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Robust reliable passive control of uncertain stochastic switched time-delay systems

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ABSTRACT

This paper investigates the problem of robust reliable passive control for a class of uncertain stochastic switched time-delay systems with actuator failures. The multiple Lyapunov functions (MLFs) technique is exploited to derive a delay-dependent sufficient condition for the stochastic switched time-delay systems to be passive and exponentially stable under a state-based switching law. Moreover, the proposed approach is extended to investigate stochastic switched systems with structured uncertainties. Finally, two numerical examples are presented to illustrate the effectiveness of the proposed method.

1. Introduction

Switched systems are often encountered in many modern systems and engineering technologies, such as automotive engine control systems, chemical process, power systems and power electronics, robot manufacture and so on (see [1–4]). Besides, switching strategy based on controllers often bring better system properties and operating performance (see [5,6]). Therefore switched systems have gained extensive attention from several scientists in the last decade (see [7–12]). A variety of methods have been used to study switched systems. The multiple Lyapunov functions (MLFs) approach which is aimed at the stability problem under some designed switching laws has been shown to be an effective tool (see [9]). On the basis of the stability study, considering the uncertainty of system parameters, actuator failure, the influence of external disturbances on the system performance and other factors, many scholars have deeply researched on robust control, reliable control, filter design, H_∞ performance analysis, see for instance the references [13–17] and the references therein. In addition, many engineering systems always involve time-delay phenomenon, which is frequently a source of instability of systems. Therefore many valuable results have been obtained for switched systems with time-delay (see [18,19]). Recently, there have been some results on stability analysis and stabilization for stochastic switched systems (see [20–22]).

Passivity, as a particular case of dissipativity, is described by the storage function and the supply rate in terms of the input and output of systems. Over the past years, passivity has attracted much attention in analysis and controller design of linear or nonlinear systems (see [23–26]). From the perspective of the supply of energy, the application of passivity presents a new method to analysis the stability, and the storage function of passive systems can be used as a Lyapunov function candidate of complex systems. Therefore, the method of passive analysis can be utilized to investigate the stability of switched systems (see [27–30]). On the other hand, due to the growing demands of system reliability in aerospace and industrial process, the study of reliable control which can guarantee the system stability and other properties has drawn considerable attention (see [31–33]). Recently, the reliable design methods have been extended to research stochastic systems (see [34–36]) and switched systems (see [36–39]). In particular, the reliable H_∞ control problem for nonlinear switched systems with actuator

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failures was solved by using the MLFs approach in [36]. In [37], the reliable control for continuous linear switched systems with sensor failures was studied by using the dwell time approach. Reliable stabilization and H_∞ control for Lipschitz nonlinear switched systems in the presence of faulty actuators were discussed in [39]. However, to the best of the authors' knowledge, few results have been reported on robust reliable passive control for uncertain stochastic switched time-delay systems.

In this paper, we introduce a switching strategy to solve the robust reliable passive control problem for uncertain stochastic switched time-delay systems. Based on the MLFs, a delay-dependent condition for stochastic switched time-delay systems to be passive and exponentially stable is proposed in terms of LMIs. Then, a solvability condition for the passification is developed. By solving the LMIs, a reliable controller and a state-based switching law are obtained.

The remainder of the paper is organized as follows. The robust reliable passive control problem for a class of stochastic switched time-delay systems is formulated in Section 2. In Section 3, the main results are presented. Section 4 gives two numerical examples to illustrate the effectiveness of the proposed approach. Finally, conclusions are provided in Section 5.

Notation: The notations throughout this paper are quite standard. R^n denotes the n-dimensional Euclidean space. A^T and A^{-1} denote, respectively, the transpose and the inverse of any square matrix A. The notation $A>0$ means the matrix is positive definite and symmetric. I is an identity matrix with an appropriate dimension. $\|\cdot\|$ refers to the Euclidean norm. The symmetric term in a matrix is denoted by '$*$'. $\mathbb{E}\{\cdot\}$ is the expectation operator. $diag\{\cdot\}$ denotes a block diagonal matrix. $\lambda_{\max}(P)$ and $\lambda_{\min}(P)$ denote the maximum and minimum eigenvalues of matrix P, respectively. $L_2[t_0,\infty)$ is the space of square integrable functions on $[t_0,\infty)$. $C_{n,\tau}$ denotes the set of all R^n-valued continuous functions defined on the interval $[-\tau,0)$. $\|\varphi\|_c=\sup_{-\tau\leqslant t\leqslant 0}\|\varphi\|$ stands for the norm of a function $\varphi\in C_{n,\tau}$.

