controller to achieve synchronization of fractional-order colored dynamical networks in this paper.

This paper is organized as follows. In Section 2, the network model of fractional-order colored network is introduced after some definitions on color nodes and color edges are given. Section 3 is devoted to deriving some synchronization criteria for the synchronization in fractional-order colored complex networks based on some lemmas. In Section 4, illustrative examples are presented to show the validity of the proposed methods. Conclusions of this paper will be drawn in Section 5.

2. Preliminaries and model description

There are many definitions of fractional derivatives [18]. The two most commonly used are Riemann–Liouville and Caputo definitions. The difference between the two definitions is in the order of evaluation, where Riemann–Liouville fractional derivative of order $q \geq 0$ of the function $f(t)$ is defined as

$$J^q f(t) = \frac{1}{\Gamma(q)} \int_0^t (t-\tau) f(\tau) \mathrm{d}\tau, \quad t > 0. \tag{1}$$

Caputo definition of the fractional derivative of the function $f(t)$ is defined as:

$$D_*^q f(t) = \frac{1}{\Gamma(m-q)} \int_0^t \frac{f^{(m)}(\tau)}{(t-\tau)^{q-m+1}} f(\tau) \mathrm{d}\tau, \quad t > 0. \tag{2}$$

Formula (2) will be used in this paper where q is the fractional order, m is an integer that satisfies $m-1 < q \leq m$, $m \in N$, $t > 0$, $f^{(m)}$ is the ordinary mth integer derivative of f, $\Gamma(\cdot)$ is the Gamma function.

$$\Gamma(s) = \int_0^\infty t^{s-1} \mathrm{e}^{-t} \mathrm{d}t. \tag{3}$$

Consider a colored fractional-order network that consists of N coupled nodes and is described by:

$$D_*^q x_i(t) = f_i(x_i(t)) + \sum_{j=1}^{N} a_{ij} H_{ij} (x_j(t) - x_i(t)), \quad i = 1, 2, \ldots, N, \tag{4}$$

where $0 < q \leq 1$ is the fractional order, $x_i = (x_{i1}, x_{i2}, \ldots, x_{in})^T \in R^n$ denotes the state vector of the ith node, and $f_i : R^n \to R^n$ is the given continuously differentiable nonlinear function describing the local dynamics of node i. $A = (a_{ij})_{N \times N}$ indicates the outer coupling matrix of the network. If there exists a link between ith node and jth node ($i \neq j$), then $a_{ij} \neq 0$, and the positive entry a_{ij} represents the strength of the connection between nodes i and j; otherwise, $a_{ij} = a_{ji} = 0$, and note that all the diagonal elements are $a_{ii} = 0$. $H_{ij} = diag(h_{ij}^1, h_{ij}^2, \ldots, h_{ij}^n)$ is the inner coupling matrix, which represents the mutual interactions between nodes i and j, if the kth component of node i is affected by that of node j, then $h_{ij}^k \neq 0$, otherwise $h_{ij}^k = 0$.

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