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Actuator and sensor fault isolation of nonlinear process systems

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HIGHLIGHTS

- An integrated FDI framework for sensors and actuator fault isolation.
- Dedicated residual design to isolate faults while accounting for nonlinearity.
- Simulation example illustrating the application subject to measurement noise and uncertainty.

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ABSTRACT

This work considers the problem of isolating actuator and sensor faults in nonlinear process systems. The key idea of the proposed method is to exploit the analytical redundancy in the system through state observer design. To this end, we consider subsets of faults, and design state observers that use information of inputs and outputs only subject to faults in each subset. We then design residuals using the process model and state estimates such that each residual is only sensitive to the corresponding subset of faults. The occurrence of faults in a subset is detected if the corresponding residual breaches its threshold. With the ability of detecting the occurrence of faults in a subset, faults can be isolated using a bank of residuals and a logic rule. The proposed method enables differentiation between and isolation of actuator and sensor faults while explicitly accounting for system nonlinearity. The effectiveness of the fault isolation design subject to plant-model mismatch and measurement noise is illustrated using a chemical reactor example.

1. Introduction

The last few decades have witnessed significant improvements in efficiency and profitability of chemical process operations due to the advances in automatic control techniques. The increased level of automation, however, also makes process control systems susceptible to equipment abnormalities, such as failures in actuators (e.g., valves and pumps) or sensors (e.g., thermocouples, flow meters, and gas chromatographs). If not properly handled, they can lead to consequences ranging from failures to meet product quality specifications to plant shutdowns, incurring substantial economic losses, safety hazards to facilities and personnel, and damages to the environment. It is desired that faults be detected and the faulty equipment be accurately located so that corrective control action can be taken before they turn into a catastrophic failure. This realization has motivated significant research efforts in the area of fault detection and isolation (FDI).

A typical approach to FDI is to utilize the information embodied in a process (identification or deterministic) model to detect and isolate faults (see, e.g., Frank, 1990; Bokor and Szabó, 2009 for reviews). In this approach, residuals are generated as fault indicators using the analytical redundancy extracted from a process model. Faults are detected by checking whether or not the residuals breach their thresholds, and isolated using certain isolation logic. This approach has been studied extensively for linear systems (see, e.g., Mehra and Peschon, 1971; Clark et al., 1975; Clark, 1978; Chow and Willsky, 1984; Frank, 1990; Patton and Chen, 1993; Chen et al., 1996; Hamelin and Sauter, 2000; Venkatasubramanian et al., 2003; Chen and Saif, 2007; Li et al., 2008). The existing results include the parity space approach, the observer approach, the fault detection filter approach, and the parameter identification approach (see, e.g., Frank, 1990). While there is a significant body of results for linear systems, they may not remain effective for chemical process systems with strong nonlinear dynamics.

Recently, the problem of FDI has also been studied for nonlinear process systems subject to actuator or process faults. In De Persis and Isidori (2001), a nonlinear FDI filter is designed to solve a fundamental problem of residual generation using a geometric approach. The objective of the filter design is to build a dynamic

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system for the generation of residuals that are affected by a particular fault and not affected by disturbances and the rest of faults. The problem of actuator fault isolation is also studied by exploiting the system structure to generate dedicated residuals (see, e.g., Mhaskar et al., 2008; Hu and El-Farra, 2011; Chilin et al., 2010; El-Farra and Ghantasala, 2007; Ghantasala and El-Farra, 2009 in the context of distributed parameter systems). In this approach, each residual, defined as the discrepancy between state measurements and their expected trajectories, is uniquely sensitive to one fault. Thus, a fault is isolated when the corresponding residual breaches its threshold. While uncertainty is not explicitly considered, the thresholds can be appropriately relaxed in the practical implementation of this approach to reduce the effect of process uncertainty and measurement noise. In addition, adaptive estimation techniques are used to explicitly account for unstructured modeling uncertainty for a class of Lipschitz nonlinear systems (see, e.g., Zhang et al., 2002, 2010). In these results, residuals, defined as output estimation errors, and time-varying thresholds are generated using a bank of estimators, and a fault is isolated when the corresponding residuals breach their thresholds. The above results rely on the FDI requirements being satisfied at the nominal operating condition. Recently, the idea of active fault isolation has been proposed to enhance isolation of faults that may be hard to isolate under nominal operation (see Du and Mhaskar, 2013). The fault isolation design exploits the process nonlinearity to drive the process to a region where the effects of faults can be differentiated from each other.

Results are also available for sensor FDI of nonlinear process systems. This problem has been studied for Lipschitz nonlinear systems (see, e.g., Vemuri, 2001; Rajamani and Ganguli, 2004; Zhang et al., 2005; Pertew et al., 2007; Zhang, 2011), and in the context of asynchronous measurements or complete sensor failures (Mhaskar et al., 2007; Martini et al., 1987; McFall et al., 2008). In Rajamani and Ganguli (2004), a nonlinear state observer is designed to generate state estimates using a single sensor. The fault isolation logic, however, is limited to systems with three or more outputs. Similar to actuator FDI, adaptive estimation techniques are used to deal with unstructured but bounded uncertainty for sensor FDI (see, e.g., Zhang et al., 2005; Zhang, 2011). The problem is also studied through sensor fault estimation in Pertew et al. (2007), where linear matrix inequality techniques are used to design an observer for the identification of the fault vector. In addition, a sliding mode observer is designed to reconstruct or estimate faults by transforming sensor faults into pseudo-actuator faults in Yan and Edwards (2007). This approach, however, requires a special system structure, and limits the kind of system nonlinearity that can be handled. While a bank of observers is used to isolate sensor faults in Mattei et al. (2005), the observer gain is obtained through the first order approximation of the nonlinear dynamics. Recently, a method that uses a bank of high-gain observers was proposed to isolate and handle sensor faults (see Du and Mhaskar, 2012). The enhanced applicability of the state observer (see also Findeisen et al., 2003) aids in the explicit consideration of process nonlinearity in the fault isolation mechanism design.