2. Problem formulation and preliminaries

Consider a stochastic switched system with time-varying delay as follows:

$$\begin{cases} dx(t)=[\hat{A}_{\sigma(t)}x(t)+\hat{A}_{d\sigma(t)}x(t-d(t))+B_{\sigma(t)}u^f(t)+B_{v\sigma(t)}v(t)]dt \\ \qquad\quad +[\hat{S}_{\sigma(t)}x(t)+\hat{S}_{d\sigma(t)}x(t-d(t))+G_{\sigma(t)}u^f(t)]dw(t), \\ z(t)=C_{\sigma(t)}x(t)+C_{d\sigma(t)}x(t-d(t))+D_{v\sigma(t)}v(t), \\ x(t_0+\theta)=\varphi(\theta),\quad \theta\in[-\tau,0], \end{cases} \tag{1}$$

where $x(t)\in R^n$ is the state vector, $u^f(t)\in R^m$ is the control input of actuator fault, $z(t)\in R^q$ is the output vector, $\varphi(\theta)\in C_{n,\tau}$ represents the initial state function, $v(t)\in R^p$ is the disturbance input which belongs to $L_2[t_0,\infty), w(t)$ is a zero-mean Wiener process on a probability space $(\Omega, \mathrm{F}, \mathrm{P})$, where Ω is the sample space, F is σ-algebras of subsets of the sample space and P is the probability measure on F. $\sigma(t)\in[t_0,\infty)\to \underline{N}=\{1,2,\ldots,N\}$ is the switching law with deterministic, piecewise constant and right continuous. The switching law $\sigma(t)$ discussed in this paper is state-dependent. Moreover $\sigma(t)=i$ means that the ith subsystem is active. For $\forall i\in\underline{N},\ B_i, B_{vi},\ G_i,\ C_i,\ C_{di}$ and D_i are real-valued matrices with appropriate dimensions, $\hat{A}_i,\ \hat{A}_{di}, \hat{S}_i$ and $\hat{S}_{di}$ are uncertain real-valued matrices with appropriate dimensions, which are assumed to have the following form

$$\hat{A}_i=A_i+M_iF_i(t)N_{1i},\quad \hat{A}_{di}=A_{di}+M_iF_i(t)N_{2i},\quad \hat{S}_i=S_i+M_iF_i(t)N_{3i},\quad \hat{S}_{di}=S_{di}+M_iF_i(t)N_{4i}, \tag{2}$$

where $A_i,\ A_{di},\ S_i,\ S_{di},\ M_i,\ N_{1i},\ N_{2i},\ N_{3i}$ and N_{4i} are known real constant matrices with proper dimensions, and $F_i(t)$ is an unknown time-varying matrix which satisfies

$$F_i^T(t)F_i(t)\leqslant I. \tag{3}$$

Moreover, $d(t)$ is the time-varying delay satisfying

$$0\leqslant d(t)\leqslant \tau,\quad 0\leqslant \dot{d}(t)\leqslant \mu<\infty, \tag{4}$$

where τ and μ are known constants.

When the uncertainties are ignored, system (1) can be represented as

$$\begin{cases} dx(t)=\left[A_{\sigma(t)}x(t)+A_{d\sigma(t)}x(t-d(t))+B_{\sigma(t)}u^f(t)+B_{v\sigma(t)}v(t)\right]dt \\ \qquad\quad +\left[S_{\sigma(t)}x(t)+S_{d\sigma(t)}x(t-d(t))+G_{\sigma(t)}u^f(t)\right]dw(t), \\ z(t)=C_{\sigma(t)}x(t)+C_{d\sigma(t)}x(t-d(t))+D_{v\sigma(t)}v(t), \\ x(t_0+\theta)=\varphi(\theta),\quad \theta\in[-\tau,0]. \end{cases} \tag{5}$$

The control input of actuator fault $u^f(t)$ can be described as

$$u^f(t)=H_{\sigma(t)}u(t), \tag{6}$$

where $u(t)=K_{\sigma(t)}x(t)$ is the switching controller which will be designed, $H_i\ (i\in\underline{N})$ are the actuator fault matrices of the following form

$$H_i=diag\{h_{i1},h_{i2},\ldots,h_{im}\}, \tag{7}$$