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Research article

Adaptive sensor fault-tolerant control for a class of multi-input multi-output nonlinear systems: Adaptive first-order filter-based dynamic surface control approach

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ABSTRACT

This paper is concerned with the adaptive fault-tolerant control (FTC) problem for a class of multivariable nonlinear systems with external disturbances, modeling errors and time-varying sensor faults. The bias, drift, loss of accuracy and loss of effectiveness faults can be effectively accommodated by this scheme. The dynamic surface control (DSC) technique and adaptive first-order filters are brought together to design an adaptive FTC scheme which can reduce significantly the computational burden and improve further the control performance. The adaptation laws are constructed using novel low-pass filter based modification terms which enable under high learning or modification gains to achieve robust, fast and high-accuracy estimation without incurring undesired high-frequency oscillations. It is proved that all signals in the closed-loop system are uniformly ultimately bounded and the tracking-errors can be made arbitrary close to zero. Simulation results are provided to verify the effectiveness and superiority of the proposed FTC method.

1. Introduction

Due to the harsh operational environment and equipment aging, the unforeseen faults such as bias, drift, loss of accuracy and loss of effectiveness are often encountered in sensors. These malfunctions can destroy the system performance, lead to instability and even to produce catastrophic accidents, especially for critical systems (e.g. chemical plants, nuclear reactors, aircraft, …etc.). So, the problem of achieving some level of performance and stability under these undesirable circumstances motivate a large number of researchers to investigate on the fault-tolerant control (FTC) approaches, where the fault effects require to be compensated to maintain the safety and reliability of the closed-loop system while continually providing a satisfactory performance.

How to effectively deal with sensor faults in the control design is an interesting but challenging topic of research that has attracted great attention in the past decades. Due to this reason, several paradigms have been applied to the FTC problem with sensor faults, including LQG technique [1], H_∞-based approaches [2–7], state feedback control [8], output feedback control [9–13], model predictive control [14], Lyapunov's direct strategy [15], sliding mode control [16,17], backstepping approach [18–20], and extensions to linear parameter varying (LPV) systems [21–23], markovian jump systems [24–26] and nonlinear discrete-time systems [27,28]. It is worth pointing out that most of these FTC systems only considered one or two kinds of constant fault cases. Investigating more kinds of sensor faults with an extension to the time-varying case imposes significant challenge, leading to a more dedicated and more comprehensive solution, which is one of the motivations of this paper.

Although backstepping control has been considered as a powerful tool to design controllers for uncertain nonlinear systems with unmatched conditions [29–31], this control technique suffers from the “explosion of complexity” problem induced by the repeated differentiations of virtual control laws during the recursive design procedure. Fortunately, a dynamic surface control (DSC) approach was proposed in Refs. [32,33] to circumvent this problem, where a first-order filter was introduced to prevent the differentiation calculations at each step of the backstepping design. In the recent years, the incorporation of DSC technique into the FTC framework have gained much attention. Nevertheless, most of the existing works focus on actuator faults (see e.g. Refs. [34–38] and the references therein), while little attention has been paid to sensor faults [39].

Among the aforementioned FTC approaches, it has been proved that the adaptive control methodology can be an effective way to accommodate actuator faults, sensor faults, parameter uncertainties and

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external disturbances. However, in this framework, the achievement of high control performance and fast adaptation under these malfunctions requires the use of high-gain learning rates, which may cause high-frequency oscillations in the control signal, where in turn, may excite unmodelled dynamics and can lead to instability. To deal with this problem, an adaptive control architecture with guaranteed fast and low-frequency adaptation has been proposed in Ref. [40] for a class of nonlinear systems with parametric uncertainties, where the effects of high-gain learning rates can be effectively attenuated by introducing a low-pass filter dynamic in the adaptive law. It should be noted that there exist a shortcoming in the proposed controller, that is, the sensitivity to modification gains, where a bad choice of their values (e.g. the use of high gains) can result in system instability by destroying the adaptation process.

