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Optimal fault detection filter design for switched linear systems

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ABSTRACT

This report investigates the problem of fault detection filter design for switched linear systems. A mixed H_-/H_∞ fault detection filter is proposed and the solution is provided in the state space paradigm. The proposed solution has the advantage that not only faults can be detected but fault isolation is also possible. Linear matrix inequalities (LMIs) and Multiple Lyapunov Function (MLF) approach are used for the design of fault detection filter. It is assumed that the switching sequence is known and the fault detection filter is designed using the average dwell time constraints.

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1. Introduction

Safe and reliable operation of a plant/process is the core issue to be addressed in designing a control system. This can be achieved by employing sophisticated control strategies. Generally speaking every controlled process has sensors, actuators, controller hardware and the process itself. Ideally the operation of the plant should be in accordance with the desired specifications after addressing all the control and stability issues in the design of a controller. However, due to the malfunctioning of the sensors and actuators, deterioration of plant equipment or even sometimes in the controller hardware, faults are developed. These faults not only degrade the system performance but may sometimes have disastrous implications. In order to ensure safe, reliable and cost effective operation of the process, the role of process monitoring or diagnostic systems is inevitable.

During the last three decades a great deal of attention has been given to model-based fault detection and isolation (FDI), see for instance [1–6] to list a few. It is evident that the process, in practice, is simultaneously influenced by unknown inputs (disturbances and noises) as well as by various faults which arise in sensors, actuators and/or process components. To this end a typical model based FDI scheme involves generation of residual signals (which carries the information of faults) and thresholds settings. The objectives of an FDI system are thus defined as (i) detection of faults as soon as possible (ii) avoidance of false alarms (which may be set due to unknown inputs). To this end, various optimization indices have been proposed in literature. These are H_2/H_2, H_∞/H_∞ and H_-/H_∞ [2,4,7]. Among these indices H_-/H_∞ is of particular interest. H_--index measures the minimum influence of faults on the residual signal and H_∞-norm measures the maximum influence of unknown inputs on the residual signal.

In the present work, a mixed H_-/H_∞ fault detection filter is proposed for switched linear systems. It is a very important class of hybrid systems [8,9]. A switched system consists of different modes that are either continuous or discrete and a

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switching law for switching among the modes [10,11]. Stability and control of these systems have been greatly investigated in literature [10,12–15]. An important issue in switched systems is the switching. Stability is greatly affected by the switching signal. There are mainly two types of switching signals that are considered in literature: (1) Time dependent switching signal (2) State dependent switching signal [10,16]. An associated concept is the dwell time. Results on stability and stabilization of slow switched systems using dwell time and average dwell time constraints can be found in [10,17–21] and the references therein. To the best of our knowledge,very little attention has been given to fault detection of aforementioned class of systems. Some important contribution is made in the recent past in this area. See for instance [22–30].

In [23] fault detection problem for switched systems using the H_-/H_∞ performance index has been discussed with a constant threshold for detection purposes. In [24] fault detection problem for uncertain discrete switched systems has been considered and an adaptive threshold has been designed for efficient fault detection. In [25] the fault detection problem is solved for discrete switched linear systems with the assumption that the switching signal is unknown. In [26] fault detection problem for switched linear systems with state delays has been discussed using a switched Lyapunov function approach. The robust fault detection filter (RFDF) designed in [27] for slow switched systems uses H_∞ optimization. The slow switched system considered consists of state delays and uncertainties in the system model. The robust fault detection filter is designed using Lyapunov–Krasovskii functional and average dwell time constraints for the slow switched system.

In the present work fault detection scheme is designed using H_-/H_∞ optimization. The state delays and uncertainties in the system model have not been considered which will be incorporated in the future. In H_-/H_∞ optimization, the maximum influence of unknown inputs on the residual signal is represented by H_∞-norm and the minimum influence of faults is represented by H_--index. In order to ensure robustness, H_∞ should be minimized and H_- should be maximized simultaneously. The solution to the fault detection problem, thus, obtained using H_-/H_∞ performance index will ensure that the residual signal is maximally sensitive to faults and simultaneously highly robust against unknown inputs. The paper in hand, inspired by [31], presents a solution to the fault detection problem for switched linear systems using the H_-/H_∞ optimization. A state space solution is provided to the fault detection problem for slow switched systems. The state space solution to the H_-/H_∞ fault detection (FD) problem presented here has the advantage that it can also achieve fault isolation. The average dwell time constraints for the slow switched systems will be considered to design the optimal fault detection filter for linear switched systems.

The rest of the paper is organized as follows: Preliminaries are given in Section 2. Section 3 states the fault detection problem for continuous switched systems and solution to the problem is then given in Section 4. Evaluation of residual and threshold computation is then given in Section 5. In Section 6 examples are provided showing the efficiency of the proposed method. The paper is then concluded in Section 7.

2. Notations and preliminaries

The notations used in this paper are standard and are described here. The set of real and complex matrices with dimensions $m \times n$ is denoted by $\Re^{m\times n}$ and $\mathbb{C}^{m\times n}$ respectively. For a matrix $A \in \mathbb{C}^{m\times n}$ the complex conjugate transpose is represented by A' and the transpose is represented by A^T. The upper singular value of a matrix A is represented by $\bar{\sigma}(A) = \sqrt{\bar{\lambda}(AA')}$ and the lower singular value by $\underline{\sigma}(A) = \sqrt{\underline{\lambda}(AA')}$ where $\bar{\lambda}$ and $\underline{\lambda}$ show the largest and smallest eigen values of the matrix. $A > 0$ means that a matrix is positive definite and $A < 0$ means that it is negative definite. $\Re(s)^{m\times n}$ shows a set of real rational matrix functions of s and $L_\infty^{m\times n}$ shows a set of matrix functions that have entries bounded on the extended imaginary axis. $H_\infty^{m\times n} \subset L_\infty^{m\times n}$ are the matrix functions that are analytic in the closed right half plane. A stable real rational matrix function of s is denoted by $\Re H_\infty^{m\times n}$. A transfer matrix function $G(s) = C(sI - A)^{-1}B + D$ is shown as either $G(s) \stackrel{s}{=} (A, B, C, D)$ or

$$G(s) \stackrel{s}{=} \left[\begin{array}{c|c} A & B \\ \hline C & D \end{array}\right].$$

If we have $G(s) \in \Re L_\infty^{m\times n}$ then the supremum of largest singular value known as the L_∞-norm is denoted by $\|G\|_\infty = \sup_{w\in\Re} \overline{\sigma}(G(jw))$ and $\|G\|_- = \inf_{w\in\Re} \underline{\sigma}(G(jw))$ is the infimum of the lower singular value. The pseudoinverse of a matrix A of order $m \times n$ is denoted by $A^\dagger$ with order $n \times m$, that is $A^\dagger A = I_n$ where I_n is an identity matrix of order n.

Lemma 1 *([32]). A switched system*

$$\dot{x}(t) = A_i x(t) + B_i u(t)$$
$$y(t) = C_i x(t) + D_i u(t)$$

where $i \in \{1, 2, \ldots, N\}$ is said to be globally uniformly asymptotically stable with average dwell time

$$\tau_a > \tau_a^* = \frac{\ln \mu}{\alpha}$$

and satisfies the H_∞ performance with index no greater than $\gamma = \max(\gamma_i)$ as well if there exist Lyapunov functions $V_i(x(t))$ $\forall i \in \{1, 2, \ldots, N\}$ such that

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