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An actuator fault reconstruction scheme for linear systems

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ABSTRACT

This paper presents an actuator fault reconstruction scheme that can be classified into an algebraic decomposition approach in which the original system is decomposed into two subsystems: a fault-free subsystem and a fault-dependent one. From the result of such algebraic decomposition, the fault estimate is obtained as a set of combinational functions of the system input, the measurement output, the estimate of certain linear functionals involving the state of the fault-free subsystem and the first-order derivative of the measurement output. Here a functional observer and robust exact differentiators are adopted to provide the estimate of the linear functionals of the state of the fault-free subsystem and the derivative of the measurement output, respectively. The proposed method is verified through two numerical examples of seventh-order aircraft and fourth-order crane models.

1. Introduction

During the last four decades, fruitful results have been reported about fault-tolerant control (FTC) methods and their applications in a variety of engineering systems [1–3]. According to whether there is the fault detection and isolation (FDI) unit or not, existing efforts in an FTC system design can be classified into two main approaches: passive FTC without the FDI unit and active FTC with the FDI unit. It is well known that active FTC has a better performance because the FDI unit offers the fault information for controller, and then the controller can adjust itself on-line, reducing the conservatism in the controller design [4,5].

FDI that plays a very important role in active FTC has become a hot research topic. During the past decade, various effective results, such as sliding mode observers (SMOs) [6,7], adaptive control strategies [8–11], unknown input observers (UIOs) [12,13], fuzzy observers [14–16] and so on, have been developed. Further investigations on this topic, with a more application-oriented character, have been proposed for reconfiguration in flight control [5,17–22], fault accommodation in vehicles [23,24] and FTC in wind turbine systems [25].

Among the methods described above, it is noteworthy that specific attention is paid to UIOs and SMOs, which have been widely employed to estimate faults and extended to reconstruct unknown inputs such as disturbances and faults [26–29]. UIOs have been constructed in two different ways: an algebraic decoupling approach and a modelling approach [30]. When the information on the unknown input is available, a mathematical modelling of the unknown input may be possible. Then, an augmented model can be obtained by combining the original system model with the unknown input model. Based on the augmented model, state observers can be developed to reconstruct the state and the unknown input [31–33]. The SMO can be also constructed to estimate simultaneously unknown inputs and measurement noises [34], actuator and sensor faults [35] and sensor faults [36] with the knowledge of boundedness of the values to be estimated. On the other hand, when the information on the unknown input is unavailable, an algebraic decoupling approach is preferable as far as the decoupling condition is satisfied. In Ref. [37], the design of a UIO was proposed for linear systems. The first step of the UIO design is to decompose the original system into a disturbance-free subsystem and a disturbance-dependent one. With the assumption that some existence conditions are satisfied, the state variables can be estimated. Recently, the UIO design was extended to the system with faults and disturbances [38]. A further result to get the finite-time converging estimate of faults that converges in a pre-determined time was reported in Ref. [39].

In this paper, based on novel combination of an algebraic decomposition of the original system, a functional observer and measurement output differentiators, an actuator fault reconstruction scheme for linear systems is presented. The scheme is formulated from the decomposition of the original system into two subsystems: a fault-free subsystem and a fault-dependent subsystem. Such a formulation gives a

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result on the fault estimate that depends on the system input, the measurement output, the estimate of certain linear functionals of the state of the fault-free subsystem and the first-order derivative of the measurement output. As a result, the performance of the actuator fault reconstruction depends entirely on the estimation algorithm of the linear functionals of the state of the fault-free subsystem and the algorithm to estimate the first-order derivative of the measurement output.

In this paper, associated with the existing works (for example Refs. [37–39]) for the design of fault reconstruction that are based on the state observer based state estimation, two problems are treated. First, the order of the fault-free subsystem obtained from the algebraic decomposition may be high. In many applications, the entire state vector is not really needed to be estimated, but rather, some function(s) of the state vector. Then, it would make sense to try to reduce the order of the observer (if possible) in order to reduce computational effort in real-time implementation. This leads to develop functional observers, which is the main research motivation of this paper. In this paper, a function observer is designed to estimate the linear functionals of the state of the fault-free subsystem. Second, the assumption that the derivative of the measurement output is available should be removed. To resolve this problem, an exact differentiator algorithm is adopted. The proposed fault reconstruction scheme is applied to the actuator fault estimates of seventh-order aircraft and fourth-order crane models.

2. System description and preliminaries

2.1. System description

Consider a linear system subject to actuator faults described by:

$$\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}\boldsymbol{u} + \boldsymbol{F}\boldsymbol{f} \tag{1a}$$

$$\boldsymbol{y} = \boldsymbol{C}\boldsymbol{x} \tag{1b}$$

where $\boldsymbol{x} \in \Re^n$ is the state vector, $\boldsymbol{u} \in \Re^m$ is the input vector, $\boldsymbol{f} \in \Re^q$ is the actuator fault vector and $\boldsymbol{y} \in \Re^p$ is the output vector. $\boldsymbol{A}$, $\boldsymbol{B}$, $\boldsymbol{F}$ and $\boldsymbol{C}$ are known real constant matrices of appropriate dimension. The concept of the fault reconstruction scheme presented in this paper is based on an algebraic decomposition of the given system ((1a) and (1b)).

2.2. Transformation matrices and decomposition

The first step of the proposed fault estimation scheme is to decompose the given system ((1a) and (1b)) into two subsystems: a fault-free subsystem and a fault-dependent one, by applying a series of transformations. Among various decoupling methods, the transformations adopted here are based on the results of the papers [37,38] as follows.

