Nonlinear Analysis: Real World Applications 12 (2011) 789–798

Contents lists available at ScienceDirect

Nonlinear Analysis: Real World Applications

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

Supervisory fault-tolerant regulation for nonlinear systems☆

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ARTICLE INFO

Article history:
Received 24 January 2009
Accepted 6 August 2010

Keywords:
Fault-tolerant control
Supervisory control
Hybrid systems
Output regulation

ABSTRACT

This paper focuses on the fault-tolerant output regulation problem for nonlinear systems with faults generated by exogenous systems that belong to a certain pre-specified set of models. The novelty is to design a fault-tolerant control (FTC) scheme for the overall system process where different faults may occur respectively at different time instants of the process, which is called the *successional faulty case*. The proposed FTC framework relies on a simple supervisory switching among a family of pre-computed candidate controllers. The output regulation goal is maintained in such a successional faulty case. A DC motor example illustrates the efficiency of the proposed method.

1. Introduction

Faults may have very undesirable consequences in safety-critical systems, such as damaging the plant, spoiling the environment, or endangering human operators. Fault detection and isolation (FDI) and fault-tolerant control (FTC) are aimed at guaranteeing the system goal to be achieved in spite of faults [1–4].

Most of existing works consider FDI and FTC separately, and assume that the fault occurs only once throughout the overall system process, as illustrated in the *classical* faulty case of Fig. 1, where the fault occurs at $t = t_f$ and the FTC law is applied at $t = t_{ftc}$. Appropriate FDI/FTC design indeed maintains the stability of the system in $[t_f, \infty)$ in spite of faults. However, in many practical situations, different faults may occur successively in one system process at different time instants, which we call the *successional* faulty case (a formal definition will be given later), as in Fig. 1. Such system behavior can be modeled by a hybrid system [5–7], where each mode represents a faulty situation. It should be pointed out that even if the FDI/FTC scheme stabilizes the faulty system in each time interval, e.g. $[t_{f1}, t_{f2})$, $[t_{f2}, t_{f3})$ in Fig. 1, the overall system process may still be unstable, as indicated in [8,9]. The FTC for the overall system process deserves further investigation.

On the other hand, only a few studies model faults by exogenous signals [4,10,11]. Faults modeled by signals generated by exosystems are very general, and such modeling enables one to describe many types of fault [4].

In this paper, we address the FDI and FTC issues for a class of nonlinear systems with faults modeled by exogenous signals. We do not explicitly design the FTC laws in each faulty situation since this can be found in many reports; see, e.g., [12–16]. We assume that the plant model belongs to a pre-specified set of models, including the nominal situation and all possible faulty situations, and that there exists a finite family of candidate controllers such that the output regulation problem of each plant model is solvable when controlled by at least one of those candidate controllers. The main contribution of this paper is to propose a supervisory FDI/FTC scheme to achieve the output regulation in the overall system process, i.e., the output of the system asymptotically tracks prescribed trajectories in the *successional* faulty case.

☆ This work is partially supported by Natural Science Foundation of China (60874051, 61034005), NUAA Research Funding (NZ2010003) and Scientific Research fund of NUAA (S1012-031).

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1468-1218/$ – see front matter
doi:10.1016/j.nonrwa.2010.08.006

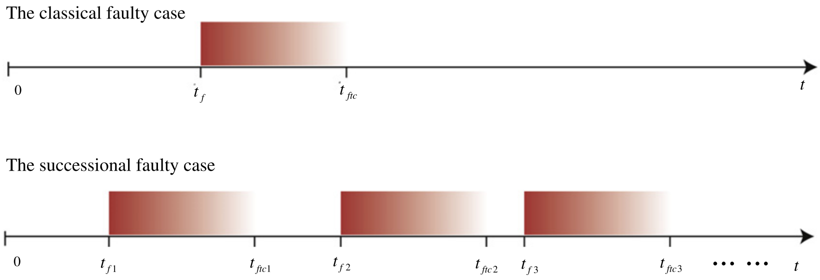

Fig. 1. FTC process.

