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Dynamic output feedback fault tolerant controller design for discrete-time switched systems with actuator fault

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ABSTRACT

This paper investigates the problem of dynamic output feedback fault tolerant controller design for discrete-time switched systems with actuator fault. By using reduced-order observer method and switched Lyapunov function technique, a fault estimation algorithm is achieved for the discrete-time switched system with actuator fault. Then based on the obtained online fault estimation information, a switched dynamic output feedback fault tolerant controller is employed to compensate for the effect of faults by stabilizing the closed-loop systems. Finally, an example is proposed to illustrate the obtained results.

1. Introduction

In complex systems, dependability is as important as performances. Once a fault (sensor, actuator, or component failures) occurred in the system, the system behavior may be drastically changed, ranging from performance degradation to instability. Fault tolerant control (FTC) technique is an effective method in order to reach the system objectives, or if this turns to be impossible, to achievable new objectives to avoid catastrophic behaviors. Therefore, FTC have been the subjects of intensive investigations over the past two decades, and a number of achievements have been obtained, which can be found in several excellent papers, see for example [1–8] and the references therein.

As for FTC, which includes two main approaches: passive and active. While passive fault tolerance considers systems faults as a special kind of uncertainties [9], active fault tolerance is based on fault detection and isolation (FDI) and accommodation technique [10]. Though FDI can give information whether there exist faults occurring [11], the magnitude of the fault cannot be precisely provided. Therefore, the next step is to search an efficient approach to estimate the magnitude of the fault, which is called fault estimate or fault reconstruction. Finally, using the estimated fault information, a fault-tolerant controller can be designed to compensate the effect of the fault. From the above discussion, it can be seen that fault estimation plays a very important role in active FTC. Therefore, the study of fault estimation has become a hot research topic owing to its importance in active FTC. During the past decade, various effective methods, such as sliding mode observer approach using equivalent output injection signal [12], adaptive technique [13], and learning method based on neural network [14] and so on, have been developed for fault estimation problem. Generally speaking, adaptive technique is usually used to obtain actuator fault information for continuous case [10]. Another commonly employed to realize fault estimation is based on descriptor observer technique, but it is usually utilized to estimate sensor fault [15]. Recently, reduced-order

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observer method is proposed to solve actuator fault estimation for discrete time systems, this motives us to investigate this issue for discrete-time switched systems.

Switched system is a class of hybrid systems, which consists of a finite number of subsystems and an associated switching signal governing the switching among them. Many real-world process and systems can be modeled as switched systems, including chemical processes, computer controlled systems, switched circuits, and so on. Therefore, it has been intensively investigated in the past decades [16–22]. Compared with fruitful stability and stabilization results for switched systems, fault diagnosis and FTC achievements are relatively few. In [23,24], fault detection for switched system was separately investigated for continuous case and discrete case. [15] investigated sensor fault estimation and accommodation approaches for continuous-time switched systems, and [25,26] separately studied actuator fault estimation and accommodation approaches for continuous-time switched systems with constant time-delay case and time-varying delay case. However, to the best of our knowledge, the problems of actuator fault estimation and compensation for discrete-time switched systems are still under research, which motivate us to study this meaningful and challenging topic.

Based on the above works, our objective of this paper is to analyze and develop a general framework of fault estimation and accommodation for discrete-time switched systems with actuator faults. Firstly, a switched reduced-order observer is designed in form of linear matrix inequality, then a fault estimation algorithm is given. By using the estimated fault signal, actuator fault compensation will be performed to realize a fault-tolerant performance.

The rest of this paper is organized as follows. Section 2 presents the system description. In Section 3, a switched reduced-order observer design, including an H_∞ performance index is proposed to estimate the actuator fault. Furthermore, in Section 4, based on the online fault estimate information, a switched dynamic output feedback controller is designed to compensate for the effect of faults. An example is illustrated in Section 5 to show the effectiveness of the proposed approach, and the paper is concluded in Section 6.

2. Problem statements and preliminaries

Consider the following discrete-time switched linear system:

$$x(t+1) = \sum_{i=1}^{N} \delta_i(t) A_i x(t) + \sum_{i=1}^{N} \delta_i(t) B_i (u(t) + f(t)) + \sum_{i=1}^{N} \delta_i(t) D_i \omega(t) \tag{1}$$

$$y(t) = \sum_{i=1}^{N} \delta_i(t) C_{1i} x(t) \tag{2}$$

$$z(t) = \sum_{i=1}^{N} \delta_i(t) C_{2i} x(t) \tag{3}$$

where $x(t) \in \mathbb{R}^n$ is the state vector, $u(t) \in \mathbb{R}^m$ is the control input vector, $y(t) \in \mathbb{R}^p$ is the measurable output vector, $f(t) \in \mathbb{R}^m$ represents the additive actuator fault, $\omega(t) \in \mathbb{R}^r$ is the disturbance which is assumed to belong to $l_2[0, \infty)$. The vector $\delta_i(t)$ is called switching signal, which specifies which subsystem will be activated at the discrete time t, where

$$\delta_i(t) : Z^+ = \{0, 1, 2 \ldots\} \to \{0, 1\}, \qquad \sum_{i=1}^{N} \delta_i(t) = 1, \quad \forall t \in Z^+.$$

A_i, B_i, C_{1i}, C_{2i}, and D_i are constant matrices with appropriate dimensions.

For the purpose of this note, we give the following assumption:

Assumption 1. The measurable output matrices: $C_{11} = C_{12} = \cdots = C_{1N} = C$, which are full column rank.

Since the matrix C is of full column rank, there always exists a matrix $C^\perp \in \mathbb{R}^{(n-p)\times n}$ such that $\begin{bmatrix} C^\perp \\ C \end{bmatrix} \in \mathbb{R}^{n\times n}$ is a nonsingular matrix.

3. Fault estimation design

3.1. State transformation

We construct nonsingular matrix $T = \begin{bmatrix} C^\perp_{(n-p)\times n} \\ C_{p\times n} \end{bmatrix}^{-1}$, which satisfies:

$$CT = \begin{bmatrix} 0_{p\times(n-p)} & I_p \end{bmatrix}.$$

Then define the following state transformation:

$$x(t) = T\tilde{x}(t). \tag{4}$$