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Actuator fault detection filter design for discrete-time systems with a descriptor system method

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ABSTRACT

In this paper, the problem of fault detection filter design for discrete-time systems is considered. By means of a descriptor system method, this paper designs a fault detection filter such that the residual system is admissible and satisfies the H_∞ performance index when control inputs, actuator faults and unknown bounded disturbances exist. Based on the Lyapunov functional approach, a sufficient condition for the admissibility of the residual system is expressed via linear matrix inequalities and the desired detection filter is obtained. A numerical example is provided to show the feasibility and applicability of the proposed method.

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1. Introduction

Descriptor systems provide a description of the dynamic as well as the algebraic relationship between the chosen descriptor variables simultaneously, thus they are a natural mathematical representation for many practical systems. They are named as singular systems, implicit systems, generalized state-space systems, differential algebraic systems or semi-state systems. Descriptor systems express a larger class of systems than the general linear system models, the fields of whose extensive applications are electrical circuit, power system, economics and so on. Many results on descriptor systems [1,5,13,34,17,23] have been proposed in recent years, and many papers on descriptor discrete-time systems are included. The problems of stability and stabilization of discrete singular systems have been considered in [25,2,28,27]. Robust H_∞ control for descriptor discrete-time Markovian jump systems has been studied in [8]. The problem of control for discrete singular hybrid systems [24] has been solved. Robust stability of discrete-time singular fuzzy systems has been investigated in [26]. For the past few years, filtering points of view have received increasing interests. Some representative prior results on this general topic have been demonstrated. The filters have developed for stochastic systems [6,15] or polytopic systems [11]. For singular systems [22,33], H_∞ filter has been designed. The filter design problem has been solved for discrete-time descriptor systems [12,7].

Modern engineering systems are more and more large-scale and complicated, and they can cause losses of people and huge property losses in the event of accident. Therefore, the reliability and security of modern complex systems is vitally significant and has been widely paid attention. Fault detection has extensive applications, such as aircraft autopilot, satellites, space shuttle, nuclear reactor, steam turbine generator set, large power grid system, petroleum and chemical process and equipment, aircraft [16] and ship engine, automobile, metallurgical equipment, mining equipment and machine tools, and other fields. In the past three decades, fault detection and isolation algorithms have been intensive research results. Many scholars pay attention to the fault detection. The source of false alarm stems from unknown inputs, uncertainties, faults, disturbances and so on in any industrial systems. The model-based approach is that a residual signal is constructed and compared with a predefined threshold via a state observer or filter. When the residual evaluation function has a value larger than the threshold, an alarm is produced. In [10,14], the problem of fault detection for networked control systems has been reported. Some papers on the fault detection filter have been recently published in [19,29,30,35,36]. The problem of fault

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detection for discrete-time systems [18,20,21] has been considered. In finite-frequency domain, fault detection filter for T–S fuzzy discrete systems has been constructed in [31]. H_∞ fault detection for linear singular system [4] has been addressed. Based on an average dwell time approach, fault detection for discrete-time switched singular system has been studied in [9]. For Markovian jump singular systems with intermittent measurements [32], the problem of fault detection filter design has been presented. To the best of the authors' knowledge, the problem of fault detection design for discrete-time systems with actuator faults based on a descriptor system method has not yet been fully investigated, which motivates the research in this paper.

This paper solves the problem of fault detection filter design for discrete-time systems with a descriptor system method. This paper designs a fault detection filter to make that the residual system be admissible and satisfy the H_∞ performance index for control inputs, actuator faults and unknown bounded disturbances. By using the Lyapunov functional approach, a sufficient condition for the admissibility of the residual system is shown in form of linear matrix inequalities. The desired fault detection filter is obtained. A numerical example is provided to illustrate the effectiveness of the proposed method.

Notation: Throughout this paper, I is the unit matrix of appropriate dimensions; T stands for the matrix transposition; $\mathbb{R}^n$ denotes the n-dimensional Euclidean space; the notation $X>Y (X\geq Y)$ means that the matrix $X-Y$ is positive definite ($X\geq Y$ is semi-positive definite, respectively); A^{-1} denotes the matrix A inverse; $\deg(B)$ and $\det(B)$ denote the degree and the determinant of the square matrix B, respectively; $\|\cdot\|$ denotes the Euclidean norm for vectors or the spectral norms of matrices; $diag\{\cdot\}$ stands for a block diagonal matrix; the symmetric terms in a symmetric matrix are denoted by $*$; $\mathrm{Re}(\cdot)$ is the real part of the argument; $l_2[0,\infty)$ means the space of square summable infinite sequence.

2. Problem formulation and preliminaries

In this paper, consider the following discrete-time systems with actuator faults:

$$x(k+1)=Ax(k)+Cu(k)+Ff(k), \tag{1}$$

$$y(k)=Bx(k)+Dd(k), \tag{2}$$

where $x(k)\in\mathbb{R}^n$ is the state vector, $y(k)\in\mathbb{R}^r$ is the measured output. $d(k)\in\mathbb{R}^p$, $u(k)\in\mathbb{R}^s$ and $f(k)\in\mathbb{R}^q$ are the output bounded disturbances, the control input and the actuator fault, respectively, and belong to $l_2[0,\infty)$. Matrices A, B, C, D and F are known matrices with appropriate dimensions and D is assumed to be full column rank.

