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Simultaneous fault detection and control for switched linear systems with mode-dependent average dwell-time

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ABSTRACT

This paper investigates the problem of the simultaneous fault detection and control (SFDC) for switched linear systems. To meet the control and detection objectives, the time-dependent detection filters and dynamic output feedback controllers are presented in SFDC under a mixed H_∞/H_- framework. A mode-dependent average dwell-time (MDADT) approach, which means that each subsystem has its own average dwell time, is adopted in this paper to reduce the conservativeness of the average dwell time method. And the discretized Lyapunov function (DLF) technique is first used to relax the MDADT constraints in SFDC. Some sufficient conditions for designing filters/controllers which satisfy the H_∞/H_- performance are given in terms of linear matrix inequalities (LMIs). What's more, a two-step algorithm to solve the SFDC problem is proposed. The effectiveness of the proposed method is illustrated through two simulation examples.

1. Introduction

Hybrid systems are powerful abstractions for modeling complex systems so that they have been used in a number of applications to provide models better reflecting the nature of control problems such as Markov jump systems, switched systems. Many problems for hybrid systems have been studied, such as dissipative control [1], stability analysis [2], dynamic output feedback control [3], H_∞ filter problem [4], estimator design [5] and so on. Specifically, switched system is a dynamical system that consists of a finite number of subsystems and a logical rule that orchestrates switching between these subsystems [6]. In recent years, the study of switched systems has received a growing attention. Many methods have been developed in the study of switched systems, such as common Lyapunov function approach [7], multiple Lyapunov functions approach [8], average dwell-time(ADT) technique [9].

Safe and reliable operation is an important issue to be addressed when design a control system. Controlled process has sensors, actuators, controller hardware, the process itself and so on. However, for the malfunctioning of the sensors and actuators, deterioration of plant equipment or the ageing of controller hardware, faults are developed. In the fault diagnosis research field, the diagnostic systems are often designed separately from the control algorithms, although it is highly desirable that both the control and diagnostic modules are integrated into one system module [10]. The simultaneous design unifies the control and detection units into a single unit which results in less complexity compared with the case of separate design; so, it is a reasonable approach [11]. Therefore, the simultaneous fault detection and control(SFDC) problem was proposed and has been attracted a lot of attention in the last two decades [12–14].

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Nowadays, fault detection (FD) has received increasing attention due to the increasing demand for higher performance, higher safety and reliability standards in engineering [15] and many FD approaches for different systems have been proposed in the literature. The FD problem study of switched systems has many results in the literature, e.g. [16–18]. Besides, the robust control problem study has many results as well, such as H_∞ control for switched systems [19,20], H_∞ control via switched scheme [21]. What's more, the SFDC study of switched systems also has received a growing attention [22,24–26]. The objectives of FD filter designing can be defined as (i) detecting faults as soon as possible (ii) avoiding false alarms for unknown inputs like disturbance. And the objectives of controller designing can be defined as minimizing the effect of the disturbance and fault on the controlled signal. However, it should be pointed out that the mentioned results [22,24,25] are presented in a ADT framework which can be replaced by the MDADT method for less conservativeness. Compared to the ADT method [27], the MDADT approach proposed in [28] is a time-dependent switching framework and permits each subsystem to have its own average dwell time. And the MDADT approach has been used in some literature [29].

The discretized Lyapunov function(DLF) technique has been widely used [30–33]. The basic idea of the DLF technique is to divide the domain of definition of matrix function into finite discrete points or smaller regions, thus reducing the choice of time-scheduled Lyapunov function into choosing a finite number of parameters. For the fact that the switched systems always have the average dwell-time requirement, it's feasible to divide the smallest average dwell time into finite regions by using DLF technique. In [33], H_∞ state feedback control for switched systems with dwell time constraint is considered based on the DLF technique. However, it's a pity that the famous ADT method is not applied. Besides, it's worth mentioning that MDADT method introduces additional constraints to guarantee the performance. In this paper, the DLF technique is first used to relax these constraints.

