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Reliable finite-time filtering for impulsive switched linear systems with sensor failures

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ABSTRACT

This paper investigates the finite-time filter design problem for a class of switched linear systems with parameter uncertainties and impulsive effects. The sensor failures with output-measurement errors and mode-detection delays are taken into account. A filter mode-dependent Lyapunov-like function construction approach is developed which can effectively reduce the filter design difficulty induced by the mode-detection delays. Sufficient conditions on finite-time boundedness and finite-time H_∞ performance are first derived for the augmented switched error systems, upon which the mode-dependent finite-time H_∞ filter is designed. Performance of the potential of the developed filter is illustrated by a numerical example and an application to PWM (Pulse-Width-Modulation)-driven boost converter.

1. Introduction

Switched systems consist of a finite set of subsystems and a logical switching rule that manages switching among subsystems, which can be efficiently applied to model many physical or man-made systems displaying switching features. Extensive research has been recently conducted on theory developments and practical applications for this special kind of hybrid systems (see [17,25,18,7,29,3,27,10,41,26,14,23] and references therein), and most results are focused on the conventional Lyapunov asymptotic stability (infinite-time interval). In some cases, however, the system behavior has been studied over an assigned finite-time interval [42,1,8]. Finite-time stability (boundedness) is a special stability concept, which assumes that the system state stays below a certain threshold during a fixed time interval [1]. Some early results with respect to the finite-time stability (boundedness) for switched systems could be found in [20,22,30,2,16,11,5].

In addition, abrupt changes in operated model structures of switched systems inevitably lead to state jumps, which may cause oscillations and result in false filtering outputs [19,36]. State jumps at switching instants could be modeled by means of impulsive switched systems, for which certain results have been obtained as well. To name a few, the exponential stability with L_2-gain condition for impulsive switched nonlinear systems has been studied in [32], a fault detection observer for uncertain switched nonlinear systems with impulsive effects has been designed in [31], and an optimal switching problem for a switched-capacitor DC/DC power converter with impulsive effects has been discussed in [21]. It should be noted that such existing results related to impulsive switched systems are always addressed in infinite-time interval. To the best of our

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knowledge, the investigations of impulsive switched systems in the finite-time sense have not yet been considered.

Moreover, filtering or state estimation for switched systems has long been a hot research topic. The filtering problems for the switched systems with and without asynchronous switching have been both widely investigated [7,29,3,23,38,15,6,40,13,24]. However, most of results are concerned with the Lyapunov asymptotic stability (LAS) over infinite-time interval, which are unpractical [2]. Sometimes, the filtering performance over the finite-time interval is more important. Furthermore, for the switched systems with asynchronous switching, the filter design is a challenging problem owing to the mode mismatched interval, especially in the continuous-time context. A common technique is to perform the calculations by two steps, which is complicated and inevitably leads to conservativeness [27,38]. Taking the impulsive effects and sensor failures with missing/fading measurements into account, the filtering problems will be more challenging [4,12].

This paper presents a robust finite-time H_∞ filter design procedure for a class of impulsive switched systems with both mode-detection delays and output-measurement errors. The paper contribution is threefold. (1) A new filter mode-dependent Lyapunov-like function is constructed to reduce the filter design difficulty induced by the asynchronous switching, and this technique can be extended to the asynchronous switching controller design for switched systems with both LAS and finite-time boundedness contents. (2) A new filtering error model is established to address the impulsive effects and sensor induced faults. (3) The obtained results can be applied to the LAS analysis over infinite-time interval.

The paper is organized as follows. Section 2 outlines the problems statement and introduces a new augmented filtering error switched system. Section 3 presents the results of finite-time boundedness (stability) and finite-time H_∞ performance for the augmented filtering error switched system. The mode-dependent filter is designed considering the parameter uncertainties in Section 4. In Section 5, two technical examples are provided to illustrate validity of the obtained techniques. Section 6 concludes this study.

Notation: The used notation is fairly standard: $\mathbb{R}^n$ and $\mathbb{R}^{n\times m}$ denote, respectively, the n-dimensional Euclidean space and the set of all $n\times m$ real matrices. $\mathbb{N}$ represents the set of nonnegative integers. P^T denotes the transpose of P. $P>0(\geq 0)$ means that P is real symmetric and positive definite (semi-positive definite), $\lambda_{\max}(P)$ and $\lambda_{\min}(P)$ denote its maximal and minimal eigenvalues.