In this paper, the problem of adaptive FTC for a class of MIMO nonlinear systems in the face of different kinds of time-varying sensor faults, system uncertainties and external disturbances is investigated. In contrast to the existing results, the main contributions of this paper are listed as follows:

1. Building on our recent results presented in Refs. [18,39], where a class of second-order MIMO nonlinear systems is considered, this paper aims to extend the recent work by the authors to the general case by taking into account a class of n-th order multivariable nonlinear systems.
2. Unlike in Refs. [34–38], where linear first-order filters are incorporated into the DSC framework. In this paper, adaptive first-order filters are introduced in the design, where adaptive parameters are used instead of the conventional filter time constants, which improves further the control performance.
3. Compared with the adaptive nonlinear filters of [39], where no prior knowledge about the upper-bounds of the derivatives of virtual controls is needed in the design, the proposed adaptive linear filters have the same advantage with lower complexity and more simpler implementation.
4. In order to achieve online fault compensation and to save significant computational time needed when using a fault detection and isolation (FDI) system, the proposed FTC method is designed based on robust adaptive fault estimation schemes.
5. Inspired by the adaptive law proposed in Ref. [40], two novel low-pass filter-based modification terms are used to construct the estimation schemes. The first one is introduced in the online fault estimation bloc to deal with different high adaptation gains (including modification gains), while the second modification is used in the adaptive first-order filters allowing for the uniform boundedness of the closed-loop system without using the projection operator [41].

The remainder of this paper is organized as follows. Section 2 formulates the FTC problem with four kinds of sensor faults. In Section 3, the proposed controller is designed based on DSC approach, adaptive first-order filters and filtered estimation laws. Section 4 provides an illustrative example of two-inverted pendulums. Finally, this paper is concluded in Section 5.

2. Problem formulation

Consider a class of MIMO nonlinear systems composed of q subsystems, where the i-th subsystem is described as

$$\Sigma_i : \begin{cases} \dot{x}_{i,j} & = x_{i,j+1},\ j = 1,\dots,n_i - 1, \\ \dot{x}_{i,n_i} & = f_i(\mathrm{x}) + g_i(\mathrm{x})u_i + d_i(t) \\ \mathrm{y} & = h(\mathrm{x}, \mathrm{f}_s) \end{cases} \tag{1}$$

where $\mathrm{x} = [x_{1,1}, x_{1,2},\dots,x_{1,n_1},\dots,x_{q,1}, x_{q,2},\dots,x_{q,n_q}]^T \in \mathbb{R}^n$ is the state vector, n_i is the order of the i-th subsystem with $n = \sum_{i=1}^{q} n_i$, $\mathrm{u} = [u_1, u_2,\dots,u_q]^T \in \mathbb{R}^q$ is the control input vector, $\mathrm{d}(t) = [d_1(t), d_2(t),\dots,d_q(t)]^T \in \mathbb{R}^q$ is the external disturbance vector which satisfies $0 \le |d_i(t)| \le d_i^*$ with d_i^*, $i = 1, \dots, q$ are unknown positive constants, $\mathrm{y} \in \mathbb{R}^p$ is the measured output vector, $\mathrm{f}_s \in \mathbb{R}^r$ $(r \le p \le n)$ is the sensor fault vector, $f_i(\mathrm{x})$ and $g_i(\mathrm{x})$, $i = 1, 2, \dots, q$ are continuous nonlinear functions.

In this paper, it is considered that the overall state vector can be measured, where the first output of the i-th subsystem is fault-free and the remainder measurements are corrupted by sensor faults, that is

$$\begin{aligned} y_{i,1}(t) &= x_{i,1}(t) \\ y_{i,j+1}(t) &= x_{i,j+1}(t) + f_{s_{i,j}}(t, x_{i,j+1}(t)),\ j = 1,\dots,n_i - 1 \end{aligned} \tag{2}$$

where $f_{s_{i,j}}$ denotes the fault in the $(j+1)$-th sensor of the i-th subsystem. It can be modeled as [18,39]

$$f_{s_{i,j}}(t, x_{i,j+1}(t)) = \underbrace{(\kappa_{s_{i,j}}(t) - 1)x_{i,j+1}(t)}_{\text{LOF}} + \underbrace{b_{s_{i,j}}(t)}_{\text{Bias, Drift, LOA}} \tag{3}$$

where $\kappa_{s_{i,j}}(t) \in [\underline{\kappa}_{s_{i,j}}, 1]$ models the loss of effectiveness (LOF) with a minimum $\underline{\kappa}_{s_{i,j}} > 0$, and $b_{s_{i,j}}(t)$ models the bias, drift and loss of accuracy (LOA). It is assumed that $\kappa_{s_{i,j}}(t)$ and $b_{s_{i,j}}(t)$ are unknown, time-varying and have bounded derivatives, in other words, there exist unknown positive constants $\kappa_{s_{i,j}}^*$ and $b_{s_{i,j}}^*$, such that $0 \le |\dot{\kappa}_{s_{i,j}}(t)| < \kappa_{s_{i,j}}^*$ and $0 \le |\dot{b}_{s_{i,j}}(t)| < b_{s_{i,j}}^*$.

