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ISA Transactions

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

Data-based fault-tolerant control for affine nonlinear systems with actuator faults

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ARTICLE INFO

Article history:
Received 17 November 2015
Received in revised form
19 January 2016
Accepted 21 April 2016
This paper was recommended for publication by Dr. Steven Ding.

Keywords:
Unknown nonlinear systems
Data-based policy iteration algorithm
Fault-tolerant control
Actuator faults

ABSTRACT

This paper investigates the fault-tolerant control (FTC) problem for unknown nonlinear systems with actuator faults including stuck, outage, bias and loss of effectiveness. The upper bounds of stuck faults, bias faults and loss of effectiveness faults are unknown. A new data-based FTC scheme is proposed. It consists of the online estimations of the bounds and a state-dependent function. The estimations are adjusted online to compensate automatically the actuator faults. The state-dependent function solved by using real system data helps to stabilize the system. Furthermore, all signals in the resulting closed-loop system are uniformly bounded and the states converge asymptotically to zero. Compared with the existing results, the proposed approach is data-based. Finally, two simulation examples are provided to show the effectiveness of the proposed approach.

1. Introduction

In the practical applications of control systems, the faults generally induce the changes of the system parameters, result in poor system performance or even cause the instability of the closed-loop system. Among all classes of possible faults, actuator failures are considered to be one of the most critical challenges to be solved. Therefore, the research on fault-tolerant control (FTC) for systems with actuator faults/failures has attracted a lot of attention from many researchers. The methods that were developed to address the presence of actuator failures in control systems are often classified into two types: passive [1–4] and active ones [5–8]. Passive approaches mainly use unchangeable controllers to control systems for both fault-free case and faulty cases; active approaches compensate for faults either by selecting designed control laws or by synthesizing new control strategies online. Apart from the aforementioned approaches, adaptive actuator failure compensation control schemes [9–11] have already been verified to be an effective method to compensate the unknown actuator failures.

Moreover, nonlinearity widely exists in many practical systems, such as flight control systems, economical systems and biological systems. Thus, the research on nonlinear systems plays an important role in FTC, while few results are available in the literature that solve the FTC problem for nonlinear systems. In [12], an adaptive fault-tolerant controller was presented for a class of affine nonlinear systems. Adaptive backstepping control schemes were developed for nonlinear systems in [13–15]. Most recently, inspired by the work of [13] and based on the backstepping design technique, two FTC schemes were proposed for stochastic nonlinear strict-feedback systems [16] and unknown nonlinear large-scale systems in strict-feedback form [17]. Nevertheless, the nonlinear systems considered in [16,17] are very special. Furthermore, by using the fuzzy logic systems to approximate the unknown nonlinearity effects and changes in model dynamics due to faults, Li et al. [18] developed an observer-based dynamic output feedback fault-tolerant controller for a class of nonlinear systems in strict-feedback form.

It is worth mentioning that most of the above results about FTC problem are model-based which require the a priori knowledge of system dynamics. Without an accurate model, most theoretical results of FTC cannot probably be guaranteed in practical applications. In fact, it is intractable or expensive to obtain the accurate model of many industrial systems due to its complexity, especially for nonlinear systems. It is well known that one of the most important features for industrial systems is the large amount of data generated by itself. Therefore, development of data-based FTC approaches for practical systems is of great practical significance, but still full of challenges. Unfortunately, only a few results have

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http://dx.doi.org/10.1016/j.isatra.2016.04.023

studied the FTC problem by using real system data. For discrete-time linear systems, several data-driven FTC schemes were developed in [19–21]. However, due to the difference between discrete-time and continuous-time systems, these data-driven approaches cannot be extended to the case of continuous-time nonlinear systems. Most recently, Xie et al. [22] proposed a novel data-based FTC scheme for uncertain continuous-time linear systems by using adaptive technique and data-based policy iteration algorithm. Nevertheless, due to the difference between linear and nonlinear systems, it cannot be extended to the case of continuous-time nonlinear systems. By modifying the cost function to account for actuator faults, a data-based FTC approach was proposed in [23] for continuous-time nonlinear systems, which guarantees that the system has a guaranteed cost bound. Nevertheless, only actuator loss of effectiveness was considered in [23]. Till present, there is no result to solve the FTC problem for unknown continuous-time affine nonlinear systems with general actuator faults including stuck, outage, bias and loss of effectiveness by using real system data. This motivates the present study.

This paper is concerned with the data-based FTC problem for continuous-time affine nonlinear systems with actuator faults including stuck, outage, bias and loss of effectiveness. The upper bounds of the unparametrisable stuck faults, bias faults and loss of effectiveness faults are assumed to be unknown. A new data-based control scheme is developed by using adaptive technique. In the scheme, the adaptive laws are designed for automatically compensating the actuator faults by estimating the upper bounds and updating the controller parameters online. Meanwhile, an additional state-dependent function solved by using real system data is introduced for helping to stabilize the system. Lyapunov techniques are employed to demonstrate that all signals in the resulting closed-loop system are uniformly bounded and the states converge asymptotically to zero.

In summary, the main contributions of this paper are as follows: (1) the proposed control scheme is easy to design and implement, where only two parameters are required to be estimated online for the implementation of the proposed approach; and (2) compared with most existing methods, the proposed approach is data-based.

