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Fault-Tolerant Control for Discrete Linear Systems with Consideration of Actuator Saturation and Performance Degradation ⋆

Z. Wang * **M. Rodrigues** ** **D. Theilliol** *** **Y. Shen** *

* *School of Astronautics, Harbin Institute of Technology, Harbin, 150001 P. R. China (e-mail: zhenhua.wang@hit.edu.cn).*
** *Automatic and Process Control Laboratory, University of Lyon, CNRS UMR 5007, F-69622 Villeurbanne-France, (e-mail: mickael.rodrigues@univ-lyon1.fr)*
*** *Centre de Recherche en Automatique de Nancy, Université de Lorraine, CNRS UMR 7039, F-54506 Vandoeuvre-les-Nancy, France (e-mail: didier.theilliol@univ-lorraine.fr)*

Abstract: This paper proposes an active fault-tolerant control method for discrete-time linear systems with actuator faults. The main contribution of this paper lies in the capability of dealing with the actuator saturation and accepting the performance degradation. In this paper, a fault estimation observer is first designed by constructing an equivalent descriptor system model of the original plant. To accept performance degradation of the post-fault system, a degradation factor is introduced into the reference model. In the fault-tolerant control design, both the actuator saturation and performance degradation are considered, and the fault-tolerant control input and the degradation factor are simultaneously designed by solving a constrained optimization problem. Finally, an aircraft example is simulated to demonstrate the effectiveness and performance of the proposed method.

Keywords: Fault estimation, descriptor system, observer design, fault-tolerant control, performance degradation.

1. INTRODUCTION

In the past decades, fault diagnosis and fault-tolerant control techniques have been widely investigated due to their capabilities in improving safety and availability of a system. Fruitful results have been proposed in the literature, see e.g. Chen and Patton (1999), Blanke et al. (2006), Noura et al. (2009), Rodrigues et al. (2014), Rodrigues et al. (2007), Ye and Yang (2006) and the references therein.

In Lunze et al. (2003) and Steffen (2005), a new methodology called fault hiding approach has been proposed to achieve fault-tolerance. The fault hiding goal is to make the reconfigured system exhibit similar behaviour to that of the nominal plant. In this paradigm, the nominal controller is kept in the loop and a reconfiguration block is inserted between faulty plant and nominal controller to generate useful control signals so as to hide the impact of faults. As pointed out in Khosrowjerdi & Soheila Barzegary (2014), this approach provides a way for minimally-invasive alternations of the loop, which is the main advantage of the fault hiding approach. In recent years, the fault hiding methodology has been applied to piecewise affine, linear parameter-varying, and Lipschitz nonlinear systems, see in Steffen (2005), Richter (2011), Rotondo et al. (2014), Tabatabaeipour et al. (2015) and Khosrowjerdi & Soheila Barzegary (2014). In spite of wide investigation, there are still some problems to be addressed in the fault-tolerant control design based on fault hiding approach. First, many existing results do not consider the fault diagnosis problem but assume that fault has already been accurately estimated, which is obviously an impractical assumption. Second, in most of the existing fault hiding approaches, the actuator saturation is not considered. This may lead to severe problem when these approaches are applied to practical systems. Moreover, little attention has been devoted to the performance degradation in the fault-tolerant design. In practice, however, the control margin of a faulty system will degrade due to the presence of faults and actuator saturation. Therefore, the fault-tolerant control scheme should be able to accept performance degradation in order to keep the operation safety. To the best of our knowledge, only few papers (Zhang & Jiang (2003); Jiang & Zhang (2006); Theilliol et al. (2008); Qi et al. (2014)) investigated the performance degradation in fault-tolerant control design.

Considering the aforementioned problems, this paper proposes a fault-tolerant control method with consideration of the actuator saturation and performance degradation. The main contribution of this paper lies the following aspects. First, an augmented state observer by constructing a descriptor system representation is proposed to estimate

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the fault. Second, the actuator saturation is considered in the proposed fault-tolerant control. Moreover, a novel degradation factor is introduced in the fault-tolerant control design so that the proposed fault-tolerant controller has the capability of accepting performance degradation.

2. PROBLEM FORMULATION

Consider the following discrete-time linear system

$$\begin{cases} x(k+1) = Ax(k) + Bu(k) \\ y(k) = Cx(k) \end{cases} \tag{1}$$

where $x(k) \in \mathbb{R}^n$ is the state, $u(k) \in \mathbb{R}^p$ is the control input, and $y(k) \in \mathbb{R}^m$ is the output. $A \in \mathbb{R}^{n\times n}$, $B \in \mathbb{R}^{n\times p}$, and $C \in \mathbb{R}^{m\times n}$ are known constant matrices.

In this paper, only actuator faults are considered. The actuator faults are modeled as a multiplicative representation, i.e. the actuator faults change the input matrix B to B_f, which is given as

$$B_f = B\Lambda \tag{2}$$

Herein, $\Lambda \in \mathbb{R}^{p\times p}$ is a diagonal matrix which implies the impact of the actuator faults, i.e.

$$\Lambda = \begin{bmatrix} \lambda_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \lambda_p \end{bmatrix} \tag{3}$$

In fact, γ_i represents the effectiveness factors of the ith actuator. $\gamma_i = 0$ means that the ith actuator is presented to be total failure, such as a stuck fault; $0 < \gamma_i < 1$ denotes the fault of the ith actuator may be a partial loss of control effectiveness; and $\gamma_i = 1$ implies the ith actuator is fault-free. For the convenience of fault estimation, the scalars λ_i, $i = 1, 2, \ldots, p$ are assumed to be constant or slow-varying.

