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Descriptor reduced-order sliding mode observers design for switched systems with sensor and actuator faults[☆]

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ABSTRACT

This paper investigates the state and fault estimation problem for linear continuous-time switched systems with simultaneous disturbances, sensor and actuator faults, and two types of observer approaches are presented to solve this design issue. The first one is a linear descriptor reduced-order observer, which generates the exact estimation of state and sensor faults together with disturbances by decoupling them from the state vector without any supplementary design. The second one refers to a descriptor sliding mode observer approach, where the state, disturbances, sensor and actuator faults can be reconstructed simultaneously. In the second method, the reachability of sliding surface is not necessary to be investigated, since the actuator faults can be estimated directly without using the equivalent output error injection scheme as in traditional sliding mode observers. Therefore, both developed observer approaches avoid the sliding surface switching problem of traditional sliding mode observers in application to switched systems. Finally, an example is given to demonstrate the effectiveness of the two designed observer methods.

1. Introduction

In practical control systems of aerospace and chemical engineering, etc., the control components (for example, sensors and actuators) are usually afflicted by failures resulted from a variety of unexpected phenomenon (Corradini, Cristofaro, & Pettinari, 2012b; Gao & Ding, 2007; Polycarpou, 2001). As sensor and actuator failures can lead to severe system performance deterioration and instability, it is of both theoretical significance and realistic necessity to investigate fault detection and estimation problems for the purpose of system safety monitoring. Recently, the problems of estimating simultaneous state and unknown faults have become an active research topic, which is indeed motivated by the possible applications to fault detection and estimation (Basin, Shi, & Calderon-Alvarez, 2009; Jiang, Staroswiecki, & Cocquempot, 2006; Yeu, Kim, & Kawaji, 2005). A variety of observer-based state and fault estimation methods have been developed (Basin & Rodriguez-Gonzalez, 2005; Scott & Campbell, 2013), for instance, sliding mode observer (SMO) (Corradini, Cristofaro, & Pettinari, 2012a; Liu & Shi, 2013), high gain observer (Gao, Breikin, & Wang, 2007), adaptive observer (Cristofaro & Johansen, 2014; Yang, Jiang, & Staroswiecki, 2007), and learning observer (Polycarpou, 2001).

Among these existing approaches, SMO is one of the most effective techniques to accomplish fault estimation (Liu & Shi, 2013). Different from traditional linear Luenberger observers, sliding mode control is proposed to inject a nonlinear switching term into the observer, which enables to reject disturbances and also induces a sliding motion in the state space of output estimation error (Niu, Ho, & Wang, 2007). In the past few years, sensor/actuator fault reconstruction and estimation design with SMO techniques has been extensively studied in the literature with respect to various types of systems, for instance, linear systems (Basin, Shi, & Calderon-Alvarez, 2010; Edwards, Spurgeon, & Patton, 2000), nonlinear systems (Niu, Ho, & Wang, 2008), Markovian jump systems (Chen, Niu, & Zou, 2013) and Itô stochastic systems (Wu, Ho, & Li, 2011).

On another research forefront, in the past decade, switched systems have attracted much attention owing to their wide practical applications in manufacturing systems (Liu, Ho, & Shi, 2015), vehicle industry (Morselli, Zanasi, & Ferracin, 2006), biological systems (DeJong, 2002), etc. So far, considerable research attention has been devoted to the filtering and synthesis problems

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and the convergence time estimation problem for switched systems (Basin, Panathula, & Shtessel, 2015; Xiong, Lam, Shu, & Mao, 2014; Zhang & Lam, 2010), and especially some researchers have begun the investigation of fault detection problems of switched systems (Wang, Wang, & Shi, 2009; Yang, Jiang, & Cocquempot, 2009). However, as a significant research topic with application potentials to practical engineering, the fault estimation problem of switched systems has not received much research attention yet, not to mention the case where sensors and actuators are considered simultaneously.

