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Actuator fault detection and estimation for the Lur'e differential inclusion system ☆

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ABSTRACT

This paper deals with actuator fault detection and estimation for the Lur'e differential inclusion system. An adaptive full-order observer is used to detect the occurrence of the actuator fault. Then, based on a reduced-order observer, an approach to estimate the actuator fault is presented. A simulation of rotor system is given to illustrate the effectiveness of the proposed method.

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1. Introduction

Recently, the investigation of the Lur'e differential inclusion (DI) system has become a hot topic in the field of control [1–8]. The research motivation originates from the need to analyze the systems with non-smooth or discontinuous behavior, such as control dynamic systems with Coulomb friction, circuits systems with ideal diode, neural networks with discontinuous neuron activations and so on. In the Lur'e DI system, the set-valued mapping is only set-valued on a countable set of points and continuous on the other points. The current research mainly focuses on two aspects: one is the stabilization problem [3]. Under the extension of a Popov-like criterion, [3] designed a state feedback law to stabilize the Lur'e DI system. The other is the observer design [4–8]. [4,5] presented the observer design method for the Lur'e DI system by passive approach, it should be noted that [5] verified the well-posed property of the observer. [6] proved the existence of the reduce-order observer under the same conditions as that in [5]. By using the theory of adaptive observer, [7] designed an adaptive observer for the Lur'e DI system with uncertain parameters. [8] considered the non-fragile observer with disturbance attenuation for the Lur'e DI system. Besides the mentioned references, there are also other works on observers for the Lur'e DI system, such as [9,10].

In many real systems, the problem of fault detection and isolation (FDI) is very important because the actuator or sensor fault always arises. Many approaches have been well developed for FDI, such as neural-network-based method [11,12], system identification method [13,14], parity relations approach [15,16], the observer-based method [17–27]. Among these approaches, observer-based method has been studied extensively and proved to be one of the most effective method. By the

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theory of eigenstructure assignment, full-order observer was constructed for FDI [17]. Sliding mode observer has been used successfully in FDI context by Edwards et al. [18], then it was extended to study the system with sensor fault and uncertainty respectively by Tan and Edwards [19,20]. By using the theory of differential geometry, nonlinear observer has been designed for FDI of nonlinear systems [21]. For a class of nonlinear systems with uncertain parameters, the adaptive observer was employed for FDI [22]. Fault estimation is also important in FDI problem, because the size and characteristics of the fault can be determined if the fault is estimated. Based on the detection observer, the fault was reconstructed to converge to the real value of the fault [19,20,23–27].

We know that the fault may occur in the actuator of the Lur'e DI system, it is important to find a strategy to determine whether the fault would happen. If the fault occurs in the actuator, it is necessary to reconstruct the fault. However, to the authors' best knowledge, little attention has been paid to the FDI problem for the Lur'e DI system. Motivated by the previous discussion, this paper considers actuator fault detection and estimation for the Lur'e DI system. The paper is organized as follows: Section 2 presents the problem formulation and preliminaries. Section 3 designs an adaptive full-order observer to detect the actuator fault. Section 4 presents a method to estimate the actuator fault based on a reduced-order observer. Section 5 gives an example of rotor system to illustrate the effectiveness of the proposed method.

Notations: Throughout this paper, R^n denotes the n-dimensional Euclidean space, $R^{n\times m}$ is the set of $n\times m$ real matrices. $||x||$ denotes the Euclidean norm of the vector x, x^T stands for the transposition of the vector x, A^T is the transposition of the matrix A, $rank(A)$ represents the rank of the matrix A and $\lambda_{\min}(A)$ denotes the minimal eigenvalue of the matrix A. $P>(<)0$ means the positive (negative) definite matrix P with $P=P^T, I$ is the identity matrix with appropriate dimensions. $Graph(\mathcal{F})$ stands for the graph of the set-valued function $\mathcal{F}(x)$, i.e., $Graph(\mathcal{F})=\{(x,x^*)|x^*\in\mathcal{F}(x)\}$. Absolutely continuous is shorten as AC.

2. Problem formulation and preliminaries

Let us consider the following Lur'e DI system with actuator fault:

$$\begin{cases} \dot{x}=Ax+G\omega+D\Phi(x)+Bu+Eu_f, \\ \omega\in-\rho(Hx), \\ y=Cx, \end{cases} \tag{1}$$

where $x\in R^n$ is the state, $u\in R^m$ is the control input, and $y\in R^q$ is the measurable output. $\rho:R^r\to R^r$ is a set-valued mapping, $\omega\in R^r$ is the output of ρ and stands for the multi-valued nonlinear input of the system. $\Phi:R^n\to R^p$ is a known smooth matrix function. The signal $u_f\in R^l$ represents the unknown actuator fault vector, the norm of which is bounded. $A\in R^{n\times n}, G\in R^{n\times r}, D\in R^{n\times p}, B\in R^{n\times m}, E\in R^{n\times l}, H\in R^{r\times n}$ and $C\in R^{q\times n}$ are determined matrices.

The nonlinear multi-valued term $\omega\in-\rho(Hx)$ plays an important role in practical applications when we have to adopt accurate models for the real systems. It is used to describe Coulomb friction in the rotor system, which can be seen from the Simulation part.

Firstly, we give some basic definitions of DI, detailed presentation is referred to [28].

Definition 1. [28] Let $J\subset R^m$. A set-valued mapping $\mathcal{F}:J\to R^m$ with non-empty values is said to be upper semi-continuous at $x\in J$, if for any open set U containing $\mathcal{F}(x)$, there exists an open neighborhood M of x such that $\mathcal{F}(M)\subset U$. The mapping $\mathcal{F}$ is said to be upper semi-continuous if it is upper semi-continuous at every $x\in J$.

Definition 2. [28] Let $\mathcal{F}(t,x(t))$ be a set-valued function. A function $x:[t_0,\infty)\to R^n$ is a solution to the DI $\dot{x}(t)\in\mathcal{F}(t,x(t))$ with $x(t_0)=x_0$, if $x(t)$ is AC and satisfies $\dot{x}(t)\in\mathcal{F}(t,x(t))$ for almost all $t\in[t_0,\infty)$.

Definition 3. [28] A set-valued function $\mathcal{F}(x):R^n\to R^n$ is called monotone if its graph is monotone in the sense that for all $(x,y),(x^*,y^*)\in Graph(\mathcal{F})$ it holds that $(y-y^*)^T(x-x^*)\geqslant 0$.

In order to establish the main results of this paper, we need the following assumptions.

Assumption 1. H and C are of full row rank and E is of full column rank, i.e., $rank(H)=r<n, rank(C)=q<n$ and $rank(E)=l<n$.

Assumption 2. The set-valued mapping $\rho(\cdot)$ satisfies:

Assumption 2-1. $\rho(\cdot)$ is non-empty, convex, closed, bounded and only set-valued on a countable set of points, and is continuous on the other points.

Assumption 2-2. $\rho(\cdot)$ is monotone.

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