We first provide a time-varying threshold to detect the fault, then propose a novel supervisory controller switching scheme. After a finite number of switchings, the fault can be isolated, and the correct controller relevant to the current situation can be selected and applied.

The novelty of this approach is twofold.

(1) Unlike in the multiple model FDI/FTC method [17–19] or supervisory control technique [20], we do not need a series of models to work concurrently with the plant in order to identify the current situation. We also do not design any adaptive scheme to estimate the exosystem of faults as in [14,21,22]. The proposed method relies only on a simple switching scheme among candidate controllers and a family of fictitious fault signals.

(2) Under the proposed supervisory FTC scheme, the states are ensured to be bounded and the output regulation performance is maintained throughout the overall system process in the successional faulty case.

The rest of the paper is organized as follows. Section 2 gives some preliminaries and details the problem formulation. In Section 3, the proposed supervisory FDI/FTC method is presented. A DC motor example illustrates the approach in Section 4, which is followed by some concluding remarks in Section 5.

2. Preliminaries

Let $\Re$ denote the field of real numbers and $\Re^r$ the r-dimensional real vector space. $|\cdot|$ is the Euclidean norm. $\mathfrak{C}^k$ denotes the set of all functions with continuous kth derivatives. t^- denotes the left limit time instant of t.

2.1. FTC in the classical faulty case

The considered system takes the general nonlinear form

$$\dot{x}(t) = G(x(t), u(t), f(t)) \tag{1}$$

$$y(t) = H(x(t), f(t)) \tag{2}$$

$$\dot{f}(t) = S(f(t)) \quad \forall t \geq t_f, \text{ with } f(t) = 0 \; \forall t \in [0, t_f) \tag{3}$$

$$e(t) = y(t) - y_r(x(t)) \tag{4}$$

with measurable state $x \in \Re^n$, input $u \in \Re^p$, and output $y \in \Re^m$. The regulated error e denotes the output tracking error between y and the continuous reference signal $y_r(x) : \Re^n \to \Re^m$. The vector fields G and H are assumed to be smooth and known.

Once the fault occurs at $t = t_f$, the fault signal $f \in \mathcal{F} \subset \Re^q$ is generated by the *neurally stable* exosystem (3), i.e., $\partial S(0)/\partial f$ has all its eigenvalues on the imaginary axis [15], which means that f is always bounded. The initial fault $f(t_f)$ is supposed to be a known value f_{in}. The function S is also assumed to be smooth and known. Such a model effectively describes process, actuator and sensor faults [4].

Assumption 1. There exist some $u = \alpha(x, f)$ with $f = 0$ such that $x = 0$ of the healthy system (1) $\dot{x} = G(x, \alpha(x, 0), 0)$ is asymptotically stable. □

Remark 1. Assumption 1 is a basic requirement for state feedback output regulation design [15]. For the affine form $G(x, \alpha(x, 0), 0) = G_1(x) + G_2(x)\alpha(x, 0)$, Assumption 1 also means that the pair $(G_1(x), G_2(x))$ has a stabilizable linear approximation at $x = 0$. □

Definition 1. The *fault-tolerant regulation problem* (FTRP) for system (1)–(4) is to find an FTC law $u = \alpha(x, f)$ such that, $\forall x(0) \in \mathcal{X}$ with $\mathcal{X} \subset \Re^n$ a neighborhood of 0 and $\forall f \in \mathcal{F}$, the trajectory of the closed-loop system (1) $\dot{x} = G(x, \alpha(x, f), f)$ is bounded $\forall t \geq 0$ and $\lim_{t\to\infty} e(t) = 0$. □

Theorem 1. *Suppose that the fault f can be approximated without any error, and that there exists a $u = \alpha(x, f)$ satisfying Assumption 1. The FTRP for system (1)–(4) is solvable if and only if there exists a $\mathfrak{C}^k$ mapping $x = \pi(f)$ with $\pi(0) = 0$ defined for $(x, f) \in \mathcal{X} \times \mathcal{F}$ satisfying*