It is worth pointing out that, the existing SMO estimation methods cannot be simply employed to fault estimation design for switched systems in the presence of sensor and actuator faults. We explain this technical difficulty in details as follows. In a SMO design, a sliding surface is constructed via the estimation error, then a switching term is designed to drive the error trajectory onto the surface, and subsequently induces a sliding motion there. In light of the sliding motion equation, the actuator faults could be approximated via the equivalent output error injection. However, in switched systems the estimation error is indeed involved with switched output matrices, which will inevitably lead to the designed sliding surface switching among several different surfaces nondeterministically. In this setting, it is rather difficult to guarantee the strict reachability of the sliding surface, which further makes the actuator faults approximation unable to be realized. If sensor faults are considered simultaneously, the design problem will become even more complicated. Therefore, new observer techniques for switched systems are desirable to be presented to overcome this design problem, which motivates our investigation work in this paper.

In this paper, we address the state and fault estimation problem for continuous-time switched systems with simultaneous disturbances, sensor and actuator faults, and two observer approaches are developed. In the first approach, by introducing an augmented vector consisting of the state, disturbance and sensor fault vectors, a linear descriptor reduced-order observer is presented to obtain the exact estimation of state and sensor faults simultaneously. In this design, the switching input term is not required to be introduced. This means that it is not necessary to use the sliding mode techniques, and the aforementioned sliding surface switching problem is avoided. In the second method, the plant is decomposed into two reduced-order systems by a coordinate transformation, and a descriptor augmentation strategy is developed for the second reduced-order system. A descriptor reduced-order sliding mode observer approach is developed to support simultaneous approximation of the state, disturbance, sensor faults and actuator faults. In the second method, the actuator faults can be estimated directly without using the equivalent output error injection as in traditional SMOs, since the actuator fault vector here has been assembled into the extended state vector of the augmented descriptor system. As a result, both of these designed observer approaches overcome the technical obstacle in applying SMO techniques to switched systems. Finally, an example is given to demonstrate the effectiveness of the two observer methods.

This paper is organized as follows. In Section 2, the problem formulation is given. The linear descriptor observer method is discussed in Section 3, and the reduced-order sliding observer approach is presented in Section 4. A numerical example is provided in Section 5 and a conclusion in Section 6 ends this paper.

2. Problem formulation

Consider the following continuous-time switched system:

$$\begin{cases}\dot{x}(t) = A(\sigma(t))x(t) + B(\sigma(t))u(t) + F_a(\sigma(t))f_a(t)\\ y(t) = C(\sigma(t))x(t) + F_s f_s(t) + D_d f_d(t),\end{cases} \tag{1}$$

where $x(t) \in \mathbb{R}^n$, $y(t) \in \mathbb{R}^p$ and $u(t) \in \mathbb{R}^m$ denote the *continuous* system state, measurement output and control input, respectively, $f_s(t) \in \mathbb{R}^s$, $f_a(t) \in \mathbb{R}^a$ and $f_d(t) \in \mathbb{R}^d$ represent the sensor fault vectors, actuator fault vectors and the bounded external disturbance vectors, respectively. $\left\{\Big(A(\sigma(t)), B(\sigma(t)), F_a(\sigma(t)), C(\sigma(t))\Big) : \sigma \in \mathbb{N}\right\}$ refers to a family of matrices parameterized by an index set $\mathbb{N} = \{1, 2, \dots, N\}$, and $\sigma(\cdot) : \mathbb{R} \to \mathbb{N}$ is a piecewise constant function of time t which denotes the switching signal. Given a time instant t, let $\sigma = i \in \mathbb{N}$, which means the ith subsystem is activated. The ith subsystem is denoted by constant matrices $A_i \in \mathbb{R}^{n\times n}$, $B_i \in \mathbb{R}^{n\times m}$, $C_i \in \mathbb{R}^{p\times n}$, $F_s \in \mathbb{R}^{p\times s}$, $D_d \in \mathbb{R}^{p\times d}$, $F_{ai} \in \mathbb{R}^{n\times a}$. Define $\{t_0, t_1, t_2, \dots, t_k, \dots\}$ as the sequence of the "**switching times**", where t_k denotes the time instant on which the system mode is updating (i.e. $\sigma(t^+) \neq \sigma(t^-)$).