Using (1) and (3), the time derivative of (2) can be formulated as

$$\begin{cases} \dot{y}_{i,1} & = (y_{i,2} - f_{s_{i,1}}) \\ & \vdots \\ \dot{y}_{i,j} & = (y_{i,j+1} - f_{s_{i,j}}) + \dot{f}_{s_{i,j-1}},\quad j = 2,\dots,n_i - 1, \\ & \vdots \\ \dot{y}_{i,n_i} & = f_i(\mathrm{y}, \mathrm{f}_s) + g_i(\mathrm{y}, \mathrm{f}_s)u_i + d_i(t) + \dot{f}_{s_{i,n_i-1}} \end{cases} \tag{4}$$

with

$$\begin{cases} \dot{f}_{s_{i,j-1}} & = (\kappa_{s_{i,j-1}} - 1)(y_{i,j+1} - f_{s_{i,j}}) + \dot{\kappa}_{s_{i,j-1}}(y_{i,j} - f_{s_{i,j-1}}) \\ & \quad + \dot{b}_{s_{i,j-1}},\ j = 2,\dots,n_i - 1, \\ & \vdots \\ \dot{f}_{s_{i,n_i-1}} & = (\kappa_{s_{i,n_i-1}} - 1)(f_i(\mathrm{y}, \mathrm{f}_s) + g_i(\mathrm{y}, \mathrm{f}_s)u_i + d_i(t)) \\ & \quad + \dot{\kappa}_{s_{i,n_i-1}}(y_{i,n_i} - f_{s_{i,n_i-1}}) + \dot{b}_{s_{i,n_i-1}} \end{cases} \tag{5}$$

Substituting (5) into (4) yields

$$\begin{cases} \dot{y}_{i,1} & = y_{i,2} - f_{s_{i,1}} \\ & \vdots \\ \dot{y}_{i,j} & = y_{i,j+1} + (\kappa_{s_{i,j-1}} - 1)y_{i,j+1} - \kappa_{s_{i,j-1}} f_{s_{i,j}} + \dot{\kappa}_{s_{i,j-1}} \\ & \quad \times (y_{i,j} - f_{s_{i,j-1}}) + \dot{b}_{s_{i,j-1}},\ j = 2,\dots,n_i - 1, \\ & \vdots \\ \dot{y}_{i,n_i} & = f_i^0(\mathrm{y}) + \delta f_i(\mathrm{y}, \mathrm{f}_s) + (g_i^0(\mathrm{y}) + \delta g_i(\mathrm{y}, \mathrm{f}_s))u_i \\ & \quad + \kappa_{s_{i,n_i-1}} d_i(t) \\ & \quad + \dot{\kappa}_{s_{i,n_i-1}}(y_{i,n_i} - f_{s_{i,n_i-1}}) + \dot{b}_{s_{i,n_i-1}} \end{cases} \tag{6}$$

where $f_i^0(\mathrm{y})$ and $g_i^0(\mathrm{y})$ denote the known fault-free parts of system dynamics, $\delta f_i(\mathrm{y}, \mathrm{f}_s) = \kappa_{s_{i,n_i-1}} f_i(\mathrm{y}, \mathrm{f}_s) - f_i^0(\mathrm{y})$ and $\delta g_i(\mathrm{y}, \mathrm{f}_s) = \kappa_{s_{i,n_i-1}} g_i(\mathrm{y}, \mathrm{f}_s) - g_i^0(\mathrm{y})$ indicate the discrepancy between the faulty dynamics of the system and the fault-free dynamics.

Setting the system uncertainties as

$$\begin{cases} \Delta_{i,j} & = (\kappa_{s_{i,j-1}} - 1)y_{i,j+1} - \kappa_{s_{i,j-1}} f_{s_{i,j}} + \dot{\kappa}_{s_{i,j-1}}(y_{i,j} - f_{s_{i,j-1}}) \\ & \quad + \dot{b}_{s_{i,j-1}},\ j = 2,\dots,n_i - 1, \\ & \vdots \\ \Delta_{i,n_i} & = \delta f_i(\mathrm{y}, \mathrm{f}_s) + \delta g_i(\mathrm{y}, \mathrm{f}_s)u_i + \kappa_{s_{i,n_i-1}} d_i(t) + \dot{\kappa}_{s_{i,n_i-1}} \\ & \quad (y_{i,n_i} - f_{s_{i,n_i-1}}) + \dot{b}_{s_{i,n_i-1}} \end{cases} \tag{7}$$