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On sliding mode control for networked control systems with semi-Markovian switching and random sensor delays☆

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ABSTRACT

This paper focuses on the problem of sliding mode control for networked control systems with semi-Markovian switching and random measurement, where the measurement channel is assumed to suffer from random sensor delays. A Luenberger observer is designed to generate the estimation of system states, and the integral sliding surface is constructed to guarantee exponential stability of networked semi-Markovian switching systems in the mean square sense. Then a proper controller is synthesized to ensure that the trajectory of the closed-loop networked semi-Markovian switching systems can be driven onto the prescribed sliding surface. Finally, numerical examples and simulations are provided to illustrate the effectiveness of the integral sliding mode control scheme.

1. Introduction

It is well known that networked control systems, where the components (such as the plant, the controller and the sensor) are connected over networks, offer many substantial benefits over traditional point-to-point system, such as high flexibility, cost-effectiveness, reduced weight, simplifying system maintenance, etc. So more and more efforts have been devoted to these systems, see [10,13,16,22,29,31,32,34,37,39,41,47,53,54] and the references therein for more details. In networked control systems, controllers and plants to be controlled often communicate with each other in a non-ideal manner due to long distance communication channels, and thus, issues such as time delay [22,31,53], noise, bandwidth limitations, channel input power constraint and network-induced related problems [16,34,37,41,54] have to be considered. As for the controller design of networked control systems, many control techniques have been proposed to ensure the stability of networked control systems, such as robust tracking control [32], predictive output feedback control [47], event-triggered control [10,39]. Besides, the effect of encoder-decoder on control systems has been well studied in [13,29]. Nevertheless, it is worth mentioning that the output of the networked control system must be measured by sensors from the perspective of engineering control. Due to the technological limitation or other reasons, the sensor often does not properly work. Then the measured output may or may not experience sensor delay, and the sensor delay randomly occurs. In fact, there are many results about this topic

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on random sensor delay, which can be found in [4,24,27,33] and the references therein. So far, the known results mainly focus on the state estimation problems, *i.e.*, adaptive Kalman filtering [27], optimal linear estimators [24,33] and distributed event-triggered H_∞ filtering [4]. However, there has been little theoretical work appeared on effective observer-based control designs for continuous-time networked control systems with random sensor delay.

In order to describe those frequent unpredictable structural changes, the networked Markovian switching systems have been presented and utilized to model the mode change of the plant in the past few years. To date, some remarkable approaches have been proposed to deal with networked Markovian switching systems, see for example [7,19,20,38,45,52], and the references therein. However, in many practical applications, Markovian switching systems have certain limitations in some senses, since the jump time of a Markov chain is exponentially distributed and the transition rates are constant. Nevertheless, semi-Markovian switching systems are characterized by a matrix of sojourn time probability density functions. It can be found that the transition rates will be time-varying in semi-Markovian switching systems instead of constant in Markovian switching systems. Actually, Markovian switching systems should be regarded as a special case of semi-Markovian switching systems. Due to the relaxed conditions on the probability distributions, semi-Markovian switching systems have much wider application prospect than conventional Markovian switching systems. Therefore, it is of both theoretical merit and practical interest to develop control theory for semi-Markovian switching systems. In contrast to substantial results for Markovian switching systems, there are few results concerning semi-Markovian switching systems, except for [9,11,40].

As a significant and hot research topic, sliding mode control has always received considerable attention and developed into a general design method for a wide spectrum of systems including nonlinear systems [1,6], uncertain stochastic systems [12,14,15], and large-scale systems [36]. As a matter of fact, sliding mode control holds a great number of notable advantages, such as convenience to be performed, good transient performance, the ability to eliminate external disturbances and reduction of the order of the state equation, etc. Then it is recognized as one of the efficient tools to design robust controllers for the complex dynamic system operating under parameter variations or external disturbances. That is why sliding mode control has been successfully applied to a wide variety of practical engineering systems in the past few decades. Due to random failures or repair of components, sudden environmental disturbances, and abrupt variations in a plant, sliding mode control for Markovian switching system is attractive, and substantial progress has been made on this subject, which can be found in [2,3,23,30,44,48,51,55] and the references therein. However, the extensively used Markovian switching scheme would not be applicable in some situations, when the practical networked control systems do not satisfy the so-called memoryless restriction and the mode change of the plant should be modeled as a semi-Markov process. Thus under such circumstances, sliding mode control scheme for semi-Markovian switching system is urgently needed. In fact, the theory and experiments suggest that a semi-Markov process captures the stochastic behavior more accurately, such as the fault-tolerant control system [17], cognitive radio system [5] and master-slave system [21]. On the basis of such a good application background, it can be seen that the investigation of networked semi-Markovian switching systems is both necessary and important not only in theory, but also in practice.

Motivated by the above considerations, we investigate sliding mode control problem for networked control system with semi-Markovian switching and random sensor delays. The main contributions of this paper are summarized as follows. First and foremost, with the help of Luenberger observer, the estimation of system states can be obtained and the closed-loop error dynamics is derived. Second, the appropriate integral sliding surface function is constructed to achieve exponential stability for networked semi-Markovian switching system with random sensor delay. Third, the effective controller is proposed to perform the reachability analysis and guarantee the trajectory driven onto the predefined sliding surface. Finally, numerical simulations are given to illustrate the applicability and effectiveness of the proposed control design scheme.

The remainder of this paper is organized as follows: Section 2 contains the problem statement and preliminaries, which include networked semi-Markovian system description and problem formulation; Section 3 presents the main results about exponential stability analysis via sliding mode control and reachability analysis for the resulting sliding mode dynamics; Section 4 provides numerical examples to verify the effectiveness of the proposed results; Concluding remarks are given in Section 5.

1.1. Notations

The following notations are used throughout the paper. The superscripts T and -1 denote matrix transposition and matrix inverse, respectively. $[a, b]$ denotes the closed interval from real number a to real number b on $\mathbb{R}$, where $a \le b$. $\mathbb{N}^+$ stands for positive integer, $\mathbb{R}^n$ denotes the n dimensional Euclidean space and $\mathbb{R}^{m\times n}$ is the set of all $m \times n$ matrices. $X < Y (X > Y)$, where X and Y are both symmetric matrices, means that $X - Y$ is negative(positive) definite. I is the identity matrix with proper dimensions. For a symmetric block matrix, we use $\star$ to denote the terms introduced by symmetry. $\mathscr{E}$ stands for the mathematical expectation. $\Gamma V(x(t), r(t))$ denotes the infinitesimal generator of $V(x(t), r(t))$. $\|v\|$ is the Euclidean norm of vector v, $\|v\| = (v^T v)^{\frac{1}{2}}$, while $\|A\|$ is spectral norm of matrix A, $\|A\| = [\lambda_{\max}(A^T A)]^{\frac{1}{2}}$. $\lambda_{\max(\min)}(A)$ is the eigenvalue of matrix A with maximum(minimum) real part. Matrices, if their dimensions are not explicitly stated, are assumed to have compatible dimensions for algebraic operations.