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Fault-tolerant control of switched nonlinear systems with strong structural uncertainties: Average dwell-time method

Ying Jin [a,*], Youmin Zhang [b], Yuanwei Jing [c]

[a] The State Key Laboratory of Synthetical Automation for Process Industries, Northeastern University, Shenyang 110819, China
[b] The Department of Mechanical and Industrial Engineering, Concordia University, Montreal, QC, Canada H3G 1M8
[c] College of Information Science and Engineering, Northeastern University, Shenyang 110819, China

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ABSTRACT

This paper studies a robust fault tolerant control of a class of nonlinear switched systems with strong structural uncertainties and actuator faults. This paper presents a new robust fault tolerant state feedback method, by using the average dwell time technique to stabilize the switched nonlinear systems exponentially under an arbitrary switching law. Comparing with the existing results, the method of this paper has three features: (1) this method is applicable to the switched nonlinear systems with strong structural uncertainties and faulty actuators and also the nominal case of the considered systems, there is no need to change any structures and/or parameters of the controller. (2) The switching law is arbitrary provided that the average switching is slow enough in the average sense. (3) This method treats all actuators in the same way, no need to separate faulty actuators from the healthy ones. The simulation result verifies the effectiveness of this method.

1. Introduction

Uncertainties are unavoidable in real applications. If the uncertainties are ignored during designing controllers then that may cause the closed-loop systems unstable. Uncertainties can be roughly classified into two categories: parameter uncertainties and structural uncertainties. For the parameter uncertainties, the way to compensate is to design adaptive estimator. For the structural uncertainties, designing robust controller is to stabilize the system with bounded uncertainties [29].

Switched systems are an important class of hybrid systems [27]. When uncertainties exist in switched systems, the methods which address the nominal switched systems degrade the system performance or even destabilize the systems. Therefore, robust control of switched systems has received more and more attention [30,11,17,24,4,12,9,26,27]. But most of the existing results are designed for switched linear systems and their applications [30,29,24]. Since the nonlinearities are an inherent nature of hybrid dynamic systems, robust control of switched nonlinear systems has been one of important research areas in control community.

Undoubtedly, stability is an important and key precondition for systems to work normally, thus the stability of switched systems has become a center task on control of switched nonlinear systems. Due to the structural complexity of the switched nonlinear systems, the existing results on stability of switched nonlinear systems are not fruitful, see Ref. [11,19,15,2,7,13,28,23]. The research mainly focuses on switched nonlinear systems with special structures [11,7,13,28,23,5,31]. Therefore, the stability of switched nonlinear systems with special structures is still a core research area since many industrial process systems can be modeled as switched nonlinear systems with special structures [22].

On the other hand, integrated automation of industrial processes has reached a new stage, the maintenances and repairs of faults cannot be achieved immediately, which affect system safety and feasibility. Taking the possibilities of occurrences of uncertainties and faults into account during systems analysis and controller designs to avoid huge economic costs and even life threaten safety caused by faults is very important [24,3,16,25,8,26]. With the fast development of modern software and computing techniques, proposing method by designing algorithm to achieve fault tolerant control can save more economic costs and provide more design freedom than replacing hardware. Thus, it is important to apply fault tolerant control to industrial process control [18,21,10,6]. Ref. [18] considered a class of interconnected nonlinear systems consisting of a limited subsystems by designing decentralized fault tolerant controller to realize tracking objective and guarantee the stability of the closed-loop systems, but ignored the fault models of actuators during the input control signal transmitting to actuators [18]. The common feature in Refs.

* Correstponding author.
E-mail address: jymontreal@gmail.com (Y. Jin).

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[21,10,6] is that actuators need to be classified that which part of actuators are faulty and which ones are robust to faults in advance during designing fault-tolerant controllers. Generally, it is hard to obtain the information about the two-part separation of actuators mentioned above in advance during implementing controllers practically.

As shown above the analysis of robust stabilization on switched systems and fault tolerant control, and many practical systems modeled as hybrid dynamic systems, fault-tolerant control of switched nonlinear systems is one of the important research areas [3,20]. The available results combing switched systems and traditional fault tolerant method are limited [24,1,20,14]. Ref. [24] adopted the proposed method from [21] to deal with actuator faults under given conditions with stability of a class of cascade switched nonlinear systems, but this paper did not consider strong uncertainties in input matrices. Du and Mhaskar [4] combined safe-parking and reconfiguration method to address a class of switched nonlinear systems which introduced two switching strategies to achieve actuator fault-tolerant control. Both strategies need to determine the reparation times once actuator fault occurs, it is usually difficult to acquire practically. Ref. [20] studied a class of switched nonlinear systems with external disturbance and designed an observer-based fault tolerant controller. From a system structure view, the nonlinear item is connected to system in a parallel way to get compensation directly by control signals. Nonlinear subsystem cascaded to another system improve the complexity of cascaded switched nonlinear systems with fault tolerant control.