The rest of this paper is organized as follows. Section 2 introduces problem statement and preliminaries. In Section 3, the adaptive fault-tolerant controller design approach is presented. In Section 4, two simulation examples are given to illustrate the effectiveness of the proposed method. Finally, the conclusions end the paper in Section 5.

Notation: The following notations are used throughout this paper. For a matrix A, A^T and $\lambda_{min}(A)$ denote its transpose and minimum eigenvalue, respectively. The notion $A>0$ ($A\geq 0$) means that A is a positive definite (positive semi-definite) matrix of appropriate dimension. A diagonal matrix with $a_1, a_2, \ldots, a_n$ on its main diagonal is denoted as $\text{diag}\{a_1, a_2, \ldots, a_n\}$. The identity matrix is denoted by I with an appropriate dimension. $\nabla = \partial/\partial x$ denotes a gradient operator notation. $\|\cdot\|$ denotes Euclidean norm of vectors or matrices.

2. Problem statement and preliminaries

2.1. System model

Consider the following nonlinear system, denoted by nominal system

$$\dot{x}(t) = f(x(t)) + g(x(t))u(t) \tag{1}$$

where $x(t)\in\mathbb{R}^n$ is the state vector, $u(t)\in\mathbb{R}^m$ is the output of actuator described in (8) below, $f(x(t))\in\mathbb{R}^n$ with $f(0)=0$, and $g(x(t))\in\mathbb{R}^{n\times m}$. When the actuators operate in the fault-free case, $f(x)+g(x)u$ is assumed to be locally Lipschitz continuous on a compact set $\Omega\subseteq\mathbb{R}^n$ which contains the origin. $f(x)$ and $g(x)$ are completely unknown functions.

2.2. Fault model

To formulate the FTC problem, the fault model must be established. In this paper, the following actuator fault model [10,11,22] is adopted:

$$u_{ij}(t) = \Lambda_i^j(t)\upsilon_i(t) + \Sigma_i^j(t)\upsilon_{si}(t) \tag{2}$$

where, for $i=1,2,\ldots,m$ and $j=1,2,\ldots,L$, $\upsilon_i(t)$ denotes the input signal of the ith actuator, the index j denotes the jth faulty mode, $u_{ij}(t)$ denotes the output signal from the ith actuator in the jth faulty mode, $\Lambda_i^j(t)\in[0,1]$ represents the unknown time-varying continuous actuator efficiency factor which indicates the degree of effectiveness of the actuator, $\upsilon_{si}(t)$ is a piecewise continuous function which represents the unparametrisable bounded stuck fault or the bounded time-varying bias fault of the ith actuator, and $\Sigma_i^j(t)=0$ or 1. L represents the number of total faulty modes.

The actuator faults considered in this paper simultaneously include stuck, outage, bias and loss of effectiveness. That is:

(1) $\Lambda_i^j(t)=0$ and $\Sigma_i^j(t)\neq 0$: This means that $\upsilon_i(t)$ is stuck at $\upsilon_{si}(t)$ in the jth faulty mode.
(2) $\Lambda_i^j(t)=0$ and $\Sigma_i^j(t)=0$: This indicates that the type of actuator faults is outage.
(3) $\Lambda_i^j(t)=1$ and $\Sigma_i^j(t)\neq 0$: This means that the type of actuator faults is bias, and $\upsilon_{sj}(t)$ represents the bias value.
(4) $0<\Lambda_i^j(t)<1$ and $\Sigma_i^j(t)=0$: This case corresponds to loss of effectiveness.

Remark 1. Note that actuators operating in the failure-free case can also be represented as (2) with $\Lambda_i^j(t)=1$ and $\Sigma_i^j(t)=0$.

Denote

$$\begin{aligned} u_j(t) &= [u_{1j}(t), u_{2j}(t), \ldots, u_{mj}(t)]^T \\ &= \Lambda^j(t)\upsilon(t) + \Sigma^j(t)\upsilon_s(t) \end{aligned} \tag{3}$$

where

$$\Lambda^j(t) = \text{diag}\{\Lambda_1^j(t), \Lambda_2^j(t), \ldots, \Lambda_m^j(t)\} \tag{4}$$

$$\upsilon(t) = [\upsilon_1(t), \upsilon_2(t), \ldots, \upsilon_m(t)]^T \tag{5}$$

$$\Sigma^j(t) = \text{diag}\{\Sigma_1^j(t), \Sigma_2^j(t), \ldots, \Sigma_m^j(t)\} \tag{6}$$

$$\upsilon_s(t) = [\upsilon_{s1}(t), \upsilon_{s2}(t), \ldots, \upsilon_{sm}(t)]^T. \tag{7}$$

For simplification, for all possible faulty modes, a uniform actuator fault model is formulated

$$u(t) = \Lambda\upsilon(t) + \Sigma\upsilon_s(t) \tag{8}$$

where $\Lambda\in\{\Lambda^1(t), \Lambda^2(t), \ldots, \Lambda^L(t)\}$ and $\Sigma\in\{\Sigma^1(t), \Sigma^2(t), \ldots, \Sigma^L(t)\}$.

Taking the actuator faults into consideration, the nominal system (1) can be rewritten as the following system, denoted by original system

$$\dot{x}(t) = f(x(t)) + g(x(t))(\Lambda\upsilon(t) + \Sigma\upsilon_s(t)). \tag{9}$$

Remark 2. The systems that we consider in this paper are most related to those in [24,25]. Nevertheless, actuator faults were not taken into account in [24,25].

In what follows, three standing assumptions are given.