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Leader-following consensus for networked multi-teleoperator systems via stochastic sampled-data control

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ABSTRACT

In this paper, the leader-following consensus problem is investigated for a networked multi-teleoperator system (NMTS) under a stochastic sampled-data controller. By utilizing the input delay approach, the sampling period is transformed into a time-varying yet bounded delay. With the help of algebraic graph theory and probability theory, a new consensus protocol is designed. Subsequently, a sufficient condition for the leader-following consensus of NMTS is derived in the form of linear matrix inequality (LMI) by constructing an appropriate Lyapunov–Krasovskii functional and by utilizing some matrix and integral inequality techniques. Based on the derived condition, the design method of the desired sampled-data controller is also obtained in terms of the solution to LMI which can be checked effectively by using available software. In addition, the effectiveness of the obtained theoretical results is illustrated by a numerical example.

1. Introduction

During the past two decades, there has been seen a significant growth in the research field of cooperative control of distributed multi-agent systems (MASs). Cooperative control occurs when a number of agents connect to a communication network. An agent could be an unmanned aerial vehicle (UAV), autonomous underwater vehicle (AUV) or any type of dynamical system. One of the primary research topics in cooperative control is the so-called consensus problem. Generally, for a given multi-agent system (MAS) which consists of multiple individual physical systems, it is required that the state of each agent converges to a common value (or function). If the condition is satisfied, then we say that the MAS has achieved consensus. Consensus has a great number of applications such as rendezvous, flocking, swarming, and formation control, see for example [1–4]. Nowadays, the consensus problem is being studied in the framework of distributed control. The mathematical theory on graph and stochastic matrices has played an important role in the analysis of convergence to consensus. In the literature, numerous methods such as the Lyapunov theory, sliding mode control, model predictive control, output regulation, neural network, and so on have been used to solve the consensus problem [5–7]. Besides, the research on consensus has received much more attention from academia as an agreement problem. In [8], authors studied the agreement algorithm in the context of parallel computation, distributed optimization and signal processing. On the other hand, time delays are ubiquitous in the natural world. It is well known that the time delays heavily influence the system performance dependent on both the quantity of delays and the properties of system dynamics. Owing to this fact, in the previous literature, the consensus problem with time delays has been widely studied. In [9], authors analyzed the average consensus for single integrator agents in the presence of single constant delay. The frequency domain approach has been used to derive the stability condition dependent on the upper bound of the delay. Afterwards, researchers have investigated the consensus problem with time-varying delays. For example, Xiao and Wang [10] deal with the consensus problem for first-order dynamics with switching topology and time-varying delays and Sun and Wang [11] examine the consensus problem for double-integrator dynamics with time-varying delays. When tackling time-varying delays, researchers shift from the classic frequency domain to time domain and the Lyapunov technique is chiefly used. In those analyses, various information may be taken into account, such as the lower and the upper bound of delays. It has been shown in the research of networked control systems (NCSs) that when considering more information on delays, the obtained results are generally less conservative. For more work on consensus with time delays, refer to [12,13] and the references therein.

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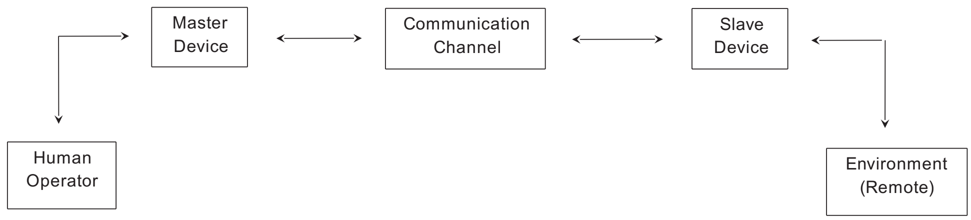

Fig. 1. A typical configuration of bilateral teleoperation.

Consensus has two types, namely, leader-following consensus and leaderless consensus. In leader-following consensus, one or more agents act as the role of leaders and the remaining agents follow the behavior of these leaders. Leaderless consensus means that there is no virtual leader. Owing to many practical applications such as large scale robotic systems, biological systems, and formation control, researchers have concentrated on leader-following consensus type. Thats why those kinds of practicals systems can be represented as leader-following MAS. For further details about leader-following consensus, see [14–18]. Moreover, it is necessary and beneficial to study leader-following consensus algorithms in the presence of delays. The authors in [19] have proposed a first-order consensus tracking algorithm with input delays, where an estimator is used to estimate the virtual leader's velocity. In [20], by choosing a Lyapunov–Krasovskii functional and by using some directed graph information, a novel delay-dependent consensus condition for distributed multi-agent system has been derived.