2. Preliminaries and problem statement

Consider a class of continuous-time impulsive switched systems given by

$$\begin{cases} \dot{x}_p(t)=A_{\sigma(t)}(t)x_p(t)+B_{\sigma(t)}w(t), \\ y(t)=C_{\sigma(t)}(t)x_p(t)+E_{\sigma(t)}w(t), \\ z_p(t)=D_{\sigma(t)}(t)x_p(t)+G_{\sigma(t)}w(t), \\ \Delta x_p(t^+)=L_{\sigma(t^-)}x_p(t^-)+h(t^-,x_p(t^-)), t=t_k, \\ x_p(t_0^+)=x_{p0}, \end{cases} \tag{1}$$

where $x_p(t)\in\mathbb{R}^n$ denotes the state vector, $\Delta x_p(t)=x_p(t_k^+)-x_p(t_k^-)$ with $x_p(t_k^+)=\lim_{h\to 0^+}x_p(t_k+h)$, $x_p(t_k^-)=\lim_{h\to 0^+}x_p(t_k-h)=x_p(t_k)$, which implies that the solution of the system (1) is left-continuous, $z_p(t)$ is the output signal to be estimated, $y(t)\in\mathbb{R}^m$ is the measurement signal, and $w(t)$ is the disturbance input, which belongs to $L_2[0,\infty)$. The switching signal $\sigma(t)$ selects one and only one subsystem at every time instant t, which is described as $\sigma(t)$: $[t_0,\infty)\to\mathcal{I}=\{1,2,\ldots,l\}$, where $l>1$ is the number of subsystems. The switching sequence σ: $\{(t_0,\sigma(t_0)),\ (t_1,\sigma(t_1)),\ldots,(t_k,\sigma(t_k)),\ldots\}$ is continuous from left everywhere.

Throughout the paper, the following assumptions are satisfied.

Assumption 1. The parameters $A_{\sigma(t)}(t)$, $C_{\sigma(t)}(t)$ and $D_{\sigma(t)}(t)$ in (1) are respectively defined as $A_{\sigma(t)}(t)=A_{\sigma(t)}+\Delta A_{\sigma(t)}(t)$, $C_{\sigma(t)}(t)=C_{\sigma(t)}+\Delta C_{\sigma(t)}(t)$ and $D_{\sigma(t)}(t)=D_{\sigma(t)}+\Delta D_{\sigma(t)}(t)$, where $A_{\sigma(t)}$, $C_{\sigma(t)}$ and $D_{\sigma(t)}$ are exactly known matrices, and the uncertain parameters $\Delta A_{\sigma(t)}(t)$, $\Delta C_{\sigma(t)}(t)$ and $\Delta D_{\sigma(t)}(t)$ are time-varying but norm-bounded and satisfy the relations

$$\begin{aligned}&\left[\Delta A^T_{\sigma(t)}(t)\ \ \Delta C^T_{\sigma(t)}(t)\ \ \Delta D^T_{\sigma(t)}(t)\right]^T \\ &=\left[M^T_{1,\sigma(t)}\ \ M^T_{2,\sigma(t)}\ \ M^T_{3,\sigma(t)}\right]^T O_{\sigma(t)}(t)H_{\sigma(t)},\end{aligned}$$

where $M_{1,\sigma(t)}M_{2,\sigma(t)}M_{3,\sigma(t)}$ and $H_{\sigma(t)}$ are known mode-dependent matrices and $O_{\sigma(t)}(t)$ is an unknown matrix with appropriate dimension, satisfying $O^T_{\sigma(t)}(t)O_{\sigma(t)}(t)\leq I$.

Assumption 2. (*Xu and Teo [32]*). $h(t,x_p(t))$ is bounded and satisfies

$$\|h(t,x_p(t))\|^2\leq\eta\|x_p(t)\|^2,$$

where η is a known positive scalar.

Assumption 3. (*Cheng et al. [2], Xu and Sun [34]*). For a given interval T_f, the disturbance input $w(t)$ satisfies

$$\int_{t_0}^{T_f} w^T(t)w(t)\,dt\leq d_w^2.$$

Remark 1. Assumptions 2 and 3 are two common conditions of the related investigations respectively for the systems with impulsive effects and the finite-time performance analysis, see, e.g., [32] and [2,34]. Impulsive effects widely exist in many practical engineering, which are usually nonlinear and globally Lipschitz continuous, therefore, Assumption 2 is rational. Besides, the studied performance of the underlying systems in this paper is over finite-time interval. It is well known that the disturbance input $w(t)$ over finite-time interval is general bounded, which guarantees Assumption 3.

The sensor-induced random measurement errors are described by

$$y^F(t)=U_{\sigma(t)}y(t), \tag{2}$$

where $U_{\sigma(t)}$ is a sensor error matrix defined for any $\sigma(t)=i\in\mathcal{I}$:

$$\begin{aligned}&U_i=diag\{u_{i,1},u_{i,2},\ldots,u_{i,r},\ldots,u_{i,m}\}, \\ &0\leq\underline{u}_{i,r}\leq u_{i,r}\leq\overline{u}_{i,r}, \\ &r=1,2,\ldots,m\end{aligned}$$