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# Fault detection and isolation in the presence of process uncertainties ☆

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**Abstract**

This paper proposes a novel scheme of sensor/actuator fault detection and isolation (FDI) for multivariate dynamic systems in the presence of process uncertainties, including model-plant-mismatch and process disturbances. Given an estimated model that can be biased from the true one, the primary residual vector (PRV), for detecting faults in output sensors, can be made completely insensitive to process uncertainties under certain conditions. For detecting faults in actuators, the PRV can be made almost insensitive to the process uncertainties. Numerical and experimental examples justify the effectiveness of the proposed scheme, where comparison with an existing robust FDI scheme is conducted.


*Keywords:* Fault detection; Fault isolation; Robustness; Uncertainty; Multivariate systems

## 1. Introduction

Since the 1970s, tremendous research effort has been invested in model-based fault detection and isolation (FDI). So far, survey papers in this area have been published by Willsky (1976), Isermann (1984), Gertler (1988, 1991), and Frank (1990). In addition, several books are also available (Basseville & Nikiforov, 1993; Patton, Frank, & Clark, 1989, 2000; Gertler, 1998). For most recent advances on FDI, reviews have been given by Qin and Li (2001), and Li and Shah (2002).

Early FDI methods assumed the availability of an accurate model of the monitored system. In practice, however, such an assumption can be invalid, because modelling errors, i.e. model-plant-mismatch (MPM), is always present in a complex system. Besides, process disturbances are inevitable in most processes. *Process uncertainties* are referred to MPM and process disturbances herein, and in the sequel throughout this paper this terminology will be always used. Process uncertainties can render most accurate model-based FDI schemes to be non-robust, making them completely unworkable in worst cases.

Recently, robust FDI schemes that enable the detection and isolation of faults in the presence of process uncertainties have drawn increasing research attention. Basically, existing FDI schemes take into consideration of process disturbances and MPM separately. Disturbances decoupling FDI methods include the works done by Frank (1994), and Patton and Chen (1992, 2000). On the other hand, a number of FDI schemes with robustness against the modelling errors have been proposed including the work by Lou, Willsky, and Verghese (1986), Frank and Ding (1994, 1997), Gertler and Kunwer (1995), Chen, Patton, and Zhang (1996), Shen and Hsu (1998), Hamelin and Sauter (2000), Qin and Li (2001), and Li and Shah (2002), in both the time and frequency domains. However, to the best of our knowledge, very few FDI schemes have the capability of simultaneously working in the presence of disturbances plus MPM, unless some restrictive assumptions on the MPM are assumed (Zhong, Ding, Lam, & Wang, 2003; Chen & Patton, 1999).

This paper proposes an online and real time sensor and actuator FDI scheme which takes care of the process disturbances and the MPM simultaneously for a

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multivariate dynamic system. By extending the well-known Chow–Willsky approach (Chow & Willsky, 1984), a primary residual vector (PRV), which is a fault-accentuated signal, is generated for fault detection. To generate the PRV, one does not need a precise state space model of the considered system. Instead, a roughly estimated model is good enough. To detect and isolate faults in the output sensors only, the PRV can be made perfectly insensitive to the process uncertainties under certain reasonable conditions. To detect and isolate faults in the actuators, the PRV can be made almost insensitive to the process uncertainties.

This paper is organized as follows. Section 2 gives the problem formulation. The design of a PRV for sensor fault detection in the presence of process uncertainties is furnished in Section 3, where a set of structured residual vectors (SRVs) is also generated by transforming the PRV for fault isolation. The detection and isolation of actuator faults are discussed in Section 4. Numerical simulation and experimental case studies are presented in Section 5, where a comparison between the newly proposed robust FDI approach and the original Chow–Willsky approach is included. The paper ends with concluding remarks in Section 6.

## 2. Problem formulation

### 2.1. System description

Assume that the normal behavior of a multivariate dynamic process can be represented by the following discrete time linear state space model:

$$\begin{aligned} \mathbf{x}_{k+1} &= \mathbf{A}\mathbf{x}_k + \mathbf{B}\mathbf{u}_k + \mathbf{E}\mathbf{d}_k, \\ \mathbf{y}_k^* &= \mathbf{C}\mathbf{x}_k, \end{aligned} \tag{1}$$

where $\mathbf{u}_k \in \Re^l$ is the process inputs; $\mathbf{y}_k^* \in \Re^m$ is the *fault-free* process outputs; $\mathbf{x}_k \in \Re^n$ is the process state vector; $\mathbf{d}_k \in \Re^q$ represents the unmeasured deterministic process disturbance vector (Gustafsson & Graebe, 1998), which can be any unknown function of time; $\mathbf{E} \in \Re^{n\times q}$ is a unknown gain matrix of the disturbances; and $\{\mathbf{A},\mathbf{B},\mathbf{C}\}$ are system matrices with appropriate dimensions. The process is assumed to be observable.

