Control Engineering Practice 18 (2010) 140–146

Contents lists available at ScienceDirect

Control Engineering Practice

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

Self-repairing control via an unstable filter

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ARTICLE INFO

Article history:
Received 13 January 2009
Accepted 5 October 2009
Available online 3 November 2009

Keywords:
Sensor failures
Fault-tolerant systems
Fault detection
System failure and recovery
Process control

ABSTRACT

This paper presents a new self-repairing control system (SRCS) for nonlinear plants with unknown sensor failures of a stuck-type. The SRCS can detect the failure and replace the faulty sensor with the healthy one. The advantage of the SRCS is that no plant model is required to detect the failure. Hence, one can construct the SRCS of an extremely simple structure. To achieve exact and early fault detection, an unstable filter and an auxiliary switching signal are introduced. The detection period can be shortened arbitrarily by choosing a large pole of the filter. Also, this paper shows an application to a nonlinear continuous stirred tank reactor. To confirm the effectiveness, several numerical experiments are explored.

1. Introduction

Stuck sensors often cause fatal and serious damages to control systems. If a measured feedback signal gets stuck at some value due to a failure, then a feedback-loop is opened and the stability cannot be guaranteed. To cope with the failure of this stuck-type, the failed sensor should be replaced with the healthy one using dynamic redundancy (Isermann, Schwarz, & Stölzl, 2002). This approach might be the only strong way to recover from the effects of stuck sensors completely.

In general, to find a failed sensor, a fault detector ought to be introduced. A large number of attractive fault detection methods have been developed (e.g., see Frank, 1990; Willsky, 1976). From a view of reliability, it might be important to guarantee exact fault detection deterministically. To achieve this, many conventional deterministic approaches, such as observer-based methods, estimator-based methods and so on, have utilized plant models. Some of statistical methods have been based on plant models (Basseville & Nikiforov, 1995; Juricek, Seborg, & Larimore, 2001). However, the use of plant models sometimes induces complexity when plants have complex structures. An exact fault detection with use of no plant model is still a challenging open problem.

In the previous works by Takahashi (2007a, b), the self-repairing control system (SRCS) has been developed that can replace the failed component with the healthy one automatically when the failure is detected. The SRCS consists of a plant, a controller, an integrator and an auxiliary switching signal. The switching signal is designed so that the output of the integrator exceeds a prescribed threshold if the system becomes an open-loop system due to the failure. Hence, the fault detector has only to make sure whether the output of the integrator hits the threshold or not. Thus, no plant model is required, and so one can construct the simple SRCS. Unfortunately, the detection time depends on the magnitude of the switching signal. So, for the purpose of early detection, the switching signal has to be large enough. However, this modification often degrades the control performance.

As a remedy, this paper develops a new SRCS with an unstable filter. Choosing a large pole of the filter makes it possible to shorten the detection period arbitrarily even if the small switching signal is used. Because the failed sensor is replaced before the signals in the SRCS diverge out, it can be guaranteed that all the signals are bounded.

This paper also presents an application to a nonlinear continuously stirred tank reactor (CSTR) which is recognized as one of the fundamental chemical equipments (Alvares-Ramirez, 1999; Seborg, Edgar, & Mellichamp, 1989; Viel, Jadot, & Basin, 1997). Several interesting fault-tolerant control strategies for the CSTR have been already investigated by Mhaskar, Gani, MacFall, Christofides, and Davis (2007) and Mhamood, Ganhi, and Mhaskar (2008). For such a typical chemical system, the concrete design of the SRCS is shown; a simple high-gain feedback controller and a simplified detection algorithm are constructed. Furthermore, to confirm the effectiveness, several numerical experiments are explored.

Throughout this paper, $\mathbb{R}$, $\mathbb{R}^+$, $\mathbb{I}$ and $\mathbb{I}^+$ denote real numbers, non-negative real numbers, integers and non-negative integers, respectively. For each vector function $\boldsymbol{v}(t) \in \mathbb{R}^n$, its norm and ∞- norm are defined by

$$\|\boldsymbol{v}(t)\| \triangleq (\boldsymbol{v}(t)^T \boldsymbol{v}(t))^{1/2}, \quad \|\boldsymbol{v}(t)\|_\infty \triangleq \sup_{0 \le s \le t} \|\boldsymbol{v}(s)\|$$

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doi:10.1016/j.conengprac.2009.10.001

2. Self-repairing control using an unstable filter

This section presents the basic design of the SRCS with an unstable filter.