In the past two decades, average dwell time technique is one of popular methods to stabilize switched systems [8,1]. The so-called average dwell time means that the number of switchings is bounded in a finite time interval, and average dwell time between continuous switching intervals is not less than an positive constant [27,8]. Many important results of using average dwell time technique on applications are available [27,1,20,25,14,9,26], the existing results on applying average dwell time method to deal with fault tolerant control of switched systems are only a few. Refs. [27,1,20,9,26] consider fault tolerant control of switched linear system, Yang et al. [25] presented fault tolerant control of switched nonlinear systems by using average dwell-time technique, where the nonlinear subsystem is cascaded to another system in a parallel way to obtain compensation directly by control signals. Ma and Yang [14] proposed adaptive-based fault tolerant control of a class of uncertain switched nonlinear systems with actuator faults, it adopted the way in Yang et al. [25] to address unmodeled dynamic systems. This paper develops a robust fault tolerant controller by using average dwell time technique to stabilize a class of nonlinear switched systems with both system matrices and input matrices existing strong disturbance uncertainties. The features are as follows:

1. The strong disturbance uncertainties are element-wise absolute-value bounded.
2. The switching law is arbitrary if the switching is slow enough in the average sense.
3. The proposed method treats all actuators by an unified way without classifying all actuators into two parts: faulty actuators and the actuators robust to faults, which is different from the mentioned methods in Veillette [18], Wang et al. [21], Liang et al. [10], Han and Yu [6], and Ma and Yang [14].

The layout of this paper is as follows: Section 2 states the problem. The details of designing controller of the switched nonlinear systems and stability analysis are presented in Section 3. Numerical simulation is given in Section 4. Section 5 concludes this paper.

2. Problem statement

Consider a class of uncertain switched nonlinear systems

$$\dot{z} = g_i(z,x),$$
$$\dot{x} = (A_i+\Delta A_i)x+(B_i+\Delta B_i)u_i \quad (1)$$

where $x \in R^r$ and $z \in R^{n-r}$ are system states, $u_i \in R^{q_i}$ is control input, $i(t) : [0,+\infty) \to M = \{1,2,\dots,m\}$ is a switching signal, $g_i(z,x)$ is a known nonlinear function, A_i,B_i is a known nonlinear function, $\Delta A_i, \Delta B_i$ are uncertain matrix functions representing structural uncertainties.

Remark 1. System (1) represents a special class of switched nonlinear systems [19,20,9], which is formed by a set of nonlinear cascade systems and a switching law to determine which nonlinear cascade system is active in use. When the set contains only one subsystem, System (1) is reduced to a non-switched nonlinear cascade system [15,2].

We make the following assumptions for system (1):

Assumption 1. Assume that (A_i, B_i) are controllable, and that the states are available for feedback.

Assumption 2. Assume there exist non-negative constant matrices E_i^A and E_i^B, so that strong structural uncertain matrices ΔA_i, ΔB_i are satisfied, i.e.

$$|\Delta A_i| \le E_i^A, \quad |\Delta B_i| \le E_i^B. \quad (2)$$

Assumption 3. $g_i(z,x)$ satisfies globally Lipschitz condition, i.e., there exists a constant $L_i > 0$ such that

$$\|g_i(z,x_1)-g_i(z,x_2)\| \le L_i\|x_1-x_2\|, \quad \forall z,x_1,x_2$$

Assumption 4. There exist a smooth positive definition function $W(z)$ with $W(0)=0$, positive constant k_1,k_2, and constant $\beta > 0, \gamma > 0, i \in M$, such that

$$\frac{dW(z)}{dz}g_i(z,0) \le -\beta_i\|z\|^2, \quad (3)$$

$$\left\|\left|\frac{dW(z)}{dz}\right|\right| \le \gamma\|z\|, \quad (4)$$

$$k_1\|z\|^2 \le \|W(z)\| \le k_2\|z\|^2. \quad (5)$$

Remark 2. The purpose of condition (4) is to assume, for stability proof, that the time derivative of $W(z)$ corresponding to the z subsystem is satisfied linear growth condition with respect to $\|z\|$.

Let the controller be in the form

$$u_i = K_i x \quad (6)$$

where $K_i \in R^{q_i \times r}$ is a constant matrix. Given whether a fault occurs on each actuator or not, propose a matrix L_s^i ($L_s^i \ne 0$) representing the actuators fault situation of the ith subsystem of the switched nonlinear systems as follows:

$$L_s^i = diag\left(l_1^i, l_2^i, \dots, l_q^i\right) \quad (7)$$

if $l_j^i = 1$, the jth actuator is normal; if $l_j^i = 0$, the jth actuator is faulty, where l_j^i ($j \in 1,2,\dots,q$).

Thus the model of nonlinear switched system with actuator faults and structural uncertainties is as follows:

$$\dot{z} = g_i(z,x),$$
$$\dot{x} = [(A_i+\Delta A_i)+(B_i+\Delta B_i)L_s^iK_i]x. \quad (8)$$

The objective is to seek feedback a gain matrix K_i ($i \in M$), such that the switched nonlinear system (8) with structural uncertainties and actuator faults existing in both system matrix and input matrix can be exponentially stabilized.