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M-matrix based robust stability and stabilization for uncertain discrete-time switched TS fuzzy systems with time-varying delays

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ABSTRACT

This paper provides novel sufficient conditions on robust asymptotic stability and stabilization for a class of uncertain discrete-time switched fuzzy with time-varying delays. The attention is focused on developing new algebraic criteria to break with classical criteria in terms of Linear Matrix Inequalities (LMIs). Firstly, based on the *M*-matrix proprieties and through $l_{1,\infty}$ induced norms notion, new delay-dependent sufficient conditions are derived to ensure the asymptotic stability and stabilization for a class of uncertain discrete-time switched fuzzy systems with time-varying delay. Secondly, these results are extended for a class of uncertain discrete-time switched fuzzy systems with time delays, modeled by difference equations. Finally, two numerical examples and practical example (a robot arm) are provided to demonstrate the advantage and the effectiveness of our results.

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1. Introduction

Switched systems are an important class of hybrid systems [1–9]. Such systems can be described by a family of discrete-time subsystems (or continuous-time subsystems) and a rule that orchestrates the switching between them; this class of systems has numerous applications aircraft and air traffic control, in the control of mechanical systems, switching power converters, the automotive industry and many other fields [10,11]. Since the introduction of T–S fuzzy models by Takagi and Sugeno [12] in 1985, a great number of industrial applications via fuzzy logic control have been reported such as [13,14], because T–S fuzzy models provide an effective representation of complex nonlinear systems [15,16].

As well known, when the subsystems are in complex nonlinear forms and due to the switching behavior among the subsystems, the so-called switched nonlinear system shows great difficulties in control systems analysis and controller design. As for controller design problem of such complex switched nonlinear systems, by adopting the T–S fuzzy model which is an alternative method to conventional control approach for complex control systems, each nonlinear subsystem can be first approximated by a T–S model which can be called fuzzy subsystem [14]. Together with the switching among these fuzzy subsystems, the overall system is the switched fuzzy system. This switched fuzzy system provides us a practical way to solve control synthesis and analysis problem for complex switched nonlinear systems (for details see [17,18], and the references cited therein). On the other hand, real systems with time delays are common in mechanics, biology, communication networks and so on [19,20]. Moreover, time-varying delay is more important and universal in real engineering processes and has more complex impacts on system dynamics than constant delay. Since time delay is a main factor of instability and deteriorated performance degradation of time-delay systems, the problem of stability analysis of time-delay systems has been one of the main concerns of researchers wishing to inspect the properties of such systems [21,22]. Furthermore, due to modeling error or external disturbance, many practical systems are always subject to various kinds of uncertainties. One of the most important requirements for a control system is the so-called robustness [23]. In fact, the switched fuzzy systems with time-varying delay are subject to extra uncertainties due to approximation error in the case of nonlinear systems approximation and switching law.

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Up to now, the main approach for stability analysis of systems with time delays is based on Lyapunov–Krasovskii Functionals (LKF) approach and formulated in the form of Linear Matrix Inequalities (LMIs). Although, in the literature, many important works have been obtained for switched linear discrete-time systems with time-varying delays [24–26], there are few results concerning the stability of switched fuzzy discrete systems with time-varying delays. It should be noted that in [27], Mathiyalagan et al. derived a set of delay-dependent sufficient condition in terms of LMIs for robust exponential stability of discrete-time switched fuzzy neural networks with time delays. Moreover in [28], sufficient conditions are derived to ensure the robust stability and stabilization for discrete-time randomly switched fuzzy systems with known sojourn probabilities, presented in the terms of linear matrix inequalities (LMIs). Unfortunately due to the problem of computations complexity over LMIs constraints, we are required to seek other conditions that guarantee the robust asymptotic stability and stabilization for discrete-time switched fuzzy systems with time-varying delays. However, to the best of our knowledge, the problem of robust stability and stabilization for discrete time switched fuzzy systems with time-varying delays, using algebraic criteria through $l_{1,\infty}$ induced norms instead of linear matrix inequalities (LMIs), has not been fully investigated yet, which motivates us for this study.

In this paper, we aim to establish the asymptotic stability and stabilization sufficient conditions for a class of uncertain discrete-time switched fuzzy systems with time-varying delays. Indeed, by constructing a new piecewise Lyapunov functional, as well by using the M-matrix properties [5–29] and through $l_{1,\infty}$ induced norms notion, new delay-dependent sufficient conditions are derived to ensure the asymptotic stability and stabilization conditions for a class of uncertain discrete-time switched fuzzy systems with time-varying delay. Secondly, these results are extended for a class of discrete-time switched fuzzy systems with time delays, modeled by difference equations. Finally, numerical examples are included to illustrate the effectiveness of the proposed results.

Note that the main contribution in this work is twofold: first, this proposed method is focused on developing new algebraic criteria to break with classical criteria in terms of Linear matrix inequalities (LMIs). Second, it is very simple and, from a theoretical point of view, efficient.

The remainder of this paper is organized as follows. Problem formulation is addressed in Section 2. Preliminary results are presented in Section 3, whereas Section 4 presents main results. In Section 5, three numerical examples are provided to demonstrate effectiveness of our results. Finally, conclusions are given in Section 6.

Notations: Throughout this paper, let $\mathbb{R}$ be the set of real numbers; $\mathbb{R}^n$ denotes the n-column real vectors; $\mathbb{R}^{n\times m}$ is the set of all real matrices of dimension $n\times m$; $\mathbb{R}^n_+$ is the nonnegative orthants of $\mathbb{R}^n$; the symbol $\rho(A)$ denotes the spectral radius of matrix A; the superscript "T" denotes matrix transpose. We define the scalar product of the vectors u and v as $\langle u,v\rangle=\sum_{i=1}^n u_iv_i$. I_n is an identity matrix with dimension $n\times n$.

