Automatica 81 (2017) 87–95

Contents lists available at ScienceDirect

Automatica

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

Brief paper

# Adaptive fault-tolerant control for actuator failures: A switching strategy[☆]

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ARTICLE INFO

*Article history:*
Received 11 November 2015
Received in revised form
12 December 2016
Accepted 22 February 2017
Available online 19 April 2017

*Keywords:*
Actuator failure
Fault detection
Fault-tolerant control
Adaptive control
Switching control

ABSTRACT

In this paper, a new adaptive fault-tolerant control (FTC) scheme based on a switching strategy is proposed for a class of nonlinear systems with uncertain parameters and actuator failures, for which some healthy actuators are available as backups. By designing a set of monitoring functions (MFs) to supervise the behavior of some variables, it is shown that the failure detection and the switching from a faulty actuator to a healthy one can be performed simultaneously without any knowledge of failure patterns, and the prescribed transient and steady-state performance for the tracking error can be achieved regardless of the switching.

## 1. Introduction

Since the pioneering works reported in the early 1990s (Patton, 1997), many fault-tolerant control (FTC) approaches against actuator failures have been proposed (Boskovic, Jackson, Mehra, & Nguyen, 2009; Boskovic & Mehra, 2010; Tao, Joshi, & Ma, 2001; Zhang & Jiang, 2008; Zhang, Parisini, & Polycarpou, 2004), in which *adaptive* FTC has been proved to be an effective way to accommodate system uncertainties, actuator failures and external disturbances. The mainstream approaches of adaptive FTC against actuator failures can be roughly divided into the following categories: MMST (Boskovic et al., 2009; Boskovic & Mehra, 2010), information-based diagnostic approach (Zhang et al., 2004), and direct adaptive actuator failure compensation (Tao et al., 2001). For MMST, a bank of identification models and a corresponding controller bank were used to implement failure detection and isolation, and to determine, through the supervision of a set of performance indices, the switching of the controller when the actuator or sensor failure occurs. Recently, with appropriately designed *selecting functions* based on tracking error, some approaches that combine adaptive control and actuator-switching have also been developed to adaptively pick out the failed ones among multiple actuators without using fault detection mechanism (Takahashi & Takagi, 2012; Yang, Ge, & Sun, 2015), but the price paid is that the tracking performance may be poor (Takahashi & Takagi, 2012). The information-based diagnostic approach (Zhang et al., 2004) provides a unified methodology for fault diagnosis and accommodation, whose architecture combines an online monitoring module consisting of a bank of nonlinear adaptive estimators, and a controller module to accommodate the effects of faults on the basis of the fault information. Motivated by control problems encountered in some control systems such as aircraft flight control, a direct adaptive actuator failure compensation approach was proposed by Tao et al. (2001) and has been extended to cover a large class of systems (Tao, 2014; Wang & Wen, 2010). With the assumption that the actuation redundancy can guarantee the control objectives even if some actuators suffer failures, the proposed approach by Tao et al. (2001) possesses some features such as no fault detection is needed, and the control reconfiguration is adaptively updated.

In this paper, an adaptive state feedback FTC is proposed based on a supervisory switching strategy for a general class of nonlinear systems with uncertain parameters and possible actuator failures, for which some healthy actuators are available as backups. The motivation behind the research is twofold. Firstly, in many applications such as civil aircrafts, satellite attitude control systems, hydraulic systems and chemical processes, some actuators are used as "backups", *i.e.*, once the actuator failure is detected, one or more of the backup actuators will be used to replace the failed

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[☆] This work was supported in part by NSFC under Grants 61673038, 61433011 and the National Basic Research Program of China (973 Program) under Grant 2014CB046406. The material in this paper was not presented at any conference. This paper was recommended for publication in revised form by Associate Editor Gang Tao under the direction of Editor Miroslav Krstic.

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http://dx.doi.org/10.1016/j.automatica.2017.03.014

one (Alwi & Edwards, 2008; Goupil, 2011; Isermann, Schwarz, & Stolzl, 2002; Muenchhof, Beck, & Isermann, 2009). Secondly, despite the great progress in adaptive FTC, the existing literature still has several drawbacks that hinder the range of their applications:

- To detect the failures, a bank containing possible failure models needs to be constructed for most of the adaptive FTC approaches against actuator failures (Boskovic & Mehra, 2010; Zhang et al., 2004). Therefore, if any failure outside the bank occurs, the system stability and performance specifications may not be guaranteed (Zhou, Rachinayani, Liu, Ren, & Aravena, 2004).
- The lack of fault detection and isolation mechanism in Tao et al. (2001) implies that the failed actuators may not be deactivated since we do not know which one fails. Consequently, if more actuators are stuck, the reconfigured inputs may saturate since more control effort is needed to overcome the effect of the stuck inputs (Peni, Vanek, Szabo, & Bokor, 2014).

In the FTC design, we first introduce two types of prescribed performance that we borrow from Bechlioulis and Rovithakis (2010), Tee, Ge, and Tay (2009) and Wang and Wen (2010) in backstepping technique: One type is used to bound the transient and steady-state performance of the tracking error, and another one is used to bound the amplitudes of the other errors of the backstepping design. They are then used to construct a Lyapunov function, by which a set of monitoring functions (MFs) is designed as tolerance bands for supervising the behavior of the errors in such a way that: (1) The adaptive control law can make the errors lie within their tolerance bands in the presence of parameter uncertainties and actuator failures, as long as the failures do not bring any error out of its band, and (2) The actuator switching is triggered only when the failure is detected by at least one of the MFs. The main contributions of this paper are summarized below.