With the presence of sensor/actuator faults and instrument noises, the inputs to the process and the observed process outputs can be represented by

$$\begin{aligned} \mathbf{u}_k &= \mathbf{u}_k^* + \mathbf{f}_k^u, \\ \mathbf{y}_k &= \mathbf{y}_k^* + \mathbf{f}_k^y + \mathbf{o}_k, \end{aligned} \tag{2}$$

where $\mathbf{y}_k \in \Re^m$ is the measured output vector; $\mathbf{u}_k^* \in \Re^l$ is the *fault-free* input vector to the process; $\mathbf{o}_k \in \Re^m$ is the output measurement noise; $\mathbf{f}_k^u \in \Re^l$ is the actuator fault; and $\mathbf{f}_k^y \in \Re^m$ is the sensor fault. It is assumed that $\mathbf{o}_k$ is a Gaussian-distributed white noise vector with covariance matrix $\mathbf{R}_o$, and is independent of the initial state $\mathbf{x}_0$ and the disturbances $\mathbf{d}_k$.

In the fault-free case, $\mathbf{f}_k^u$ and $\mathbf{f}_k^y$ are null vectors. In the case that some sensors/actuators are faulty, the corresponding elements in $\mathbf{f}_k^y$ and $\mathbf{f}_k^u$ will be non-zero, while the other elements remain zero. For instance, to indicate that the first output sensor is faulty, the first element in $\mathbf{f}_k^y$ is non-zero while other elements are zero.

It is assumed that $\mathbf{u}_k^*$ and $\mathbf{y}_k$ are available, because they are controller outputs and the observed process outputs, respectively. The detailed process setup is displayed in Fig. 1.

### 2.2. Process uncertainties

In most cases, the true values of the system matrices $\{\mathbf{A},\mathbf{B}\}$ are never exactly known. However, an estimate $\{\mathbf{A}_\circ,\mathbf{B}_\circ\}$ of $\{\mathbf{A},\mathbf{B}\}$ can be available, and one has

$$\begin{aligned} \mathbf{A} &= \mathbf{A}_\circ + \delta\mathbf{A}, \\ \mathbf{B} &= \mathbf{B}_\circ + \delta\mathbf{B}, \end{aligned} \tag{3}$$

where $\{\delta\mathbf{A},\delta\mathbf{B}\}$ is the error between $\{\mathbf{A},\mathbf{B}\}$ and $\{\mathbf{A}_\circ,\mathbf{B}_\circ\}$, representing the MPM. Assume that $\mathbf{C}$ is

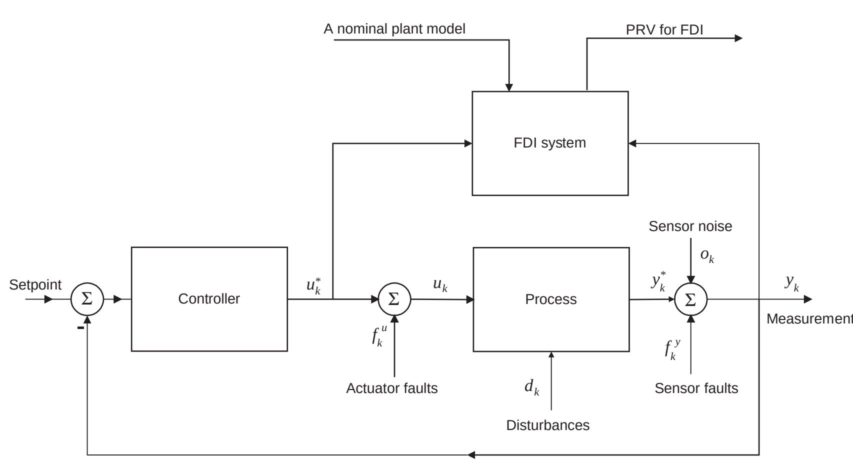

Fig. 1. Schematic diagram of the FDI system.