Define

$$h(k)=Dd(k),\quad \overline{x}(k)=\begin{bmatrix}x(k)\\ h(k)\end{bmatrix},$$

$$\overline{E}=\begin{bmatrix}I&0\\0&0\end{bmatrix},\quad \overline{A}=\begin{bmatrix}A&0\\0&-I\end{bmatrix},$$

$$\overline{C}=\begin{bmatrix}C\\0\end{bmatrix},\quad \overline{D}=\begin{bmatrix}0\\I\end{bmatrix},\quad \overline{F}=\begin{bmatrix}F\\0\end{bmatrix},$$

$$\overline{B}=[B\ \ I],$$

then the augmented descriptor system is obtained as follows:

$$\overline{E}\overline{x}(k+1)=\overline{A}\overline{x}(k)+\overline{C}u(k)+\overline{D}h(k)+\overline{F}f(k), \tag{3}$$

$$\overline{y}(k)=y(k)=\overline{B}\overline{x}(k). \tag{4}$$

For system (3)–(4), design the following filter:

$$\hat{\overline{x}}(k+1)=A_f\hat{\overline{x}}(k)+B_f\overline{y}(k), \tag{5}$$

$$r(k)=C_f\hat{\overline{x}}(k)+D_f\overline{y}(k), \tag{6}$$

where $\hat{\overline{x}}(k)=[\hat{x}^T(k)\hat{h}^T(k)]^T\in\mathbb{R}^{n+p}$ is the state of the filter and $r(k)$ is the residual signal. Matrices A_f, B_f, C_f and D_f are the design parameters to be determined. The estimation of the state $x(k)$ and disturbances $d(k)$ can be obtained in terms of the fault detection filter, simultaneously. The estimation of disturbances can be shown in form of $\hat{d}(k)=(D^TD)^{-1}D^T\hat{h}(k)$.

In order to obtain the residual generation for system (3)–(4), our aim is to construct a fault detection filter. For a given stable weighting matrix, $W_f(s)$, introduce the weighted fault $\hat{f}(s)=W_f(s)f(s)$. One minimal realization of $\hat{f}(s)=W_f(s)f(s)$ is supposed that

$$\tilde{x}(k+1)=A_w\tilde{x}(k)+C_wf(k), \tag{7}$$

$$\hat{f}(k)=B_w\tilde{x}_k+D_wf(k), \tag{8}$$

where $\tilde{x}(k)\in\mathbb{R}^{nw}$ is the state of the weighted fault, $f(k)\in\mathbb{R}^q$ is the original fault, $\hat{f}(k)\in\mathbb{R}^q$ is the weighted fault. A_w, B_w, C_w and D_w are known constant matrices.

Remark 2.1. Similar to the existing fault detection literature [9,21,32,37], $W_f(s)$ could limit the frequency ranges where the faults could be identified and improve the system performance. $W_f(s)$ is the full rank vector, diagonal or identity matrix.

Define

$$e(k)=[\overline{x}^T(k)\ \ \hat{\overline{x}}^T(k)\ \ \tilde{x}^T(k)]^T,$$
$$\omega(k)=[u^T(k)\ \ h^T(k)\ \ f^T(k)]^T,$$
$$r_e(k)=r(k)-\hat{f}(k),$$

and considering (3)–(4), (5)–(6), (7)–(8), we can have the following residual system:

$$\overline{E}_ee(k+1)=\overline{A}_ee(k)+\overline{C}_e\omega(k), \tag{9}$$

$$r_e(k)=\overline{B}_ee(k)+\overline{D}_e\omega(k), \tag{10}$$

where

$$\overline{E}_e=\begin{bmatrix}\overline{E}&0&0\\0&I&0\\0&0&I\end{bmatrix},$$

$$\overline{A}_e=\begin{bmatrix}\overline{A}&0&0\\B_f\overline{B}&A_f&0\\0&0&A_w\end{bmatrix},$$

$$\overline{C}_e=\begin{bmatrix}\overline{C}&\overline{D}&\overline{F}\\0&0&0\\0&0&C_w\end{bmatrix},$$

$$\overline{B}_e=[D_f\overline{B}\ \ C_f\ \ -B_w],$$
$$\overline{D}_e=[0\ \ 0\ \ -D_w].$$

Next, two definitions used in main results are introduced.

Definition 2.1 (*Dai* [5]). The discrete-time descriptor system $\overline{E}_ee(k+1)=\overline{A}_ee(k)$ is said to be admissible if it is regular, causal and asymptotically stable, that is, the following conditions hold:

- The pair $(\overline{E}_e,\overline{A}_e)$ is said to be regular if $\det(s\overline{E}_e-\overline{A}_e)$ is not identically zero.
- The pair $(\overline{E}_e,\overline{A}_e)$ is said to be causal if $\deg(\det(s\overline{E}_e-\overline{A}_e))=\mathrm{rank}(\overline{E}_e)$.
- The pair $(\overline{E}_e,\overline{A}_e)$ is said to be stable if $\{s|\det(s\overline{E}_e-\overline{A}_e)=0\}\subset\{s|s\in\mathbb{C},\mathrm{Re}(s)<0\}$.

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