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Stochastic bounded consensus tracking of leader–follower multi-agent systems with measurement noises based on sampled-data with small sampling delay

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ABSTRACT

This paper is concerned with the stochastic bounded consensus tracking problems of leader–follower multi-agent systems, where the control input of an agent can only use the information measured at the sampling instants from its neighborhood agents or a virtual leader with a time-varying reference state, the measurements are corrupted by random noises, and the signal sampling process induces a small sampling delay. The augmented matrix method, probability limit theory and algebra graph theory are employed to derive the necessary and sufficient conditions guaranteeing mean square bounded consensus tracking. It turns out that the convergence of the proposed protocol simultaneously depends on the constant feedback gains, the network topology, the sampling period and the sampling delay, and that the static consensus tracking error depends on not only the above-mentioned factors, but also the noise intensity, the number of agents and the upper bound of the changing rate of the virtual leader's state. The obtained results cover no sampling delay as a special case. Simulations are provided to demonstrate the effectiveness of the theoretical results.

1. Introduction

In recent years, distributed coordinated control of multi-agent systems, due to its broad applications, including swarming, flocking, rendezvous, formation control, distributed sensor networks and so on, has attracted a great deal of attention. Consensus plays an important role in the distributed coordinated control of multi-agent systems, since the idea for consensus that each agent updates its own state based on the states of its local neighbors such that the states of all the agents converge to a common value can be extended to deal with other kinds of distributed coordinated control tasks. For most of the existing consensus protocols [1–4], the final common value to be achieved is a function of initial states of all the agents and is inherently a prior unknown constant. This is the so-called χ-consensus [5,6]. However, in real applications, it is often required that all the agents converge to a desired common value, which evolves over time, as occurs in consensus tracking, where all the agents exchange their own state information with their neighbors with the common goal of tracking a time-varying reference state that is available to only a portion of agents. Thus, χ-consensus protocols are ineffective at directly dealing with the consensus tracking of a desired time-varying reference state. To solve this problem, consensus

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protocols of leader–follower multi-agent systems have been proposed, and significant attention has been focused on the consensus tracking of leader–follower multi-agent systems [7–13]. Jadbabaie et al. considered the nearest neighborhood principle and proved that, if all the agents are jointly connected with their leader, then their states will converge to the state of the leader as time goes on Ref. [7]. Ren and Beard extended the results of Ref. [7] to the directed topology case and gave some more relaxed topology conditions [8]. In Ref. [9], Ren proved that proportional like continuous-time consensus protocols cannot guarantee that all the agents track a virtual leader with a time-varying reference state that is available to only a subset of agents, whereas proportional and derivative like continuous-time consensus protocols can do.

Most research on the consensus tracking of leader–follower multi-agent systems in the above literature assumes that each agent measures the states of its neighbors and the leader accurately. Obviously, this assumption is only an ideal approximation for real communication channels, since real networks are often in uncertain communication environments with various source noises, channel noises and sink noises. Thus, it is necessary to study the effects of measurement noises on the consensus tracking of leader–follower multi-agent systems. Recently, consensus of leaderless multi-agent systems with measurement noises has been widely studied in Refs. [14–20]. Ren et al. and Kingston et al. introduced time-varying consensus gains, designed consensus protocols based on a Kalman filter structure, and proved that, when there is no noise, the protocols designed can ensure consensus to be achieved asymptotically [14,15]. Xiao et al. considered the first-order discrete-time average consensus of multi-agent systems with additive input noises and designed an optimal weighted adjacency matrix to minimize the static mean square error [16]. Since the consensus gain and the adjacency matrix are both time invariant, the average state will diverge with probability 1 as time goes on, even if the noises are bounded. In Ref. [17], stochastic approximation type protocols with decreasing consensus gains were employed to guarantee the mean square or almost sure consensus of first-order discrete-time multi-agent systems with measurement noises. In Ref. [18], Li and Zhang considered the average consensus of first-order discrete-time multi-agent systems with measurement noises and time-varying topologies, and proved that, if the network switches among jointly-containing-spanning-tree, instantaneously balanced graphs, then the designed protocol can guarantee that each individual state converges, both almost surely and in mean square, to a common random variable, whose expectation is just the average of the initial states of all the agents. In Ref. [19], Li and Zhang investigated the average consensus of first-order continuous-time multi-agent systems with measurement noises and obtained the convergence conditions guaranteeing a mean square consensus. However, compared with the consensus of leaderless multi-agent systems with measurement noises, the consensus tracking of leader–follower multi-agent systems with measurement noises has attracted only a little attention [21–25]. Huang and Hanton considered the consensus of discrete-time leader–follower multi-agent systems with measurement noises, and derived the sufficient conditions guaranteeing stochastic approximation type protocols with decreasing consensus gains to reach a mean square consensus by using stochastic Lyapunov analysis [21]. Ma et al. investigated the consensus of continuous-time leader–follower multi-agent systems with measurement noises, and obtained the sufficient conditions for a mean square consensus by employing stochastic analysis and algebra graph theory [22]. In Ref. [23], Hu and Feng developed a distributed tracking control scheme with distributed estimators based on a novel velocity decomposition technology for a continuous-time leader–follower multi-agent system with measurement noises, proving that the closed-loop tracking control system is stochastically stable in mean square and that the estimation errors converge to zero in mean square as well.

In most of the work in the above literature, continuous-time consensus protocols were used for guaranteeing the consensus of multi-agent systems with continuous-time dynamics, and discrete-time consensus protocols were used for guaranteeing the consensus of multi-agent systems with discrete-time dynamics. However, due to the application of digital sensors and controllers, in many cases, though the system itself is a continuous process, only sampled-data at discrete sampling instants is available for the synthesis of control laws. Compared with full-state information transmission, which might result in high communication traffic, the transmission of the state information at the sampling instants can effectively save the bandwidth of networks and communication cost. Considering the broad applications of digital communication and control in distributed systems, it is of great significance to study the consensus of multi-agent systems based on sampled-data control. Considerable efforts have been focused on the sampled-data consensus of leaderless multi-agent systems without measurement noises [26–31], but only a little attention has been paid to the sampled-data consensus of leaderless multi-agent systems with measurement noises [32] and the sampled-data consensus of leader–follower multi-agent systems without measurement noises [33]. To the best of our knowledge, there is no open report on the sampled-data consensus tracking of leader–follower multi-agent systems with measurement noises. Moreover, in real applications, a sampling delay induced by the signal sampling process indeed exists and might cause multi-agent systems based on sampled-data to oscillate or diverge. Thus, the effects of the sampling delay on stability of multi-agent systems should be considered. In Refs. [30,31], consensus of leaderless multi-agent systems without measurement noises based on sampled-data with small sampling delay, i.e., the small sampling delay is less than the sampling period, has been studied. However, so far, there is no open report on the consensus tracking of leader–follower multi-agent systems with measurement noises based on sampled-data with small sampling delay.

Based on the above considerations, in this paper, we investigate the stochastic bounded consensus tracking problems of leader–follower multi-agent systems, where the control input of an agent can only use the information measured at the sampling instants from its neighbors or the virtual leader with a time-varying reference state, the measurements are corrupted by random noises, and the signal sampling process induces a small sampling delay.