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A sojourn probability approach to fuzzy-model-based reliable control for switched systems with mode-dependent time-varying delays☆

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ABSTRACT

This paper addresses reliable control design for a switched system (SS) described by T-S fuzzy model subject to actuator failures and mode-dependent time-varying delay. A different type of switching law is introduced with the aid of sojourn probabilities (SPs) technique. The sojourn probability depicts the probability of a switched system staying in subsystem. It should be pointed out that, the SPs describe the probabilities of SSs stay in each subsystems which is easily measured. Both completely known and partly unknown SPs are proposed for the T-S fuzzy SSs. By using a matrix inequality approach and by constructing a proper Lyapunov–Krasovskii functional, less conservatism sufficient conditions are achieved in the form of linear matrix inequalities. A single link robot arm system is given to illustrate the validity of proposed design procedure.

1. Introduction

Many researchers have been interested in SSs, which are characterized as succession evolutions of elemental driving systems and can be efficiently used to model range of physical systems. It is well known that, an SS contains a family of continuous or discrete time subsystems and a switching signal orchestrating the switching among the subsystems. Over the past decades, stability analysis and controller synthesis for SSs have been widely investigated and significant achievements have been obtained, such as network congestion control, communication industries and robot control system [1–3], thus many results on stability and control design of SSs have reported [4–8]. Note that the set may vary which consists of switching signals, and obtained results are dependent on the switching signals [9–13].

SSs can be modeled as different systems because of its different switching rules, such as dwell-time switching, arbitrary switching and Markov process switching [14–16]. Taking Markovian jump systems (MJSs) as example, the switching in MJS is determined by Markov process, which has attracted much attention due to the widespread use of its applications [17–25]. Note that the switching law can be described as a class of piecewise constant map, which constant of random dwell time (RDT) and fixed dwell time (FDT). The RDT is called the exponentially distributed sojourn-time (EDST) and FDT is similar to DT in deterministic SSs. It should be noted that the existing literature are mainly about the completely known

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information of switching [18,26–28]. However, the transition probabilities are crucial in MJSs and it is very difficult to obtain the precisely information of switching [24,25,29–31], it is of interest to consider the SSs with switching rules which are easily measured. Thanks to [3,31], the SPs method is first proposed, which can be easily achieved with the information of the history subsystems. On the other hand, there always exist actuator failures in the SSs. In the case of existence of some nonlinearity sources in the model due to actuator models [17]. Thus, the traditional controller becomes conservative and may destroy the system performance if failure appears. The reliable control for SSs with actuator failures are not fully developed in recent years except for [32–34]. Summarizing the discussions made so far, it is necessary to study the SSs which can tolerate faults of actuators.

As is well known, the applications of SSs are the phenomenon of nonlinear in essence, for example, networked control. Therefore, the nonlinear control can be represented by the T-S fuzzy model, that is, a combination of linear time-invariant systems connected by IF–THEN rules [15,20]. It is reasonable to apply the T-S model to represent nonlinear systems with the aid of a few simple linear systems. Nowadays, rapidly growing attention has been shifted to stability analysis and controller synthesis for T-S fuzzy systems, and many achievements have been reported [35–37]. Furthermore, the unmeasurable premise variables can be involved in the T-S fuzzy systems [38]. However, up to now, there are very few results dealing with reliable control for T-S fuzzy SSs, there is a practical need to study in this issue.

Motivated by the above discussion, in this paper, as a first attempt, we address the issues of reliable control for T-S fuzzy SSs with mode-dependent time-varying delays subject to actuator failures. A different type of switching law is introduced with the aid of SPs technique. The SPs describe the probabilities of SSs stay in each subsystems which is easily measured. Both completely known and partly unknown SPs are proposed for the T-S fuzzy SSs. Less conservatism sufficient conditions are achieved with the tighter bounds for the derivative of Lyapunov–Krasovskii functional, which can be verified by the MATLAB toolbox. At last, numerical simulation is provided to demonstrate the effectiveness of the proposed theory.

2. Preliminaries

Consider a class of nonlinear discrete-time switched system with mode-dependent time-varying delays which described by the following T-S fuzzy model:

Plant Rule i:

IF ξ_1 is M_{i1} and $\cdots$ and ξ_p is M_{ip}

THEN

$$\begin{cases} x(k+1) = A_{1i,r_k}x(k) + B_{1i,r_k}x(k-\tau_{r_k}(k)) + C_{1i,r_k}u(k) + D_{1i,r_k}\omega(k) \\ z(k) = A_{2i,r_k}x(k) + B_{2i,r_k}x(k-\tau_{r_k}(k)) + D_{2i,r_k}\omega(k) \\ x(k) = \phi(k),\, k = \{-\tau_2, -\tau_2+1, \ldots, 0\} \end{cases} \quad (1)$$

where $x(t) \in \mathbb{R}^{n_x}$ represents the state vector; $u(t) \in \mathbb{R}^{n_u}$ is the control input vector; $\omega(k) \in \mathcal{R}^{n_\omega}$ is the external disturbance signal which belongs to $l_2[0,\infty)$, $z(k) \in \mathcal{R}^{n_z}$ is the controlled output vector, and $\phi(k)$ describes the initial condition sequence and $\tau_2 = \max\{\tau_{2s}, s \in \mathcal{N}\}$. When $r_k = s$, the matrices $(A_{2i,s}, A_{2i,s}, B_{1i,s}, B_{2i,s}, C_{1i,s}, D_{1i,s}, D_{2i,s})$ denote the sth subsystem, are known real constant matrices with compatible dimensions. $r_k : [0, +\infty) \rightarrow \mathcal{N} = \{1, 2, \ldots, N\}$ denotes the switching sequence which is independent of the state.

Let $r_k = s$, $\tau_s(k)$ is the mode-dependent discrete time delays and satisfying

$$\tau_{1s} \le \tau_s(k) \le \tau_{2s}$$

where τ_{1s} and τ_{2s} are constant positive scalars denoting the lower and upper bounds of $\tau_s(k)$ in mode sth subsystem, respectively. The fuzzy sets and premise variables are defined as ξ_j and M_{ij} $(i = 1, 2, \ldots, q, j = 1, 2, \ldots, p)$, the scalar q indicates the number of IF–THEN rules. The fuzzy basis functions are given by

$$h_i(\xi(t)) = \frac{\prod_{j=1}^{p} \mu_{ij}(\xi_j(t))}{\sum_{i=1}^{q} \prod_{j=1}^{p} \mu_{ij}(\xi_j(t))},$$

in which $\mu_{ij}(\xi_j(t))$ denotes the grade of membership of $\xi_j(t)$ in μ_{ij}. It follows from the theory of fuzzy sets, one has $\sum_{i=1}^{q} h_i(\xi(t)) = 1$ with $h_i(\xi(t)) > 0$.

By fuzzy blending, the system is inferred as follows:

$$\begin{cases} x(k+1) = \sum_{i=1}^{q} h_i(\xi(k)) \left[A_{1i,s}x(k) + B_{1i,s}x(k-\tau_s(k)) + C_{1i,s}u(k) + D_{1i,s}\omega(k)\right] \\ z(k) = \sum_{i=1}^{q} h_i(\xi(k)) \left[A_{2i,s}x(k) + B_{2i,s}x(k-\tau_s(k)) + D_{2i,s}\omega(k)\right]. \end{cases} \quad (2)$$

It is noted that actuator always experiences failures in the real application, and $u^F(t)$ is utilized to represent the control signal which comes from actuator. Throughout the paper, we consider a more general actuator failure model:

$$u^F(t) = \alpha_s u(t) \quad (3)$$