Now, consider a nonlinear system of the form:

$$\Sigma_P : \dot{\boldsymbol{x}}(t) = \boldsymbol{f}(t, \boldsymbol{x}(t), u(t)), \quad y(t) = g(t, \boldsymbol{x}(t), u(t)) \tag{1}$$

where $\boldsymbol{x}(t) \in \mathbb{R}^n$, $y(t) \in \mathbb{R}$ and $u(t) \in \mathbb{R}$ are the state, the output and the input, respectively. Suppose that $\boldsymbol{f} : \mathbb{R}^+ \times \mathbb{R}^n \times \mathbb{R} \to \mathbb{R}^n$ and $g : \mathbb{R}^+ \times \mathbb{R}^n \times \mathbb{R} \to \mathbb{R}$ are sufficiently smooth. Furthermore, assume that the plant Σ_P is input-to-state stable (ISS), that is, the state $\boldsymbol{x}(t)$ satisfies

$$\|\boldsymbol{x}(t)\| \le \gamma_0(\|\boldsymbol{x}(0)\|, t) + \gamma_1(\|u(t)\|_\infty), \quad t \ge 0 \tag{2}$$

where $\gamma_0 : \mathbb{R}^+ \times \mathbb{R}^+ \to \mathbb{R}^+$ is a $\mathcal{KL}$ class function and $\gamma_1 : \mathbb{R}^+ \to \mathbb{R}^+$ is a $\mathcal{K}$ class function (see the rigorous definitions of the functions by Khalil, 1996). Without loss of generality, the initial state $\boldsymbol{x}(0)$ is supposed to be bounded. Hence, the ISS property assures that the state $\boldsymbol{x}(t)$ is bounded for the bounded input $u(t)$.

To accommodate the failure, the two sensors ♯1 (the primary) and ♯2 (the backup) are prepared. Then the feedback signal $y_S(t) \in \mathbb{R}$ is given by

$$y_S(t) = \sigma(t) y_1(t) + (1 - \sigma(t)) y_2(t) \tag{3}$$

where $y_i(t) \in \mathbb{R},\ i \in \{1, 2\}$ is the signal measured by the sensor ♯*i*. If there is no sensor failure, then the measured signals are identical with the actual output, i.e.,

$$y_i(t) = y(t), \quad i = 1, 2 \tag{4}$$

However, the sensor ♯1 fails as follows:

$$y_1(t) = y_1(t_F), \quad t \ge t_F \tag{5}$$

where $t_F > 0$ is the unknown failure time. The role of the sensor ♯2 is just a standby module for occasions of failures. The sensor ♯2 should be inactivated and be out of the feedback-loop until the primary sensor ♯1 fails (precisely, the failure is detected). This is called "cold standby" (Isermann et al., 2002). Hence, fortunately, it can be supposed that the sensor ♯2 is always healthy.

The switching function $\sigma : \mathbb{R}^+ \to \{0, 1\}$ is given by

$$\sigma(t) = \begin{cases} 1 & (t < t_D) \\ 0 & (t \ge t_D) \end{cases} \tag{6}$$

where $t_D \ge 0$ is a detection time determined by the detection algorithm which will be designed later. As mentioned above, normally, the sensor ♯1 is used. If the failure (5) is detected, then the reserved sensor ♯2 is activated. This means that only the primary sensor ♯1 is available for fault detection. In addition, the difficulty of sensor fault detection arises when the measured signal $y_1(t)$ gets stuck at an ideal or admissible value, such as a set-point. The main function (objective) of the SRCS is to find an appropriate detection time t_D with use of only the measurement from the sensor ♯1.

For the plant Σ_P with the sensor failure (5), the SRCS is constructed as follows (also see Fig. 1).

