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Adaptive sliding-mode insensitive control of a class of non-ideal complex networked systems

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ABSTRACT

This paper addresses the problem of insensitive tracking control for a class of complex networked systems with faulty and perturbed networks and controller additive coefficient variations. The coupled networks are supposed to be faulted randomly and perturbed by bounded time delays and disturbances. Moreover, additive controller gain variations that can also be considered as actuator bias faults are proposed. Adaptive sliding mode compensation control schemes were developed to update control gains in order to eliminate these non-ideal factors. Then, a class of distributed robust adaptive sliding mode controllers was constructed to automatically compensate for the faulted and variational effects based on the information from adaptive schemes. On the basis of Lyapunov stability theory, it is shown that average tracking of the resulting adaptive complex networked systems can be achieved. An example is provided to further illustrate the effectiveness of the proposed adaptive sliding mode design technique.

1. Introduction

With the deep investigation and application of networks, researchers have paid more and more attention to complex networked system designs in recent years. Many complicated problems of various networked systems in the fields of physics, industry, and aviation have been studied in regard to their autonomy, distribution, coordination [14], robustness and reliability [5]. The tracking behavior of complex networked systems has also been studied extensively over the last few years. Many actions in practical control systems and many physical phenomena are involved in the tracking behavior, including the consensus of multi-agent systems [30], synchronization of complex networks and chaotic systems [33], rendezvous in space [23], formation of aircrafts [31], and flocking theory [28].

Multi-agent systems and complex networks have been developed rapidly. The inherent stabilization and tracking characteristics of complex networked systems are basically illustrated by research based on graph theory and control theory [29,35]. Among these studies, considerable results have been given in the cases of time delays, disturbances, communication failures, and constrained networks. One paper [4] considered constant and time-varying delays that are uniformly or non-uniformly distributed in the network, and presented some sufficient and necessary conditions for the existence of average consensus with bounded communication delays. Recently, constant delays [24], unbounded time-varying delays [25], and non-uniform multiple time-varying delays [37] have been considered in second-order multi-agent system designs.

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Moreover, many results of stability analysis have been proposed in complex network studies with finite and infinite delays [20], distributed delays [26], and stochastic delays [39]. Note that the robustness analysis results against time delays have been widely illustrated in the existing literature. However, the compensation for the effects of time delays has rarely been investigated.

The study of time delays regarding their adverse impacts on stabilization and tracking is similar to the problem of disturbances (communication noise), which has also been generally investigated. Some results have been given with respect to the stochastic noise in the networks [22,42] and bounded continuous noise [11,12]. In a recent paper [3], a lazy consensus protocol was given against unknown but bounded disturbances, and bounded consensus results were achieved. From these studies, it should be noted that the asymptotic consensus cannot be achieved if noise always exists in networks. An asymptotic tracking result has been obtained under a matching condition [15]. However, the results were feasible based on a norm-bounded assumption, which means the disturbances are affected within a constant region. Disturbances in communications may be caused by inaccuracy of the transmitted mechanism, which reveals that the disturbances might rely on the transmitted signals. Thus, the affected region may be time-varying according to the change of transmitted signals. In allusion to this practical case, more effective methods for asymptotic tracking against communication noise with a time-varying affected region need to be investigated in further studies.

Communication failures may result in more serious degradation of the system performance than time delays and disturbances. In recent research, many types of faults on networks have been dealt with, such as stochastic link faults [19,32,41], lossy networks [36], missing data [13], limited communication data rate [21], packet loss [45], network deterioration [16], and network attenuations [17]. In these studies, the failure of communications can be generally considered as a random independent probability process. In one study [32], an average consensus problem was presented in the case of independent probability communication failures. The decay factor was characterized in terms of the eigenvalues of a Lyapunov-like matrix recursion. In another study [19], a necessary and sufficient condition for consensus was presented with spatially correlated (Markovian) dependent random link failures and time Markovian noise sequences. A recent paper [13] considered the consensus problem by way of missing data in actuators and Markovian communication failure, where the communication failure process was reduced to a Bernoulli process. The limited communication data rate and energy constraint problems of consensus were also investigated [21]. It shall be noted theses papers considered discrete-time multi-agent systems, and a Markovian stochastic process was always used to formulate the communication failures. For continuous-time networked systems, the failures were generally described as signal attenuations or lossy networks [17]. In this paper, the faulty factor of networks described by a random coefficient is considered in the continuous-time complex networked systems.

These works were based on an implicit assumption that the controller will be implemented exactly. However, small variations in controller coefficients may result in huge performance degradation or even instability of the systems [8,27]. Thus, the gain variations and uncertainties of controllers are widely studied on insensitive, non-fragile designs. Additive and multiplicative controller gain variations were presented in non-fragile designs in linear/non-linear continuous-time systems [6,40], time-delay systems [7], uncertain fuzzy systems [43], and fault-tolerant systems [18]. In the above works, H_2, H_∞, and the guaranteed cost performance of systems was optimized by linear matrix inequality methods. However, insensitive control in complex networked systems has not received great attention. Moreover, the compensation problem of gain variations of controllers has rarely been investigated in networked systems. Thus, motivated by the compensation of external disturbances with robust control, the compensation problem of gain variations with asymptotic tracking designs in complex networked systems is addressed in this paper.

We consider the insensitive tracking control problem of complex networked systems in the presence of random communication failures with perturbations occurring due to bounded time-varying delays and disturbances. The probability of failures and the bounds of disturbances do not need to be known. Similarly, the size of time delays and the bounds of controller coefficient variations are also unknown. Based on Lyapunov stability theory, a novel adaptive sliding mode control strategy was developed to achieve asymptotic tracking of the complex networked systems. Some adaptive schemes are proposed to estimate the switching gains. Then, adaptive sliding mode controllers are constructed relying on the updated switching gains. By using the designed controllers, the faulty and perturbed factors and variational effects can be completely compensated for and the average tracking can be achieved in a finite amount of time.

The average tracking problem formulation is described in Section 2. In Section 3, the distributed adaptive sliding mode controllers are developed. Section 4 gives an example and simulation. Finally, conclusions are given in Section 5.

2. Preliminaries and problem statement

We first introduce our notation and gather some elementary facts. R stands for the set of real numbers. For a real matrix E, E^T and E^{-1} denote its transpose, and inverse, respectively. Given values $m_k, k = 1, \dots, n$, the notation diag$[m_k]$ denotes the diagonal matrix with m_k along the diagonal. The sign of $\otimes$ denotes the Kronecker product, and $\mathbf{1}_N$ represents $[1, 1, \dots, 1]_N^T$.

We consider a complex networked system G composed of N interconnected linear time-invariant continuous time subsystems $G_i, i = 1, 2, \dots, N$. Each edge corresponds to an available information link from one subsystem to another. Then, the N subsystems constitute a network as in following state-space equation: