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Robust $H\infty$ sliding mode observer design for a class of Takagi–Sugeno fuzzy descriptor systems with time-varying delay

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ABSTRACT

This paper focuses on the problem of robust $H\infty$ sliding mode observer (SMO) design for a class of Takagi–Sugeno (T–S) fuzzy descriptor systems with time-varying delay. A SMO is designed by taking the control input and the measured output into account. Then a novel integral-type sliding surface, which involves the SMO gain matrix, is constructed for the error system. By using an appropriate Lyapunov–Krasovskii functional, a delay-dependent sufficient condition is established in terms of linear matrix inequality (LMI), which guarantees the sliding mode dynamic to be robustly admissible with $H\infty$ performance and determines the SMO gain matrix. Moreover, a sliding mode control (SMC) law is synthesized such that the reachability can be ensured. Finally, simulations are presented to show the effectiveness of our results.

1. Introduction

Descriptor system, which can be described by a set of differential and algebraic equations, has been widely studied in the past few decades. It is also referred to as singular system, generalized state-space system, differential-algebraic system or semistate system [1]. Descriptor system describes a wider class of practical system models. It is more general, and it can maintain the physical characteristics of the system better than a standard state-space model. Therefore it has been used in electrical circuits, mechanical systems, moving robots, economics and many other fields which have to be modeled by additional algebraic constraints. However, a distinctive characteristic of descriptor system is the impulse behavior, which is harmful and undesirable. During the past years, a lot of research directions about descriptor system have been studied, such as, stability and stabilization problems [2–5], passive control [6], robust $H\infty$ control [7], sliding mode control (SMC) [8–10] and observer design [11–15], many significant results have been reported in the literature.

The linear system theories can be used to deal with many control problems [16]. For example, the Kalman filter is used to estimate the state of the noise system, the maximum principle can solve some optimal control problems and so on. However, it is well known that most physical systems and processes in the real world are nonlinear and complex [17,18]. For these nonlinear systems, the linear system theories cannot be fully applied. Therefore, a lot of efforts have been devoted to seeking an effective way of controlling nonlinear systems, and there are many results have been reported. Among the

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results, fuzzy control strategies have been developed [19,20]. At first, the analysis and design of fuzzy systems are based on the usual fuzzy model representation, that is, the fuzzy model is described by a set of fuzzy conditional statements (fuzzy language rules). In 1985, Takagi and Sugeno established another fuzzy model (referred to as T–S fuzzy model) [7,13,20,21]. The nonlinear system is regarded as a fuzzy approximation of a lot of local linear systems, and the whole fuzzy model can be obtained by a fuzzy blending of these local models, which can effectively approximate any smoothly nonlinear functions. Thus, based on this alternative model of nonlinear system, the control becomes simpler. In 1999, Taniguchi extended the normal T–S fuzzy model to a more general case and put forward the T–S fuzzy descriptor model. Recently, a wider class of fuzzy systems are described by singular form [3,7–9,11,13,14]. Over the past few years, there have been many applications of T–S fuzzy system theories in various fields. For example, the stability and stabilization problems [3,5], robust control [5,12,19], Observer design [13,14] and sliding mode control [8,9] for T–S fuzzy descriptor systems.

It is well known that time-delay appears in many real world systems, and it is often unavoidable [2–5,19,22–27]. Generally speaking, the dynamic behavior of systems with time-delay is more complicated than that of systems without time-delay. It is often the major source of instability and performance degradation. So far, a large number of results related to time-delay systems have been reported. In fact, there are a lot of nonlinear descriptor systems with time-delay can be described by T–S fuzzy descriptor systems [7–9,12,28]. They are significant both in theory and practice.

