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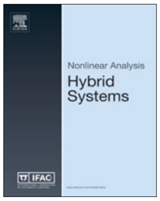

Dual-mode robust fault estimation for switched linear systems with state jumps

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ABSTRACT

Fault detection and estimation is a critical part of modern control system design and ensures safety and reliability of expensive machinery. In this paper, a dual-mode state and fault estimation scheme is proposed for switched linear systems with a class of state jumps in the presence of simultaneous actuator and sensor faults. In the absence of sensor faults, a switched sliding mode observer is developed to estimate the state and actuator fault signal. A residual signal is computed to detect the inception of a sensor fault. Upon detecting the sensor fault, a robust state observer is triggered which guarantees ultimate boundedness of the state estimation error. The performance of the proposed dual-mode switched observer is illustrated using a numerical example.

1. Introduction

An increasing demand for safety and reliability has motivated research in the area of fault detection and isolation (FDI) [1]. Excellent surveys of the field are [2–4]. One method for fault detection is to employ a state observer to construct a residual signal and determine whether a fault has occurred based on the magnitude of the residual signal relative to a predefined threshold. In an industrial application, exogenous signals such as unknown disturbances or sensor errors could produce false alarms. Hence, there is a need to construct robust fault detection methods which function satisfactorily in the presence of exogenous inputs.

Recent methods involve modeling a system's fault dynamics to enable the analysis of fault detection. This type of modeling often uses switched system models (see [5] for an overview of switched systems). Results are available in the FDI literature for linear, stochastic, and uncertain systems, for example [6–15]; however, FDI for switched linear systems (SLS) is an open problem. In [16,17], methods are proposed to estimate discrete-time SLS with state delays in an $\mathcal{H}_\infty$ framework. For time varying delays, methods are proposed for fault detection in [18,19]. A recent paper [20] addresses the case of fault detection with intermittent measurements. A design method for fault-tolerant controllers for switched linear systems is discussed in [21]. A common limitation of these methods is that sensor faults are not considered explicitly. Generally, the fault detection problem is posed therein as a safe-to-failure mode transition detection problem. Some results in this field are discussed in [22,23].

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Design of observers for switched systems has proven to be a rich problem. In [24], sliding mode observers constructed for each mode are used to estimate the unknown switching signal and the state. Observer construction in [24] is extended in [25] to the case of partially unknown inputs. Estimating the switching signal and the discrete state for discrete-time switched systems is analyzed in [26] for the case of bounded uncertainties. Uniform convergence of the continuous and discrete state is investigated in [27], where a bank of observers is used to reconstruct the switching signal and continuous state based on a residual signal for determining the active mode. In contrast, this work uses the residual signal to detect the presence of abrupt sensor faults. When the switching signal is known, asymptotic observers can be constructed to guarantee estimator convergence in the presence of bounded disturbances via a common quadratic Lyapunov function as described in [28]. In this paper, a similar problem is addressed. A key difference is that the actuator faults are simultaneously reconstructed in addition to the state estimates.

An open problem in observer design of switched linear systems is constructing observers to handle state jumps. Observer design using a common Lyapunov framework for switched systems with state jumps is found in [29–31]. Some results using multiple Lyapunov functions are described in [32] to reduce conservativeness of the observer design. In this paper, we use a common Lyapunov approach which guarantees exponential stability of the observer error under known but arbitrary switching and a class of state jumps. We also incorporate state jumps within our dual-mode observer to provide ultimate bounds on the estimation error and reconstruct the actuator fault signal.

In this paper, we propose a systematic method to design dual-mode observers for state estimation of switched linear systems with state jumps. These systems are additionally disturbed by bounded sensor and actuator faults. In the presence of actuator faults only, we propose a sliding mode observer for state and fault signal estimation. We compute a residual signal which is utilized to detect a sensor fault. If a sensor fault is detected, a robust observer is triggered. This robust observer operates at a specified performance level, which is intrinsic to the design. Our contributions include: (i) formulating new linear matrix inequality conditions for sliding mode observer for switched systems; (ii) proposing linear matrix inequalities for $\mathcal{L}_\infty$-gain attenuating observer design for switched linear systems with guaranteed performance, and (iii) extending these observer designs to incorporate state and actuator fault estimation for switched systems with state jumps.

