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Robust stability and stabilization analysis for discrete-time randomly switched fuzzy systems with known sojourn probabilities

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ABSTRACT

The stability and stabilization analysis problem is considered in this paper for a class of discrete-time switched fuzzy systems with known sojourn probabilities. By using Lyapunov functional, new delay-dependent sufficient conditions are derived to ensure the stability of the system. Convex combination technique is incorporated and the stability criteria are presented in terms of Linear matrix inequalities (LMIs). Furthermore, the developed approach is extended to address the robust stability and stabilization analysis of the delayed discrete-time switched fuzzy systems with randomly occurring uncertainties. Finally numerical examples are exploited to substantiate the theoretical results.
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1. Introduction

Switched system is a hybrid system consisting of a finite number of subsystems, both continuous-time or discrete-time dynamical systems and a switching law which orchestrates the switching between the subsystems. Switched systems have strong engineering background and have drawn considerable research attention in recent years. Some examples for switched systems are automotive highway systems, constrained robotics, power systems and power electronics, air traffic control, transmission and stepper motors [1,2]. Therefore, study on switched systems has both theoretical significance and practical value. The concept of linear switched delay systems was first introduced in [3]. It is interesting to note that the stability for each subsystem cannot imply that of the overall system under arbitrary switching. Another interesting fact is that the stability of a switched system can be achieved by choosing the switching signal even when each subsystem is unstable [4].

Control of nonlinear system is a challenging task since no systematic mathematical tools are available to guarantee the stability of the system. Takagi–Sugeno (T–S) fuzzy approach provides a powerful and systematical control methodology to complex nonlinear systems [5,6]. It combines the flexible fuzzy logic theory and fruitful linear system theory into a unified framework to approximate a wide range of complex nonlinear systems. In most of these applications, the fuzzy systems were thought of as universal approximators for nonlinear systems. A great number of significant results on the analysis and synthesis problems for T–S fuzzy systems have been reported via various approaches in the literature [7–10]. Subsequently, this fuzzy control was successfully applied in many areas such as servo control design [11], industries [12], medicine [13], speed wind turbine [14], energy resource systems [15], etc.

It is well known that time-delay exists in many engineering systems such as networked systems, long distance transportation systems and so on. Such phenomena may result in system instability if it is not handled properly. This

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motivates many scientists to do research on switched systems with time-delay. Results on stability analysis of systems with time-delay have been reported in [16–18], where the exponential stability criteria under average dwell-time switching signals are proposed in [3]. On the other hand, parametric uncertainties which are commonly encountered due to the inaccuracies and changes in the environment of the model might lead to system instability. Therefore, it is important to ensure that the system is stable with respect to uncertainties, and robust stability analysis of switched system has gained much research attention in recent years, see [19,20] and references therein. It has been pointed out that very recently, the concept of randomly occurring uncertainties (ROUs) has been originated by [21] and some efforts have been made towards the study of ROUs [22–24].

A switched linear system is modeled as a Markovian jump system (MJS) where the switching is governed by a Markov process. Packet dropouts and channel communication delays in networked control systems can be modeled by Markov Chains. For switched systems with the random switching signal, the dwell-time in each subsystem consists of two parts: the fixed dwell-time and the random dwell-time. The fixed dwell-time plays a similar role as the dwell-time in deterministic switched systems [25]; the random dwell-time is corresponding to the exponentially distributed sojourn-time in MJSs [26]. In jump linear systems, the sojourn-time is the time duration between the two jumps. The sojourn-time is a random variable following probability distribution in jump linear systems. If it follows exponential distribution, then the transition rate is a constant. This time-invariant property of the transition rate can also be derived from the memory less property of the exponential distribution. It should be noted that in [27], the observer design problem for discrete-time switched systems has been studied with impulses. Moreover in [27,28] the parameter uncertainties are not included and sojourn probabilities are not taken into account in [19]. Besides, in [29,30] stability and stabilization problem has been reported for discrete-time linear switched systems. However, to the best of authors knowledge, the problem of stability and stabilization for discrete-time nonlinear switched systems with known sojourn probabilities has not been fully investigated yet, especially in T–S fuzzy frame work with ROUs, while research in this area is clearly very important from both theoretic and practical points of view, which motivates the present study.