FDI designs that consider actuator and sensor faults separately, however, typically cannot differentiate between the two types of faults (see, e.g., Mhaskar et al., 2008; Du and Mhaskar, 2012, 2013). To illustrate this point, we consider a residual that is designed for isolating only actuator (or, alternatively, only sensor) faults. Such a residual is often computed using information of measurements (or prescribed inputs). There are two cases where this residual can breach its threshold. One case is that an actuator (or sensor) fault takes place (and this residual is designed to be sensitive to this fault). The other case is that a sensor (or actuator) fault takes place, and the computation of this residual uses the erroneous measurement (or the incorrect input to the plant). Because the design of residuals does not consider the two types of faults in a unified framework, a differentiation between actuator and sensor faults cannot be achieved.

In comparison, there exist limited results on distinguishing between and isolating actuator and sensor faults in a unified framework for nonlinear process systems. In the literature, the problem has been studied using two unscented Kalman filters dedicated to detect actuator and sensor faults, respectively, in Shang and Liu (2011), where a squared residual is used to diagnose if an actuator or sensor fault takes place. However, the FDI design works with the assumption that only one actuator or sensor is faulty. In contrast, the present work considers at most two simultaneous faults, where the problem is tackled by designing a bank of residuals (aided by a bank of state observers) and a logic rule for fault isolation. In addition, it is able to differentiate between and isolate actuator and sensor faults while explicitly accounting for process nonlinearity.

Motivated by the above considerations, this work considers the problem of isolating actuator and sensor faults in nonlinear process systems. The key idea of the proposed method is to exploit the analytical redundancy in the system through state observer design. The rest of the paper is organized as follows: The system description and a state observer are presented in Section 2. The fault isolation method is proposed in Section 3, where subsets of faults are considered, and for each subset, a residual is designed such that it is only sensitive to faults in a subset. The occurrence of faults can be detected when the corresponding residual breaches its threshold. With the ability of detecting the occurrence of faults in a subset, faults can be isolated by checking whether the corresponding residuals breach their thresholds using a logic rule. The effectiveness of the fault isolation design subject to plant-model mismatch and measurement noise is illustrated using a chemical reactor example in Section 4. Finally, Section 5 gives some concluding remarks.

2. Preliminaries

Consider a multi-input multi-output nonlinear system described by

$$\dot{x} = f(x) + G(x)(u + \tilde{u}) \quad y = h(x) + \tilde{y} \tag{1}$$

where $x \in \mathcal{X} \subset \mathbb{R}^n$ denotes the vector of state variables, with $\mathcal{X}$ being a compact set of the admissible state values, $u = [u_1, \dots, u_m]^T \in \mathbb{R}^m$ denotes the vector of prescribed control inputs, taking values in a nonempty compact convex set $\mathcal{U} \subseteq \mathbb{R}^m$, $\tilde{u} = [\tilde{u}_1, \dots, \tilde{u}_m]^T \in \mathbb{R}^m$ denotes the unknown fault vector for the actuators, $y = [y_1, \dots, y_p]^T \in \mathbb{R}^p$ denotes the vector of output variables, $\tilde{y} = [\tilde{y}_1, \dots, \tilde{y}_p]^T \in \mathbb{R}^p$ denotes the unknown fault vector for the sensors, and $G(x) = [g_1(x), \dots, g_m(x)]$. Due to the presence of physical constraints, the actual input $u + \tilde{u}$ implemented to the system takes values from the set $\mathcal{U}$ as well. It is assumed that the functions $f : \mathbb{R}^n \to \mathbb{R}^n$, $g_i : \mathbb{R}^n \to \mathbb{R}^n$, $i = 1, \dots, m$, and $h : \mathbb{R}^n \to \mathbb{R}^p$ are smooth over their domains of definitions. Throughout the paper, $\|\cdot\|$ denotes the Euclidean norm.

In this work, we consider the problem of FDI for at most two faults. It encompasses the cases of a single actuator or sensor fault, two actuator or sensor faults, and the simultaneous occurrence of one actuator fault and one sensor fault. It follows that the total number of faulty scenarios $n_f = m + \frac{1}{2}m(m-1) + p + \frac{1}{2}p(p-1) + mp$. Since a large number of simultaneous faults would occur less frequently, the consideration of two faults would meet most of the practical needs. More importantly, the proposed method would still serve as a fault detection mechanism clearly detecting that more than two faults have taken place simultaneously, which would likely necessitate a more drastic corrective action, such as shutdown, in any case.

Preparatory to the presentation of the fault isolation mechanism, we review a high-gain observer design for a generalized class