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Reliable finite-time sliding-mode control for singular time-delay system with sensor faults and randomly occurring nonlinearities

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ABSTRACT

This paper focuses on the finite-time sliding-mode control problem for singular time-delay system with sensor failures and uncertain nonlinearities. Based on the proposed sliding-mode control law, sufficient criteria are provided to guarantee the closed-loop system is singular sliding-mode finite-time boundedness in both reaching phase and sliding motion phase. The prescribed sliding-mode control law can drive the state trajectories onto the specified sliding surface in a short time interval. Furthermore, the singular H_∞ finite-time boundedness conditions for error system have been established with sensor faults over the whole interval. Through the linear matrix inequalities technique, gain matrices for controller and estimator can be obtained. Finally, numerical examples have been given to demonstrate the potentials of the proposed method.

1. Introduction

Singular systems have the advantage of describing practical systems as its containing of differential equations and algebraic equations which can express the dynamic properties and the interconnection properties of the system, respectively. However, these special characteristics may result in irregularity, impulses and non-causality. Singular systems (also known as descriptor systems and differential-algebraic systems) have extensive applications in areas such as power systems, economical systems, robotic systems, chemical processes, etc [1,2]. Many recent explorations about stability and stabilization problems for singular systems have been given in [3–8]. H_∞ control problems have been discussed for singular Markovian jump systems in [9] with time delay. It should be noticed that time delays are ubiquitous in engineering systems and have bad effects on stabilities of the control systems [10]. Thus, it is necessary but challenging to cope with time delays in our research. Moreover, the discrete and distributed delays were investigated in [11] for networked systems subject to quantization and packet dropout. The finite frequency H_∞ filtering was explored in [12] for time-delayed singularly perturbed systems.

Since the concept of finite-time stability(FTS) had been firstly proposed, the problems of finite-time stability and finite-time boundedness (FTB) are growing in popularity [13,14]. Noting that Lyapunov stability pays more attention to the asymptotic pattern of system trajectories by concerning the steady-state behavior of systems over an infinite time interval [15], which limits the applications in practical. Therefore, we are more interested in what happens in a short interval. For

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instance, the finite-time stabilization problem was considered for discrete-time linear systems in [16] subject to disturbances. The sliding-mode control design problem based on finite-time boundedness had been studied in [17] for nonlinear systems. The robust finite-time H_∞ control problem was discussed for singular stochastic systems via static output feedback in [18]. With transition jump rates partially known, the problem of robust finite-time filtering was explored in [19] for nonlinear Markov jump systems. Consequently, the investigation of the issue is currently meaningful and practical.

Sliding-mode control (also known as variable structure control) is an effective approach for practical engineering system. In the past decade, the efficient control technic has been extensively studied. There are two stages can be used to illustrate the method: First, a sliding surface is designed with some appropriate performance criterion to control the system trajectories. Second, a discontinuous control law is considered such that the system's states are driven to the surface and stay there. Many outstanding achievements have been accomplished by the worldwide researchers [20–23]. Moreover, an augmented sliding-mode observer approach was explored for Markovian jump systems in [24]. The sliding-mode control design method for singular stochastic Markovian jump systems was discussed in [25] with uncertainties exist. For instance, the sliding-mode control problem was considered for discrete-time descriptor Markovian jump systems in [26] with two mutually independent homogeneous Markov chains.

Actually, control systems often suffer from nonlinearities and disturbances. The two impacts are the main reasons that contributing to the system's complexities. Nonlinear disturbance may occur in a probabilistic way which is named as randomly occurring nonlinearities (RONs). The robust H_∞ sliding-mode control problem was concerned for discrete time-delay systems with stochastic nonlinearities in [27]. The reliable finite-time H_∞ filtering problem was explored for discrete time-delay systems with Markovian jump and randomly occurring nonlinearities in [28]. The further results have been extended to robust sliding mode control problem in [29] for a class of uncertain nonlinear stochastic systems with mixed time delays.

Nowadays, due to the increasingly demand of reliability and safety for engineering systems, reliable control problems have attracted closely attentions and been explored by worldwide researchers [30–34], such as fault tolerant control (FTC), fault detection and isolation (FDI). For detail, robust adaptive fault-tolerant control in [35] had been solved for uncertain linear systems through sliding-mode output feedback. The adaptive H_∞ problem was investigated for continuous-time systems with stochastic sensor failures in [36] via a static output feedback (SOF) control technique. Sensor fault estimation and tolerant control problem was concerned for Itô stochastic systems with disturbances in [37] by using a descriptor sliding mode approach. The reliable finite-time control problem for discrete-time singular Markovian jump systems was explored in [38]. It should be noticed that fault-tolerant control also has huge potentiality in aerospace applications and provides the ability to maintain the failure systems acceptable and reliable. It should be worthy mentioned that little attention has been paid to finite-time sliding-mode control for nonlinear singular systems with time-varying delays and sensor failures while the dynamic behaviors were considered in.

Motivated by the above statements, in this paper, the problem of reliable finite-time control for singular time delay systems with sensor faults and randomly occurring nonlinearities is investigated by using the sliding-mode method. Firstly, integral switching function is proposed and sliding-mode control law is designed to make sure the reachability of the sliding surface in a finite time interval. Analysis to the dynamic process contains two aspects: finite-time boundedness on the reaching phase and finite-time boundedness on the sliding motion phase. Next, sufficient criteria are given via Lyapunov–Krasonskii function to guarantee the time-delay system is singular sliding-mode finite-time boundedness. Then, state feedback controller gain and some auxiliary scalars can be obtained by solving corresponding optimization problems and using linear matrix inequalities. The error system with sensor failures is proved to be singular H_∞ finite-time boundedness by employing a fault tolerant control method. Finally, simulation examples are given to illustrate the validity of the proposed approach. The rest of this paper is organized as follows. Section 2 introduces the problem statement and basic definition. The main results are provided in Section 3. Numerical examples are given in Section 4, and Section 5 concludes the paper.

Notation: Throughout this paper, R^m denotes the m dimensional Euclidean space. $\|A\|$ refer to Euclidean vector norm. We denote $|B| = diag\{|b_1|, |b_2|, \dots, |b_n|\}$ for $B = diag\{b_1, b_2, \dots, b_n\}$, $|b_i|$ is the absolute value of b_i. The symbol $*$ is used as an ellipsis for terms induced by symmetry in symmetric block matrices. For simplicity, $sym(C)$ stands for $C + C^T$.

$\underline{\rho}(D)$ denotes the minimum and $\bar{\rho}(D)$ denotes the maximum eigenvalue of the symmetric matrix D respectively. E$\{\cdot\}$ is the expectation operator of a stochastic process.

2. Problem formulation and preliminaries

Consider the following singular time-delay systems with randomly occurring nonlinearities

$$\begin{cases} E\dot{x}(t) = Ax(t) + A_\tau x(t-\tau(t)) + Bu(t) + \alpha(t)G\varphi(x(t),t) + Hd(t) \\ y(t) = C_y x(t) \\ z(t) = Cx(t) + Dd(t) \\ x(t) = \phi(t), t \in [-\tau, 0] \end{cases} \tag{1}$$

where $x(t) \in R^n$ is the system state, $u(t) \in R^p$ is the controlled input, $y(t) \in R^q$ and $z(t) \in R^m$ stand for the system measured output and controlled output, $d(t) \in R^{n_d}$ is the disturbance input, for a given interval $[t_1, t_2]$, it satisfies

$$\int_{t_1}^{t_2} d^{\mathrm{T}}(\varpi)d(\varpi)\mathrm{d}\varpi \le \sigma^2. \tag{2}$$