In this paper, we aim to establish the asymptotic stability and stabilization conditions for a class of discrete-time randomly switched fuzzy systems with known sojourn probabilities and randomly occurring uncertainties. Choosing appropriate Lyapunov–Krasovskii functionals and utilizing some most updated techniques for achieving the refined delay-dependence, novel conditions are established in terms of LMIs. The feasibility of derived criteria can be easily checked by resorting to Matlab LMI Toolbox. Finally, numerical examples are included to illustrate the applicability of the proposed results.

This paper is organized as follows. Problem formulation and preliminaries are given in Section 2. Section 3 gives the sufficient stability conditions for the discrete-time switched fuzzy systems and the robust stability conditions for switched fuzzy systems with ROUs are presented in Section 4. Numerical examples are demonstrated in Section 5 to illustrate the effectiveness of the proposed method. Finally, conclusions are drawn in Section 6.

Notations: Throughout this paper, $\mathbb{R}^n$ and $\mathbb{R}^{n\times n}$ denote the n-dimensional Euclidean space and the set of all $n \times n$ real matrices, respectively. The superscript T and (-1) denote the matrix transposition and matrix inverse, respectively. Matrices, if they are not explicitly stated, are assumed to have compatible dimensions. $\|\cdot\|$ is the Euclidean norm in $\mathbb{R}^n$. I is an identity matrix with appropriate dimension.

2. Problem description and preliminaries

Consider the following nonlinear discrete-time switched system with time-varying delays

$$\begin{cases} x(k+1) = f_{\sigma(k)}(x(k), x(k-\tau_{\sigma(k)}(k)), u(k)), \\ x(s) = \phi(s), \quad \forall\, s = -\tau^M, -\tau^M+1, \dots, 0 \end{cases} \tag{1}$$

where $x(k) \in \mathbb{R}^n$ is the state vector, $u(k) \in \mathbb{R}^m$ is the control input, $f_{\sigma(k)}(\cdot) : \mathbb{R}^n \longrightarrow \mathbb{R}^n$ is continuous and satisfies $f_{\sigma(k)}(0) = 0$. $\sigma(k) : [0, +\infty) \to \mathbb{S} = \{1, 2, \dots, N\}$ denotes the switching sequence independent of the state. Let $\sigma(k) = \upsilon$, $\tau_\upsilon(k)$ is the time-varying delay satisfying $\tau_\upsilon^m \le \tau_\upsilon(k) \le \tau_\upsilon^M$, where $\tau_\upsilon^m,\ \tau_\upsilon^M$ are known positive integers representing the lower and upper bounds of $\tau_\upsilon(k)$ for the υth subsystem. $\phi(s)$ is the initial condition and $\tau^M = \max\{\tau_\upsilon^M,\ \upsilon \in \mathbb{S}\}$.

Using T–S fuzzy model the ith rule of the υth subsystem of the nonlinear system (1) is described as follows:

Plant Rule $R^i_{\sigma(k)}$: IF $\theta_1(k)$ is $\eta^i_{\sigma(k)1}$, and $\cdots$ and $\theta_q(k)$ is $\eta^i_{\sigma(k)q}$, THEN

$$\begin{cases} x(k+1) = A_{\sigma(k)i}x(k) + A_{d\sigma(k)i}x(k-\tau_{\sigma(k)}(k)) + B_{\sigma(k)i}u(k), \\ x(s) = \phi(s), \quad \forall\, s = -\tau^M, -\tau^M+1, \dots, 0 \end{cases} \tag{2}$$

where $\theta_p(k),\ p = 1, 2, \dots, q$ are the premise variables, $\eta^i_{\sigma(k)j}$ are fuzzy sets and $i = 1, 2, \dots, r_{\sigma(k)}$, $r_{\sigma(k)}$ is the number of inference rules in the σth switched subsystem. $A_{\sigma(k)i},\ A_{d\sigma(k)i}$, and $B_{\sigma(k)i}$ are known constant matrices of appropriate dimensions of the σth switched subsystem. Then, the global model of the fuzzy switched system (2) is given by

$$x(k+1) = \sum_{i=1}^{r_\upsilon} h_{\upsilon i}(\theta(k))\{A_{\upsilon i}x(k) + A_{d\upsilon i}x(k-\tau_\upsilon(k)) + B_{\upsilon i}u(k)\}, \quad \upsilon \in \mathbb{S}, \tag{3}$$

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