Assume rank($\boldsymbol{C}$) = p and rank($\boldsymbol{F}$) = rank($\boldsymbol{CF}$) = q, where $q < p \leq n$. Then one can choose a nonsingular matrix,

$$\boldsymbol{T} = \begin{bmatrix} \boldsymbol{N} & \boldsymbol{F} \end{bmatrix}, \ \boldsymbol{N} \in \Re^{n\times(n-q)} \tag{2}$$

In Eq. (2), $\boldsymbol{N} = \boldsymbol{P}\boldsymbol{N_o}$, where $\boldsymbol{N}_o \in \Re^{n\times(n-q)}$ is an arbitrary matrix such that the matrix $[\boldsymbol{N_o}\ \boldsymbol{F}]$ is nonsingular and $\boldsymbol{P} \in \Re^{n\times n}$ is an idempotent matrix defined as:

$$\boldsymbol{P} = \boldsymbol{I}_n - \boldsymbol{F}(\boldsymbol{CF})^{+}\boldsymbol{C} \tag{3}$$

where + means the left pseudoinverse. It should be noticed that the matrix $\boldsymbol{T}$ is nonsingular if the matrix $[\boldsymbol{N_o}\ \boldsymbol{F}]$ is nonsingular [38].

With the transformation matrix given by Eq. (2), the given system ((1a) and (1b)) can be rewritten as:

$$\dot{\bar{\boldsymbol{x}}} = \bar{\boldsymbol{A}}\bar{\boldsymbol{x}} + \bar{\boldsymbol{B}}\boldsymbol{u} + \bar{\boldsymbol{F}}\boldsymbol{f} \tag{4a}$$

$$\boldsymbol{y} = \bar{\boldsymbol{C}}\bar{\boldsymbol{x}} \tag{4b}$$

where $\boldsymbol{x} = \boldsymbol{T}\bar{\boldsymbol{x}} = \boldsymbol{T}\begin{bmatrix} \bar{\boldsymbol{x}}_1 \\ \bar{\boldsymbol{x}}_2 \end{bmatrix}$, $\bar{\boldsymbol{A}} = \boldsymbol{T}^{-1}\boldsymbol{A}\boldsymbol{T} = \begin{bmatrix} \bar{\boldsymbol{A}}_{11} & \bar{\boldsymbol{A}}_{12} \\ \bar{\boldsymbol{A}}_{21} & \bar{\boldsymbol{A}}_{22} \end{bmatrix}$, $\bar{\boldsymbol{B}} = \boldsymbol{T}^{-1}\boldsymbol{B} = \begin{bmatrix} \bar{\boldsymbol{B}}_1 \\ \bar{\boldsymbol{B}}_2 \end{bmatrix}$, $\bar{\boldsymbol{F}} = \boldsymbol{T}^{-1}\boldsymbol{F} = \begin{bmatrix} 0 \\ \boldsymbol{I}_q \end{bmatrix}$, $\bar{\boldsymbol{C}} = \boldsymbol{C}\boldsymbol{T} = \begin{bmatrix} \boldsymbol{CN} & \boldsymbol{CF} \end{bmatrix}$ with $\bar{\boldsymbol{x}}_1 \in \Re^{n-q}$, and $\bar{\boldsymbol{x}}_2 \in \Re^q$.

In Eq. (4a), the differential equations of $\bar{\boldsymbol{x}}_2$ that involve the terms of $\boldsymbol{f}$ can be represented by $\bar{\boldsymbol{x}}_1$ and $\boldsymbol{y}$ through another transformation described below. Under the assumption of rank($\boldsymbol{CF}$) = q, where $q < p$, there exist a nonsingular matrix,

$$\boldsymbol{U} = \begin{bmatrix} \boldsymbol{CF} & \boldsymbol{Q} \end{bmatrix}, \boldsymbol{Q} \in \Re^{p\times(p-q)} \tag{5}$$

In Eq. (5), $\boldsymbol{Q} = \boldsymbol{M}\boldsymbol{Q_o}$, where $\boldsymbol{Q}_o \in \Re^{p\times(p-q)}$ is an arbitrary matrix such that the matrix $[\boldsymbol{CF}\,\boldsymbol{Q_o}]$ is nonsingular and $\boldsymbol{M} \in \Re^{p\times p}$ is an idempotent matrix defined as:

$$\boldsymbol{M} = \mathbf{I}_p - [(\boldsymbol{CF})^T]^{-}(\boldsymbol{CF})^T, \boldsymbol{M} \in \Re^{p\times p} \tag{6}$$

where − denotes the right pseudoinverse. As shown in Ref. [38], the matrix $\boldsymbol{U}$ is nonsingular if the matrix $[\boldsymbol{CF}\,\boldsymbol{Q_o}]$ is nonsingular.

Defining

$$\boldsymbol{U}^{-1} = \begin{bmatrix} \boldsymbol{U}_1 \\ \boldsymbol{U}_2 \end{bmatrix} \tag{7a}$$

gives

$$\boldsymbol{U}^{-1}\boldsymbol{U} = \begin{bmatrix} \boldsymbol{U}_1 \\ \boldsymbol{U}_2 \end{bmatrix}\begin{bmatrix} \boldsymbol{CF} & \boldsymbol{Q} \end{bmatrix} = \begin{bmatrix} \boldsymbol{U}_1\boldsymbol{CF} & \boldsymbol{U}_1\boldsymbol{Q} \\ \boldsymbol{U}_2\boldsymbol{CF} & \boldsymbol{U}_2\boldsymbol{Q} \end{bmatrix} = \begin{bmatrix} \boldsymbol{I}_q & 0 \\ 0 & \boldsymbol{I}_{p-q} \end{bmatrix} \tag{7b}$$