2. Problem formulation

Consider the following nonlinear discrete-time switched system:

$$\begin{aligned}&x(k+1)=f_{\sigma(k)}(x(k),x(k-\tau(k)),u(k)),\\&x(k)=\phi(k),\quad k\in\{-\tau_M,-\tau_M+1,\ldots,-1,0\}\end{aligned}\tag{1}$$

where $x(k)\in\mathbb{R}^n$ is the state vector, $u(k)\in\mathbb{R}^m$ is the control input, $\phi(k)\in\mathbb{R}^n$ is an initial state function, and $\tau(k)$ is the time-varying delay satisfying $\tau_m\le\tau(k)\le\tau_M$, where τ_m and τ_M are known positive integers representing the lower and upper bounds of $\tau(k)$ respectively. Define a set $\mathcal{P}=\{1,2,\ldots,N\}$, where N is the number of subsystems, $\sigma(k):\mathbb{R}^n\to\mathcal{P}$ is a piecewise constant function of the state called switching signal, as in [24], we assume that the switching signal $\sigma(k)$ is unknown a priori, but its instantaneous value is available in real time.

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

Plant Rule R_r^p: IF $z_1(k)$ is $M_{r1}{}^p$ and … and $z_Q(k)$ is M_{rQ}^p THEN

$$\begin{aligned}&x(k+1)=A_{pr}(k)x(k)+D_{pr}(k)x(k-\tau(k))+B_{pr}u(k)\\&x(k)=\phi(k),\quad k\in\{-\tau_M,..,-1,0\}\end{aligned}\tag{2}$$

where $M_{rq}{}^p$ is fuzzy sets and $z_q(k)$, for $q=1,\ldots,Q$, are the premise variables. The overall fuzzy subsystem $\sigma(k)=p$ is obtained by fuzzy blending r_p-rules as follows:

$$x(k+1)=\sum_{r=1}^{r_p}h_{pr}(z(k))\big(A_{pr}(k)x(k)+D_{pr}(k)x(k-\tau(k))+B_{pr}u(k)\big)\tag{3}$$

where $A_{pr}(k)\in\mathbb{R}^{n\times n}$, $D_{pr}(k)\in\mathbb{R}^{n\times n}$ and $B_{pr}\in\mathbb{R}^{n\times m}$ are real matrices of the local models with appropriate dimensions. r_p is the number of model rules of the subsystem p and

$$\begin{aligned}&h_{pr}(z(k))\ge 0,\quad \sum_{r=1}^{r_p}h_{pr}(z(k))=1\\&r\in\mathcal{R}_p=\{1,\ldots,r_p\}\end{aligned}\tag{4}$$

where

$$h_{pr}(z(k))=\frac{\beta_{pr}(z(k))}{\sum_{r=1}^{r_p}\beta_{pr}(z(k))},\quad \beta_{pr}(z(k))=\prod_{q=1}^{Q}M_{rq}^p(z_q(k))\tag{5}$$

Assume that all subsystems are uncertain systems of polytopic type described as follows:

$$A_{pr}(k)=\sum_{i=1}^{N_{pr}}\mu_{pr}^i(k)A_{pr,i}\tag{6}$$

$$D_{pr}(k)=\sum_{i=1}^{N_{pr}}\nu_{pr}^i(k)D_{pr,i}\tag{7}$$

where $A_{pr,i}$ and $D_{pr,i}$, $i\in\mathcal{I}_{pr}=\{1,\ldots,N_{pr}\}$, are respectively the matrices denoting the extreme points of the polytope A_{pr} and D_{pr}, $p\in\mathcal{P}$, $r\in\mathcal{R}_p$ is the number of the vertex matrices $A_{pr,i}$, $D_{pr,i}$ and the weighting factors $\mu_{pr}^i(k)$, $\nu_{pr}^i(k)$, $i\in\mathcal{I}_{pr}$, are unknown polytopic uncertain parameters for each $p\in\mathcal{P}$, $r\in\mathcal{R}_p$ belong to $\mu_{pr}(k):\sum_{l=1}^{N_{pr}}\mu_{pr}^i(k)=1$, $\mu_{pr}^i(k)\ge 0$ and $\nu_{pr}(k):\sum_{i=1}^{N_{pr}}\nu_{pr}^i(k)=1$, $\nu_{pr}^i(k)\ge 0$.

Define the following functions $\xi_p(k)$, $\forall p\in\mathcal{P}$ that will be used to represent our system [5]:

$$\xi_p(k)=\begin{cases}1 & \text{if } \sigma(k)=p\\ 0 & \text{otherwise,}\end{cases}\tag{8}$$

Based on (3)–(8), the switched fuzzy system (1) can be rewritten as follows:

$$x(k+1)=\sum_{p=1}^{N}\sum_{r=1}^{r_p}\xi_p(k)h_{pr}(z(k))\big(A_{pr}(k)x(k)+D_{pr}(k)x(k-\tau(k))+B_{pr}u(k)\big)\tag{9}$$

where $\xi_p(k)$ is defined in (8) and $\sum_{p=1}^{N}\xi_p(k)=1$, $\forall k\in\mathbb{N}$, which guarantees that there is only one active subsystem at any time.

3. Preliminary results

Now, the following definitions and lemmas are preliminarily presented for later development.

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