In the past decades, SMC has been proven to be an effective robust control scheme for systems with uncertainties, nonlinearities and disturbances. It also has been extensively applied to a wide variety of engineering applications [22,29,30], and we can find a lot of important results. For examples, SMC of stochastic system [10,22], SMC of time-delay system [8,31] and so on. The biggest advantage of SMC scheme is that we can design sliding surface and equivalent control law, and the sliding mode dynamics have complete adaptability to the parameter uncertainties and disturbances. Once in the sliding motion, the state variables will converge to the control objective quickly. Therefore, it provides an effective control way for time-delay systems [8] and uncertain systems [9]. However, it should be noted that, the biggest problem of SMC strategy is the chattering, and it will cause a great impact on control effect. So there are also many results about weakening chattering have been reported.

As we all know, feedback is an important method both in classical control theory and modern control theory. In modern control theory, the system is described by its internal states. So in addition to output feedback, it also has state feedback [32]. In fact, state feedback can solve many complex problems, and it can improve the quality of the system in terms of eigenvalue allocation, system stabilization, decoupling control and no static error tracking. This is because that the state variables contain a lot of informations of the system. However, in most practical situations, state variables are generally not easy to obtain for many reasons, such as the limitation of measurement equipment. One of the ways to overcome this difficulty is to utilize observer to reconstruct the state variables [33,34]. The sliding mode observer (SMO) we study in this paper is based on SMC scheme. In fact, SMO is different from the traditional observer. It has a nonlinear and discontinuous part which depends on the output estimation error, so it has better robustness to uncertainties and disturbances [11,15,35]. The discontinuous part is designed to drive the trajectories of the error system onto the sliding surface such that the sliding motion has desired properties, such as, stability, disturbance rejection capability and tracking ability. So far, a lot of research results related to SMO have been extensively reported, such as, the SMO design for stochastic systems [10], the SMO design for T–S fuzzy systems [11,20], the SMO design for descriptor systems [15], the SMO design for normal systems [36], fault estimation [37–39] and so on. However, it should be noted that, there are few results related to the problem of SMO design for T–S fuzzy descriptor systems. The aim of this paper is to shorten such a gap.

In this paper, we investigate robust $H\infty$ SMO design for a class of T–S fuzzy descriptor systems with time-varying delay. It is necessary to point out the differences between our work and the existing works. Firstly, Refs. [7,12,40] consider the observer-based SMC for nonlinear uncertain singular systems. Secondly, Refs. [13,14,41] consider the observer design for T–S fuzzy descriptor systems. Furthermore, Refs. [11,20,35–38] consider the SMO design for normal systems. As mentioned above, the problem of SMO design for T–S fuzzy descriptor systems has not been fully investigated. Therefore, we are motivated to study this issue. The main contributions of this paper are summarized below.

(1) A SMO is presented by taking the nonlinear part, control input and measured output into account.
(2) A novel integral-type sliding surface, which involves the SMO gain matrix, is constructed for the error system.
(3) A delay-dependent sufficient LMI condition which guarantees the sliding node dynamic to be admissible with $H\infty$ performance is presented.
(4) A new sliding mode controller is synthesized by using our assumptions such that the reachability condition can be guaranteed.

The rest of this paper is organized as follows. Section 2 describes the T–S fuzzy descriptor system. Section 3 is divided into four parts. In Section 3.1, a SMO is designed for the T–S fuzzy descriptor system by taking the nonlinear and discontinuous part, input vector, measured output into account. In Section 3.2, we propose a novel integral-type sliding surface for the error system. In Section 3.3, a delay-dependent sufficient condition is developed to ensure the admissibility of the sliding mode dynamic. In Section 3.4, a SMC law is designed such that the reachability condition can be guaranteed. Simulation examples are given in Section 4 to show the effectiveness of our results. Finally, conclusions are given in Section 5.

Notations: The notations used throughout this paper are standard. For a matrix $X\in\Re^{n\times n}$, X^T, X^{-1} and X^+ denote the transpose, inverse and pseudo-inverse respectively. $\|.\|$ denotes the Euclidean norm of a vector and its induced norm of a matrix. I_n and $0_{m\times n}$ are used to denote the $n\times n$ identity matrix and $m\times n$ zero matrix, respectively. $X>0$ or $(X<0)$ means