Considering the actuator faults, the model of the faulty plant is given by

$$\begin{cases} x(k+1) = Ax(k) + B_f u(k) \\ y(k) = Cx(k) \end{cases} \tag{4}$$

Moreover, the actuator saturation is considered in this paper. That is, the control input $u(t)$ is subject to the following saturation constraint

$$u(k) \in \mathscr{U} := \{u \in \mathbb{R}^p | \underline{u}_i \le u_i \le \bar{u}_i\} \tag{5}$$

where $\underline{u}_i$ and $\bar{u}_i$ denote the minimum and the maximum actions of the ith actuator, respectively.

The aim of this paper is to design a fault-tolerant scheme such that the reconfigured state of the faulty plant (4) exhibits similar output to that of the following nominal model

$$\begin{cases} x_r(k+1) = Ax_r(k) + Bu_r(k) \\ y_r(k) = Cx_r(k) \end{cases} \tag{6}$$

where $x_r(k) \in \mathbb{R}^n$, $u_r(k) \in \mathbb{R}^p$ and $y_r(k) \in \mathbb{R}^m$ are the state, the control input and the output of the nominal system, respectively. Without loss of generality, it is assumed that $u_r(k)$ is designed such that the nominal output $y_r(k)$ tracks a given reference $r(k)$, i.e. $y_r(k) \to r(k)$.

Due to the presence of the actuator faults and saturation, it is reasonable to allow the faulty plant (4) to have certain performance degradation compared to the nominal model (6).

3. FAULT ESTIMATION OBSERVER DESIGN

Recently, descriptor system approach has been used to deal with fault diagnosis (Gao and Wang (2006), Gao and Ding (2007)). However, these works focus on sensor fault diagnosis. On the other hand, the descriptor system approach has not fully investigated in the actuator fault diagnosis. In view of this, this paper proposes an actuator fault estimation observer based on the descriptor system approach.

First, the actuator faults is converted into an additive representation by letting

$$f(k) = (I_p - \Lambda)u(k) \tag{7}$$

where $f(k) \in \mathbb{R}^n$ is an virtual equivalent fault, I_p is used to denote a $p \times p$ identity matrix.

By using (7), the model (4) becomes

$$\begin{cases} x(k+1) = Ax(k) + Bu(k) - Bf(k) \\ \qquad\qquad\; = Ax(k) + B_f u(k) \\ y(k) = Cx(k) \end{cases} \tag{8}$$

Let

$$\bar{x}(k) = \begin{bmatrix} x(k) \\ f(k-1) \end{bmatrix} \tag{9}$$

the faulty system (8) is equivalent to

$$\begin{cases} E\bar{x}(k+1) = \bar{A}\bar{x}(k) + \bar{B}u(k) \\ y(k) = \bar{C}\bar{x}(k) \end{cases} \tag{10}$$

where

$$E = \begin{bmatrix} I_n & B \\ 0 & 0 \end{bmatrix}, \bar{A} = \begin{bmatrix} A & 0 \\ 0 & 0 \end{bmatrix}, \bar{B} = \begin{bmatrix} B \\ 0 \end{bmatrix}, \bar{C} = [\, C \;\; 0 \,] \tag{11}$$

Using the relation in (7), the estimate of Λ can be easily obtained the additive fault term is estimated (this will be shown later). Moreover, according to the definition of $\bar{x}(k)$ in (9), the actuator fault $f(k-1)$ can be estimated if the estimation of the augmented state $\bar{x}(k)$ is obtained. Therefore, it can be concluded that fault estimation for system (4) is converted as an observer design problem for the descriptor system (10).

In the literature, there has been some results on observer design for discrete-time descriptor systems, see e.g. Dai (1988), Darouach et al. (2010), Wang et al. (2012). Among these results, Wang et al. (2012) proposes a new observer structure and presents a systemic design approach based on LMI technique. In this paper, the method in Wang et al. (2012) is used to address fault estimation problem. The proposed observer has the following form

$$\begin{cases} \zeta(k+1) = T\bar{A}\hat{\bar{x}}(k) + T\bar{B}u(k) + L\left[y(k) - \bar{C}\hat{\bar{x}}(k)\right] \\ \hat{\bar{x}}(k) = \zeta(k) + Ny(k) \end{cases} \tag{12}$$

where $\hat{\bar{x}}(k) \in \mathbb{R}^{(n+p)}$ is the estimate of the augmented state $\bar{x}(k)$ and $L \in \mathbb{R}^{(n+p)\times m}$ the gain matrix to be synthesized. Moreover, the matrices $T \in \mathbb{R}^{(n+p)\times(n+p)}$ and $N \in \mathbb{R}^{(n+p)\times m}$ are designed such that

$$TE + N\bar{C} = I_{n+p} \tag{13}$$

Remark 1. A necessary condition to use the observer (12) is the matrices E and $\bar{C}$ satisfy

$$\text{rank}\begin{bmatrix} E \\ \bar{C} \end{bmatrix} = n + p \tag{14}$$