In recent years, in order to reduce cost and time in cooperative control systems, teleoperation has been utilized widely. A typical configuration of the teleoperation system is given in Fig. 1. In general, a teleoperation system or a bilateral teleoperation system (BTS) is a complex electro-mechanical system comprehending a master and a slave device, interconnected by a communication channel and a controller. Through interaction with the master device, the human operator is able to communicate control signals for the slave. The slave device actually interacts with the environment (remote), thereby staying under the full control of human operator. Information gathered at the remote side is transmitted back to the human operator through the master device. The main applications of master slave teleoperation systems are submarine explorations, robotic surgery, repairing of electric lines and livestock nourishing. Because of its day to day life applications, nowadays researchers are eagerly studying the BTSs and recent literature witnesses it, for instant, see [21–25]. In [23], authors proposed a new control law for controlling teleoperator systems with time delay. In [24], the adaptive fuzzy method was proposed for the teleoperation design with the consideration of stochastic time-varying delays. Furthermore, authors in [25] have derived the delay-dependent LMI stability criterion for the closed-loop teleoperation system with time-varying delays. Very recently, in [26], authors introduced the concept of leader-following consensus in teleoperation systems and obtained novel delay-dependent consensus stability and stabilization conditions for networked multi-teleoperator systems (NMTSs) with interval time-varying communication delays.

Alongside, as the modern control systems usually employ digital technology for controller implementation, sampled-data control theory has attracted great attention in recent years. For these systems, selecting proper sampling period is essential to guarantee a desired control performance. In order to improve the inter-sampling performance, hybrid system models with both continuous and discrete-time signals are generally built through a zero-order hold (ZOH), which is also named as sampled-data systems [27]. In such systems, the control signals are kept constant during the sampling period and cannot be changed to deal with the nonlinearity of the plant [28]. Thus, it is more practical to apply sampled-data control in many real-world systems, such as radar tracking systems, power systems and temperature control. Comparing continuous-time systems with continuous-time controller, continuous-time systems via sampled control have many advantages, such as flexibility, robustness and low cost [29,30]. For consensus problems of continuous-time multi-agent systems via sampled control, some interesting results have been reported in the literature, see [31–36]. In [35], the authors have studied the second-order consensus in multi-agent dynamical systems with sampled position data, whose control protocol is induced from linear consensus protocol with both the current and past sampled position data. In [36], authors have considered the second-order consensus problem via sampled control, whose control protocol is induced from continuous-time linear consensus protocol using periodic sampling technology and zero-order hold circuit.

In addition, the possibility of a random change in sampling interval has been considered in [37], which is said to be a further extended scheme to the case of time-varying sampling intervals. Therefore, the necessity of the controller design problem using sampled-data with stochastically varying sampling interval has been highlighted. A unified framework for stochastically bounded consensus tracking of leader–follower multi-agent systems with measurement noises based on sampled data with a general sampling delay has been presented in [38]. The authors in [39] have investigated the stochastic bounded consensus tracking problems of second-order multi-agent systems with measurement noises and the virtual leader with the time-varying reference state which is available to only a portion of agents based on sampled-data with the general sampling delay by employing the delay decomposition technique. Therefore, we will also study the case when stochastically varying sampling delay exists.

Contributions of this paper: It is highly noted that, in the aforementioned works, very little attention has been paid on the consensus problems of bilateral teleoperation systems. In this connection, more recently, the networked multi-teleoperation systems with time-varying delays under leader-following consensus control have been studied in [26]. To make an extension of this work, we have included sampled-data control with stochastic sampling in the present paper. In this paper, similar to [42], we have constructed a newly augmented Lyapunov–Krasovskii functional with a four integral term and derived the sufficient condition ensuring the asymptotic consensus of the multi-teleoperation system. Due to this integral term, the augmented vector consists of the double integral term $\int_{t-d_m}^{t-d_{m-1}} \int_{s}^{t-d_{m-1}} e(u)\, du\, ds$ while calculating the upper bound of the time derivative of $\mathcal{V}(e_t)$. However, to the best of our knowledge, the leader-following consensus for networked multi-teleoperator system through stochastic sampled-data controller has not been fully investigated in the previous literature. This paper fulfills such a gap.

The rest of this paper is arranged as follows: In Section 2, the leader-following consensus problem is formulated for a networked multi-teleoperator system and some useful preliminaries are given. In Section 3, an asymptotic consensus criterion is