First of all, an unstable filter Σ_D is introduced:

$$\Sigma_D : \dot{v}(t) = \alpha v(t) + \beta (e_S(t) + \tau(t)) \tag{7}$$

where $\alpha \in \mathbb{R}^+$ and $\beta \in \mathbb{R}^+$ are arbitrary positive constants. The error signal $e_S(t) \in \mathbb{R}$ is defined by

$$e_S(t) \triangleq r - y_S(t) \tag{8}$$

with the reference input $r \in \mathbb{R}$. The auxiliary switching signal $\tau(t) \in \mathbb{R}$ is injected to achieve the exact fault detection for any

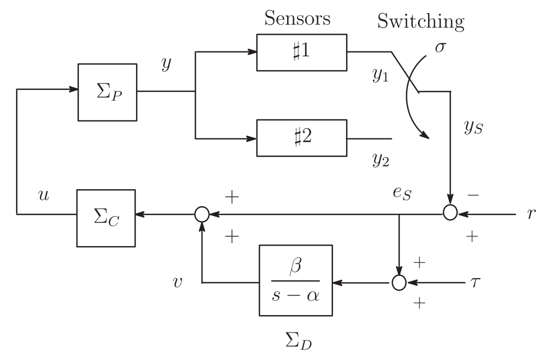

Fig. 1. The SRCS with the unstable filter.

stuck value $e_S(t_F)$:

$$\tau(t) = \tau_0 \left(\frac{1 + (-1)^k}{2} \right), \quad t \in [t_k, t_{k+1}), \ \ k = 0, 1, \ldots \tag{9}$$

where $\tau_0 \in \mathbb{R}$ is an arbitrary small non-zero constant. For every $k \in \mathbb{I}^+$, the switching time $t_k \in \mathbb{R}^+$ is given by

$$t_k = \frac{k(k+1)}{2} \tag{10}$$

The switching signal $\tau(t)$ is well-designed so that $v(t)$ hits a threshold if the SRCS becomes an open-loop system due to the sensor failure.

The controller Σ_C which stabilizes the overall control system, is given by

$$\Sigma_C : \dot{\boldsymbol{z}}(t) = \boldsymbol{f}_C(\boldsymbol{z}(t), e_S(t) + v(t)), \quad u(t) = g_C(\boldsymbol{z}(t),\ e_S(t) + v(t)) \tag{11}$$

where $\boldsymbol{z}(t) \in \mathbb{R}^{n_c}$ is the state of the controller Σ_C which is assumed to be available. Suppose that $\boldsymbol{f}_C : \mathbb{R}^{n_c} \times \mathbb{R} \to \mathbb{R}^{n_c}$ and $g_C : \mathbb{R}^{n_c} \times \mathbb{R} \to \mathbb{R}$ are sufficiently smooth. Here, assume that the overall closed-loop system satisfies the following assumption.

Assumption 1. If no failure occurs ($t_F = \infty$), then there exist bounded functions $\Gamma_v : \mathbb{R}^+ \to \mathbb{R}^+$, $\Gamma_u : \mathbb{R}^+ \to \mathbb{R}^+$ and $\Gamma_z : \mathbb{R}^+ \to \mathbb{R}^+$ such that

$$|v(t)| < \Gamma_v(t), \quad |u(t)| < \Gamma_u(t), \quad \|\boldsymbol{z}(t)\| < \Gamma_z(t) \tag{12}$$

Under Assumption 1, from the ISS property of the plant Σ_P, all of the signals $\boldsymbol{x}(t)$, $v(t)$, $u(t)$ and $\boldsymbol{z}(t)$ are bounded when the activated sensor is healthy. In this paper, to satisfy Assumption 1, it is implicitly supposed that the overall closed-loop system, which contains the plant Σ_P and the unstable filter Σ_D, is stabilized by the controller Σ_C with the healthy sensor. Precisely, the nominal closed-loop system without the external (perturbation) signals r and $\tau(t)$ is assumed to have an asymptotically stable equilibrium point at the origin. It is well known that for an arbitrary stable nonlinear system with any bounded perturbation signals, all the signals in the system are bounded (Khalil, 1996). Therefore, because the external signals r and $\tau(t)$ are bounded, all the signals in the closed-loop system perturbed by r and $\tau(t)$ are bounded. When the signal $v(t)$ is set some value at each switching time t_k as shown in Theorem 1, the exponential stability of the nominal closed-loop system will be required (e.g., see the proof of Theorem 2).

The stabilizing controller Σ_C can be constructed by the design methods in a large number of the previous works. Also, it is not difficult to specify the functions in Assumption 1 by exploiting prior experimental data.

Finally, the detection time t_D is defined by

$$t_D \triangleq \min[t \,|\, |v(t)| \ge \Gamma_v(t) \text{ or } |u(t)| \ge \Gamma_u(t) \text{ or } \|\boldsymbol{z}(t)\| \ge \Gamma_z(t)] \tag{13}$$