- To the best of our knowledge, this is the first adaptive FTC based on supervisory switching that guarantees the tracking error to satisfy a prescribed transient and steady-state performance regardless of actuator switching.
- Under the supervision of the proposed MFs, fault detection and actuator switching can be performed simultaneously without using any bank of fault detection estimators.
- The tolerance bands given by the MFs, together with the inherent robustness of the adaptive control, can accommodate a certain degree of actuator and other system component faults without triggering switching. Moreover, the "width" of the tolerance bands can be altered according to practical engineering problem.
- The MFs guarantee that all the closed-loop states belong to $\mathscr{L}_\infty$ for finite switchings of the actuators without any additional assumption. By comparison, some strict assumptions are required in Zhang et al. (2004) to ensure that the failure can be detected before possible occurrence of an unbounded growth of some state variable.

## 2. Problem statement

We consider the following nonlinear plant in strict-feedback form

$$\begin{aligned}\dot{x}_i &= x_{i+1} + \theta^T\varphi_i(\bar{x}_i), \quad i = 1, 2, \ldots, n-1,\\ \dot{x}_n &= u + \varphi_0(x) + \theta^T\varphi_n(x),\\ y &= x_1, \end{aligned} \tag{1}$$

where $\bar{x}_i := [x_1, x_2, \ldots, x_i]^T \in \mathbb{R}^i$, $i = 1, 2, \ldots, n$, are state vectors with $x = \bar{x}_n$, which are assumed available for measurement, $\theta \in \mathbb{R}^r$ is an unknown constant vector, $\varphi_0(x) \in \mathbb{R}$, $\varphi_i(\bar{x}_i) \in \mathbb{R}^r$ and $\varphi_n(x) \in \mathbb{R}^r$ are known smooth nonlinear functions, $y \in \mathbb{R}$ is the system output and $u \in \mathbb{R}$ is the input whose components may fail during the system operation.

The control objective of this paper is to design an adaptive FTC based on a switching strategy so that the output $y$ can track a desired trajectory $y_r$ with a prescribed transient and steady-state performance even if actuator failures occur. Fig. 1 shows the schematic diagram of the control structure, where we assume that there are total $m$ actuators, among which only one actuator is connected to the controller at any given moment. If at some time instant, the failure of the current actuator is detected by one of the appropriately designed MFs, the current actuator will be switched to the next one. Here, by actuator switching we mean that the controller is switched from the faulty actuator to a healthy one.

We make the following assumptions.

**Assumption 1.** Each actuator can be connected to the control signal $v$ only once and is failure free at the switching instant when the actuator is applied. Moreover, it is assumed that one actuator has been connected to the system at $t = 0$.

**Assumption 2.** The $m$ actuators can guarantee that the closed-loop system works normally on $[0, +\infty)$.

**Assumption 3.** The unknown parameter vector $\theta$ lies in a known bounded convex set

$$\Pi_\theta = \{\hat{\theta} \in \mathbb{R}^r | \mathscr{P}(\hat{\theta}) \le 0\}, \tag{2}$$

where $\mathscr{P}$ is a convex smooth function.

**Assumption 4.** The reference signal $y_r$ and its derivatives up to order $n$ are known, bounded, and piecewise continuous.

**Remark 1.** Assumption 1 implies that there is no switching at $t = 0$. Assumption 3 implies that an upper bound of $\|\theta\|$, say, $\theta_M$, can be obtained such that $\|\theta\| \le \theta_M$.

**Remark 2.** Usually, actuator dynamics are much faster than the plant to be controlled and therefore, can be ignored without causing significant error (Yu & Jiang, 2012). In this paper, the same as many publications, we assume that the gain of the actuators has been normalized to unity when they are failure free; in this case, from Fig. 1, $u = u_i = v$. If actuator dynamics are taken into account and can be described by a stable linear model (Boskovic & Mehra, 2010), Fig. 1 shows that simply combining the actuator model with the plant, the proposed scheme can still be applied.

## 3. Adaptive fault-tolerant control based on monitoring functions

### 3.1. Prescribed performances

First of all, since the system (1) is in strict-feedback form, we shall use backstepping technique to design the adaptive controller, for which the tracking error and the other error variables are defined as follows[1]:

$$\epsilon = y - y_r, \tag{3}$$

$$z_i = x_i - \alpha_{i-1}, \quad i = 2, \ldots, n, \tag{4}$$

where $\alpha_{i-1}$ are the virtual control signals to be designed. The motivation for introducing prescribed performances for the tracking error $\epsilon$ and the errors $z_i$ is twofold: to provide criteria under which the MFs can be constructed to detect the failures of the actuators, and on the other hand, to make $\epsilon$ and $z_i$ satisfy the prescribed performances even if actuator failures occur.

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[1] Throughout of the paper, for the sake of brevity, we shall drop the argument of some functions unless otherwise specified; for example, $y$ is used to denote $y(t)$.