The rest of the paper is organized as follows. The overall fault detection and isolation problem is discussed in Section 2. The actuator fault detecting observer is analyzed in Section 3. In the event of a sensor fault a disturbance rejecting observer is developed in Section 4. Finally, simulation results are shown in Section 5 and conclusions are presented in Section 6.

2. Problem statement

2.1. System description

We consider a class of dynamical systems modeled as a switched linear system (SLS) with state jumps at switching times t_k modeled by

$$\begin{aligned} \dot{x}(t) &= A_{\sigma(t)}x(t) + B_{\sigma(t)}u(t) + G_{\sigma(t)}f_a(t)\boldsymbol{1}^+(t-\Delta_a), \\ y(t) &= C_{\sigma(t)}x(t) + D_{\sigma(t)}f_s(t)\boldsymbol{1}^+(t-\Delta_s), \\ x(t_k^+) &= \Theta_{\sigma(t_k^-),\sigma(t_k^+)}x(t_k^-) + \Gamma_{\sigma(t_k^-),\sigma(t_k^+)}, \end{aligned} \tag{1}$$

where $x(t) \in \mathbb{R}^n$ denotes the state vector of the SLS, $u(t) \in \mathbb{R}^{m_1}$ is the vector of known control inputs and $y(t) \in \mathbb{R}^p$ represents the measured outputs at time t. The switching signal $\sigma(t) \in \{1, \dots, N\}$ indicates the active mode amongst N subsystems at time t. The vectors $f_a(t) \in \mathbb{R}^{m_2}$ and $f_s(t) \in \mathbb{R}^q$ represent the actuator and sensor fault, respectively. The unit step function $\boldsymbol{1}^+(t-\tau)$ is a step signal which comes into effect after delay τ. In this paper, we consider that the actuator fault occurs after Δ_a seconds and that the sensor fault occurs after Δ_s seconds. Note that the times of fault occurrence Δ_a, Δ_s are *unknown*.

Remark 1. Suppose that $\Delta_a < \Delta_s$. This implies that the sensor fault occurs after the actuator fault. Note that this is not a restrictive assumption. If a sensor fault occurs before the actuator fault, that is, if $\Delta_s < \Delta_a$, then the residual will trigger the $\mathcal{O}^+$ observer after Δ_s second until the faulty sensor is replaced. If $\Delta_s = \Delta_a = 0$, then the robust observer $\mathcal{O}^+$ will run shortly after the initial time, as soon as the residual threshold condition $r \geq \bar{r}$ is triggered.

For $i = 1, \dots, N$, the matrices $A_i \in \mathbb{R}^{n\times n}$ are state matrices, $B_i \in \mathbb{R}^{n\times m_1}$ are input matrices, $C_i \in \mathbb{R}^{p\times n}$ are output matrices and $G_i \in \mathbb{R}^{n\times m_2}$ and $D_i \in \mathbb{R}^{p\times q}$ represent how the *unknown* actuator and sensor faults enter the system in the ith mode, respectively.

Finally, the *known* matrices $\Theta_{r,s} \in \mathbb{R}^{n\times n}$ and $\Gamma_{r,s} \in \mathbb{R}^n$ for all $r, s \in \{1, 2, \dots, N\}$ represent the linear state jumps considered in this paper. Note that such a linear form of state jumps has been explored previously in [33] and [34]. Finally, in our notation, we drop the argument t for brevity; for example $A_{\sigma(t)}$ is written as A_σ. We make the following technical assumptions to enable the development of our main results.

Assumption 1. The switching signal σ is known and has finite number of switches per unit time interval, that is, it does not exhibit Zeno behavior.

Assumption 2. For $i = 1, \dots, N$, $\text{rank}(C_iG_i) = \text{rank}(G_i) = m_2$.