As mentioned in Section 1, SMO technique is difficult to be applied to switched systems to solve the state and estimation problem. Therefore, the main objective of this paper is to present two novel observer design schemes for continuous-time system (1) to obtain the exact estimation of state vector $x(t)$ in the simultaneous presence of sensor fault $f_s(t)$, actuator fault $f_a(t)$ and disturbance $f_d(t)$.

3. Linear descriptor reduced-order observer design

In this section, we present a linear descriptor reduced-order observer approach to solve the estimation problem. The proposed observer dispenses using the sliding mode control technique to reject faults effects, but decouples the fault vectors from system state to obtain the estimation. A preliminary step of this design is to introduce a descriptor augmentation transformation for system (1). We define the following augmented vectors and matrices:

$$\bar{x}(t) = \begin{bmatrix} x(t)\\ \psi(t)\end{bmatrix}, \qquad d(t) = \begin{bmatrix} f_a(t)\\ f_s(t)\\ f_d(t)\end{bmatrix}, \qquad \bar{E} = \begin{bmatrix} I_n & 0_{n\times p}\\ 0_{p\times n} & 0_{p\times p}\end{bmatrix},$$

$$\bar{A}_i = \begin{bmatrix} A_i & 0_{n\times p}\\ 0_{p\times n} & -I_p\end{bmatrix}, \qquad \bar{B}_i = \begin{bmatrix} B_i\\ 0_{p\times m}\end{bmatrix}, \qquad \bar{C}_i = \begin{bmatrix} C_i & I_p\end{bmatrix},$$

$$\bar{F}_i = \begin{bmatrix} F_{ai} & 0_{n\times s} & 0_{n\times d}\\ 0_{p\times a} & F_s & D_d\end{bmatrix}, \qquad \psi(t) = F_s f_s(t) + D_d f_d(t),$$

and we construct the following augmented descriptor system:

$$\begin{cases}\bar{E}\dot{\bar{x}}(t) = \bar{A}_i\bar{x}(t) + \bar{B}_i u(t) + \bar{F}_i d(t)\\ y(t) = \bar{C}_i\bar{x}(t),\end{cases} \tag{2}$$

where $\bar{E} \in \mathbb{R}^{(n+p)\times(n+p)}$, $\bar{A}_i \in \mathbb{R}^{(n+p)\times(n+p)}$, $\bar{B}_i \in \mathbb{R}^{(n+p)\times m}$, $\bar{F}_i \in \mathbb{R}^{(n+p)\times(a+s+d)}$, $\bar{C}_i \in \mathbb{R}^{p\times(n+p)}$. Assume for each $i \in \mathbb{N}$, C_i has full row rank, then it is obvious that $\bar{C}_i$ is of full row rank. Denote

$$\bar{C}_i = \begin{bmatrix} c_{i11} & \cdots & c_{i1,(n+p)}\\ \vdots & \ddots & \vdots\\ c_{ip1} & \cdots & c_{ip,(n+p)}\end{bmatrix} \tag{3}$$

and $\xi_{ij} = [c_{ij1} \ \cdots \ c_{ij,(n+p)}]^T \in \mathbb{R}^{n+p}$, $c_{ijk} \in \mathbb{R}$ with $i \in \{1, 2, \dots, N\}$, $j \in \{1, \dots, p\}$ and $k \in \{1, 2, \dots, n+p\}$, then it is obvious that $\bar{C}_i = [\xi_{i1}, \dots, \xi_{ip}]^T$. In the *Euclidean Space* $\mathbb{R}^{n+p}$, there must exist *orthogonal base vectors* $\xi_{i,(p+1)}, \dots, \xi_{i,(p+n)} \in \mathbb{R}^{n+p}$ such that for each $j \in \{p+1, \dots, p+n\}$, $\xi_{i,j}$ is orthogonal to $\xi_{i1}, \dots, \xi_{i,(p+n)}$, and these $n+p$ vectors $\xi_{i1}, \dots, \xi_{i,(p+n)}$ are linearly independent of each other. We define

$$\bar{C}_i^{\perp} = [\xi_{i,(p+1)}, \dots, \xi_{i,(p+n)}], \tag{4}$$