Applied Mathematics and Computation 293 (2017) 575–585

Contents lists available at ScienceDirect

Applied Mathematics and Computation

journal homepage: www.elsevier.com/locate/amc

Fault detection for discrete-time linear systems based on descriptor observer approach☆

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ARTICLE INFO

Keywords:
Descriptor observer
Fault detection filter
Linear system

ABSTRACT

This paper investigates the problem of actuator fault detection filter design for discrete-time linear systems with output disturbance. By using the descriptor observer method, an H_∞ fault detection filter is designed to guarantee the residual system is admissible and satisfies the H_∞ performance. By utilizing Lyapunov function approach, a sufficient condition for the admissible of the residual system is obtained in the form of linear matrix inequality (LMI). The desired fault detection filter can be designed by solving a set of LMIs. Finally, a numerical example is proposed to illustrate the effectiveness of the developed method.

1. Introduction

It is a common phenomena that the practical engineering systems are affected by the unexpected variations in external surroundings, normal wear in components, or sudden changes in signals. Due to these accidental reasons, different kinds of malfunctions or imperfect behaviors may appear during normal operations, and these phenomenons are so-called faults. Once the fault cannot be deleted immediately, it may cause catastrophic result. The appearance of fault diagnosis (FD) and fault tolerant control (FTC) techniques provide an efficient opportunity to deal with various fault cases. FTC can be divided into two types: active and passive. Passive FTC is so-called reliable control, which needs to design a feedback controller tolerating all kinds of faults [1,2]. However, as for active FTC, the first step is fault diagnosis, its tasks are to detect the fault and give the location and magnitude of the fault [3], then bases on the obtained online fault information to adjust the control input. It can be deduced that fault detect is the first step to realize active FTC. Therefore, the study of fault detection problem is not only theoretically interesting but also practically important.

For the past decades, many researchers have devoted themselves to investigating fault detection problem for various dynamic systems, and fruitful results can be found in several excellent papers ([4–10] and references therein) and books [11,12]. Presently, there are many methods have been employed in dealing with this issue, such as the model-based fault detection approach [13], the parameter estimation approach [14], and the generalized likelihood method [15]. Among these methods, the model-based method is the most common way, which is to design a fault detection filter or observer generating a residual and compare it with a predefined threshold. When the residual evaluation function has a value larger than the threshold, an alarm is generated. For examples, fault detection filter design for linear time-invariant systems was solved in [16]. Fault detection for Markov jump systems and uncertain fuzzy systems is separately studied in [17] and [18].

☆ This work is supported by Natural Science Foundation of Jiangsu Province (BK20140457) and Fund of Huaiyin Institute of Technology (HGC1309).
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http://dx.doi.org/10.1016/j.amc.2016.08.052
0096-3003/

In reviewing of the development of these theories and techniques for different fault detection system designs, one of the commonly adopted ways in fault detection is to introduce a performance index and formulate the fault detection as an optimization problem, see [19–21] and the references therein, in which the H_∞ norm of transfer-function matrix from unknown input to residual is accepted as a suitable and effective measure to estimate the influence of the unknown inputs, the H_∞ norm (the smallest nonzero singular value) of transfer function from fault to residual has been proposed to evaluate the system sensitivity to the faults. An H_∞ filtering formulation of fault detection has also been presented to solve robust fault detection for uncertain systems, and has received much attention, see for instance [22]. Different from the former scheme, the later one is to make the error between residual and fault (or, more generally, weighted fault) as small as possible, and provides an effective approach to uncertain system fault detection with the aid of an optimization tool, such as the LMI technique [23].

Until now, the problem of actuator fault detection for discrete-time linear systems with output disturbance has not been considered yet. Therefore, it motivates us to study this interesting and challenging issue in this paper. The advantages of this paper are shown as the following aspects: Firstly, the actuator fault detection problem for discrete-time linear systems is resolved by using descriptor observer approach; Secondly, for control input, actuator fault and unknown output disturbance in the system, a fault detection filter is constructed such that the residual system is admissible with H_∞ performance index; Thirdly, based on Lyapunov function method and LMI technique, a sufficient condition for the admissibility of the residual system is obtained. All the results are formulated in the form of LMIs; Fourthly, the estimation of the state and disturbance can be obtained via designing the descriptor observer simultaneously. Finally, to demonstrate the feasibility and effectiveness of the proposed method, a simulation example is included.

The rest of the paper is organized as follows. Section 2 formulates the problem under consideration. Section 3 presents the fault detection filter design for the discrete-time linear system. A numerical example is illustrated in Section 4 to show the usefulness and applicability of the proposed approach, and the paper is concluded in Section 5.

Notations: Throughout this paper, a real symmetric matrix $P > 0$ denotes P being a positive definite matrix, and $A > B$ means $A - B > 0$, M^T denotes the transpose of the matrix M. I is used to denote an identity matrix with appropriate dimension. The notation $l_2[0, \infty)$ refers to the space of square summable infinite vector sequences with the usual norm $\|\cdot\|_2$. Matrices, if their dimensions are not explicitly stated, are assumed to have compatible dimensions for algebraic operations.

2. Problem statements and preliminaries

Consider the following discrete-time linear system:

$$x(t+1) = Ax(t) + Bu(t) + Ff(t) \tag{1}$$

$$y(t) = Cx(t) + Dd(t) \tag{2}$$

where $x(t) \in \mathbb{R}^n$ is the state vector, $u(t) \in \mathbb{R}^m$ is the control input vector, $d(t) \in \mathbb{R}^d$ is the output disturbance signal, $f(t) \in \mathbb{R}^f$ is the fault vector, and $y(t) \in \mathbb{R}^p$ is the measurable output vector. A, B, C, D and F are constant matrices with appropriate dimensions.

For the purpose of this paper, the following assumptions are given:

- (A, C) is observable;
- Matrices D have full column rank.

Define the augmented states and matrices:

$$\bar{x}(t) = \begin{bmatrix} x(t) \\ d(t) \end{bmatrix}, \quad \bar{E} = \begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix}, \quad \bar{A} = \begin{bmatrix} A & 0 \\ 0 & -D \end{bmatrix},$$
$$\bar{B} = \begin{bmatrix} B \\ 0 \end{bmatrix}, \quad \bar{D} = \begin{bmatrix} 0 \\ D \end{bmatrix}, \quad \bar{F} = \begin{bmatrix} F \\ 0 \end{bmatrix}, \quad \bar{C} = \begin{bmatrix} C & D \end{bmatrix}. \tag{3}$$

then the augmented descriptor system is expressed:

$$\bar{E}\bar{x}(t+1) = \bar{A}\bar{x}(t) + \bar{B}u(t) + \bar{D}d(t) + \bar{F}f(t) \tag{4}$$

$$y(t) = \bar{C}\bar{x}(t) \tag{5}$$

Construct the following fault detect filter for system (4)-(5):

$$\hat{\bar{x}}(t+1) = A_f\hat{\bar{x}}(t) + B_f y(t) \tag{6}$$

$$r(t) = C_f\hat{\bar{x}}(t) + D_f y(t) \tag{7}$$

where $\hat{\bar{x}}(t) \in \mathbb{R}^{n+d}$ is the filter's state, $r(t) \in \mathbb{R}^p$ is the so-called residual signal. The matrices A_f, B_f, C_f and D_f are the filter parameters to be determined.