What's more, to satisfy the objectives of FD filter designing, among the existing results, various optimization methods have been proposed, such as H_∞ [22,23] optimization method and mixed H_∞/H_- [24,25] optimization method. H_- index can measure the maximum influence of the fault on the residual signal. Besides, H_∞ indexes can measure the minimum influence of the disturbance on the residual signal and the minimum influence of the disturbance and fault on the controlled signal. Besides, to deal with the H_- index, a method in [34] introduces a weighting matrix to transform the H_- constraint into a H_∞ constraint. However, it's not easy to select appropriate weights and the additional weights will increase the complexity of the fault detection systems.

In this paper, the problem of SFDC for a class of switched linear systems is investigated. The contributions in this paper are summarized as follows. (i)MDADT method is introduced to reduce the conservativeness. (ii)Compared to [24,25], the DLF approach is first used to relax the average dwell time constraints and time-dependent filters/controllers parameters are designed with the similar structures to the DLF. (iii)More general results are proposed, by introducing adjusting parameters. (iv)A two-step algorithm is proposed to obtain a set of suitable tuning matrices and fixed parameters when these matrices and parameters are not easy to find. It makes solving the SFDC problem more convenient than the result in [26]. Finally, a simulation example and a two-tank benchmark system example are given to show the effectiveness of the proposed method.

The following sections of this paper are organized as: in Section 2, the FD filters and controllers design, the definition of DLF and preliminary are presented. The FD filter and controller design conditions and a two-step algorithm are proposed in Section 3. The fault detection threshold is given in Section 4 and in Section 5, two simulation examples are given.

Notation. Standard notations are used in this paper. For a matrix P, P^T denotes its transpose and $He(P) \triangleq P + P^T$. $P > 0$ and $P < 0$ denote positive definite and negative definite, respectively. $\mathbb{R}^n$ denotes the n-dimensional Euclidean space and $\mathbb{R}^{n\times m}$ is the set of all $n \times m$ real matrices. The notation $\|x\|_2$ refers to the Euclidean vector norm of vector $x \in \mathbb{R}^n$. $\lambda_{min}(P)$ and $\lambda_{max}(P)$ denote the minimum eigenvalue of P and the maximum eigenvalue of P, respectively.

2. Preliminaries and problem statement

2.1. System description

Consider the following continuous-time switched linear systems

$$\begin{aligned} \dot{x}(t) &= A_{\sigma(t)}x(t) + B_{\sigma(t)}u(t) + B_{d\sigma(t)}d(t) + B_{f\sigma(t)}f(t) \\ y(t) &= C_{\sigma(t)}x(t) + D_{d\sigma(t)}d(t) + D_{f\sigma(t)}f(t) \\ z(t) &= E_{\sigma(t)}x(t) + F_{d\sigma(t)}d(t) + F_{f\sigma(t)}f(t) \end{aligned} \tag{1}$$

where $x(t) \in \mathbb{R}^n$ is the state, $u(t) \in \mathbb{R}^p$ is the control input, $y(t) \in \mathbb{R}^q$ is the measured output, $z(t) \in \mathbb{R}^m$ is the controlled output, $d(t) \in \mathbb{R}^d$ is the disturbance input, $f(t) \in \mathbb{R}^f$ represents the fault signal. Piecewise constant function $\sigma(t)$ which takes values in the finite set $\mathbb{N} = \{1, 2, \ldots, r\}$, $r > 1$ is the switching signal and $\sigma(t) = i$ means the ith subsystem is activated. The switching instants are expressed by a sequence $\{t_0, t_1, \ldots, t_k, \ldots\}$ where t_0 denote the initial time and t_k denotes the kth switching instant and the i_kth subsystem is activated when $t \in [t_k,\ t_{k+1})$. $A_i, B_i, B_{di}, B_{fi}, C_i, D_{di}, D_{fi}, E_i, F_{di}, F_{fi}$ are constant matrices of the appropriate dimensions.