Operator based Fault Detection System Design to an Actuator Fault of a Thermal Process

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Abstract: This paper proposes a fault detection method for an actuator fault of an aluminum plate thermal process with input constraints. Operator-based robust right coprime factorization approach is utilized in this method. In details, after creating a mathematical model, a robust tracking operator system is designed. Following this, design of the fault detection system is given. Finally, experiment is conducted to support the proposed design method.

1. INTRODUCTION

Process control is very popular in real control systems. The main purpose of the process control system is to stabilize the process and to minimize the negative effect of disturbances, noises and process input constraints. Understandable examples of the process are tanks, compressors and heat exchangers. These process controls water level, pressure and temperature respectively. To stabilize such real control systems, which contain some negative factors mentioned above, the process model seems to be created based on a few physical laws or system identification. Following this, the controllers for the process can be designed. However, a real process is likely to contain a fault signal owing to various environmental factors. Besides, the process control system needs to deal with some input constraints, such as limited power of heater or compressor. Furthermore, a real process has uncertainties whose linearity is unknown. Therefore, the uncertain process with an input constraint is a considerable issue in the real process. As for fault detection, a large number of interesting design methods have been researched (see Deng et al., 2007; Clark, 1978; Wang, 1997). In general, fault signals are classified as three kinds, namely sensor fault, actuator fault and process fault. From the viewpoint of process safety, the control systems should have the capability of detecting the fault signal, because the process will be corrupted unless the system has the capability. To detect the fault signal, one approach is to locate a lot of sensors. On the other hand, this approach has a large number of costs to detect all sensors' data and to monitor them. For this reason, analytical methods that utilize measurable information in the process have been considered.

In this paper, different from the tracking filter fault detection in Deng et al., (2007), an operator-based robust right coprime factorization approach (see Chen and Han, 1998; Deng et al., 2006) is applied to an uncertain thermal process of an aluminum plate with process input constraints. Firstly, the thermal process is modeled as a right coprime factorization description. Next, a robust tracking control system is shown. Then, the Bezout identity can be given for stabilizing the system by robust right coprime factorization based on operator theory (see Chen and Han, 1998,-,Vidyasagar, 1985). Finally, the fault signal on an actuator is analysed using two sorts of operators. An experimental result is represented to support the designed control system and fault detection system. The organization of the paper is as follows. First of all, modelling and problem setup are presented in Section 2. Subsequently, Section 3 gives how to design operators. After that, Algorithm of the fault detection system is proposed in Section 4. An experimental result is shown in Section 5, and its discussion is also given. Finally, Section 6 draws the conclusion.

2. MODELLING AND PROBLEM SETUP

Most definitions and lemmas concerned with operator and bounded input and bounded output stability are in Deng et al., (2007). Therefore, in this paper, a few significant definitions are given. Then, the process model is explained briefly. Detailed information in regards to modelling is written in Deng et al., (2007).

2.1 Definitions of right coprime factorization and the Bezout identity

Let (N, D) be a right factorization of $P : U \to Y$. P is said to be a right coprime factorization if there are two stable operators $S : Y \to U$, $R : U \to U$ and R is invertible, S, N, R and D satisfy the Bezout identity

$$SN + RD = M, \tag{1}$$

where, $M \in \mathcal{U}(W, U)$. The Bezout identity is often used in the following equation for simplicity

$$SN + RD = I, \tag{2}$$

where I is identity operator.

2.2 Modelling and problem setup

There are three main parts for the experimental setup. They are shown as follows.

- Aluminum part
- Interface part
- Computer part

The first part consists of an aluminum board divided into three blocks hypothetically, that is, three thermal sensors, and three the heaters whose maximum outputs are 40[W]. Besides, the sensors and the heaters are both fixed on three spots of those three blocks.

For measuring the temperature of an aluminum plate, thermal sensors can measure the temperature of the plate, and the measured temperatures are outputted as a voltage. Then, the binary data is converted to base 10 at the computer. Their model is shown in Fig.1, and photo of the process is shown in Fig. 2.

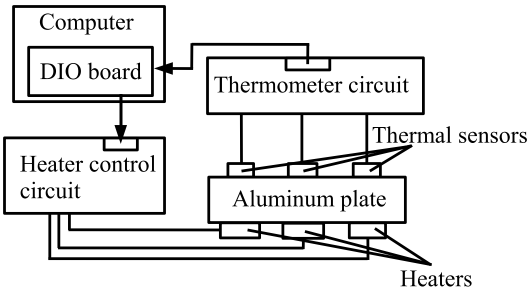

Fig. 1. General diagram of the thermal process

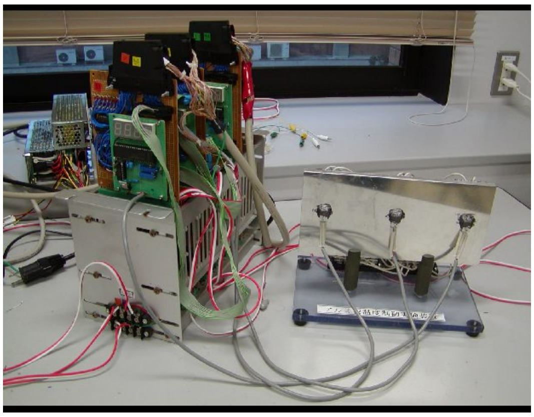

Fig. 2. Photo of the thermal process

The configuration of the aluminum plate thermal process is shown in Fig. 3. Fourier's law of heat conduction, Newton's law of cooling, and the equation between heat capacity and objects and their specific heat are used in the development of the mathematical model. From these three laws, the thermal process is described as follows:

$$y(t) = \frac{1}{cm} e^{-At} \int e^{A\tau} u_d(\tau) d\tau, \tag{3}$$

where,

$$A = \frac{\alpha(4s_1 + 2s_2 + 4s_3 + s_4 + 2s_5 - s_6)}{cm}. \tag{4}$$

In addition to this, u_d is defined as process input.

From (3), consider the nominal thermal process described by the following right coprime factorization:

$$y(t) = P(u_d)(t) = ND^{-1}(u_d)(t). \tag{5}$$

Where D^{-1} is invertible, the following two equations are given

$$D(w)(t) = cmw(t),\ D^{-1}(u_d)(t) = \frac{1}{cm} u_d(t) \tag{6}$$

$$N(w)(t) = e^{-At} \int e^{A\tau} w(t) d\tau. \tag{7}$$

In a real system, a thermal process is necessary to deal with uncertainties or disturbances, and the above perturbations should affect on D or N in (5). Therefore, suppose that the process P has a bounded perturbation ΔP in this paper. That is, assume that only N has a bounded perturbation ΔN, and the operators and $N + \Delta N$ is stable such that

$$P + \Delta P = (N + \Delta N)D^{-1} \tag{8}$$

$$(N + \Delta N)(w)(t) = (e^{-At} + \Delta_1) \int e^{A\tau} w(\tau) d\tau \tag{9}$$

where, D: $W \to U$, and N: $W \to Y$ are stable operators, respectively, and the space W is called a $quasi-state$ space (see Chen and Han, 1998; Deng et al., 2004) of P. D is invertible. Δ_1 in (9) is regarded as an uncertainty created by the approximation of the aluminum plate in modeling. The modelling of the uncertain factor is written in Deng et al., (2007).

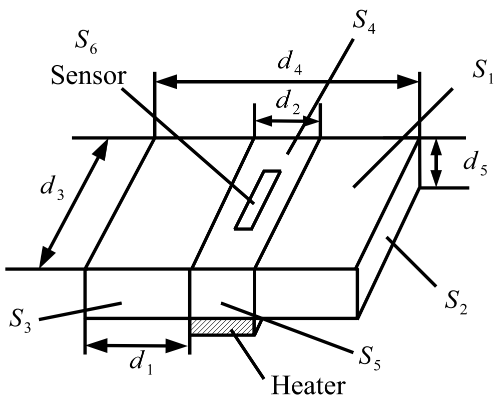

Fig. 3. The aluminum plate thermal process

Here, define that the process input $u_d(t)$ is subject to the following constraint on its magnitude,

$$u_d(t) = \sigma(u_1(t))$$

$$\sigma(v) = \begin{cases} u_{max} & if\ v > u_{max} \\ v & if\ u_{min} \le v \le u_{max} \\ u_{min} & if\ v < u_{min} \end{cases}. \tag{10}$$

Where, $u_1(t)$ is the control input before the constraint.

3. OPERATORS' DESIGN

To control the thermal process, two stable operators $S : Y \to U$ and $R : U \to U$ are required to be designed under the condition of well-posedness and that of N and D being said to have a right coprime factorization. If these two operators exist, which satisfy the following Bezout identity

$$(SN + RD)(w)(t) = I(w)(t), \quad (11)$$

where R is invertible and I is the identity operator, the process can be controlled. As for the case of containing additive perturbation ΔP, the process is likely to be represented as

$$P + \Delta P = (N + \Delta N)D^{-1}. \quad (12)$$

Assume that two stable operators S and R exist satisfying the perturbed Bezout identity

$$(S(N + \Delta N) + RD)(w)(t) = I(w)(t). \quad (13)$$

When the process input is limited, the process uncertainty is described as the following operator

$$\Delta\tilde{N} : W \to Y. \quad (14)$$

Tracking system shown in Fig.4 can be designed to satisfy the following two conditions

$$(N + \Delta\tilde{N})M(r)(t) = r(t) \quad (15)$$

$$(S(N + \Delta\tilde{N}) + RD)(w)(t) = I(w)(t), \quad (16)$$

where $M : Y \to U$ is a stable tracking operator and $r \in Y$ is a reference signal. Furthermore, in the case that there is no process input constraint, (11) and (13) and the following conditions should be satisfied

$$(N + \Delta N)M(r)(t) = r(t) \quad (17)$$

$$NM(r)(t) = r(t) \quad (18)$$

The system is internally stable due to Lemmas 1 and 2 in Deng et al., (2007) and the fact that three sorts of Bezout identities mentioned above are satisfied, where the all operators are BIBO stable.

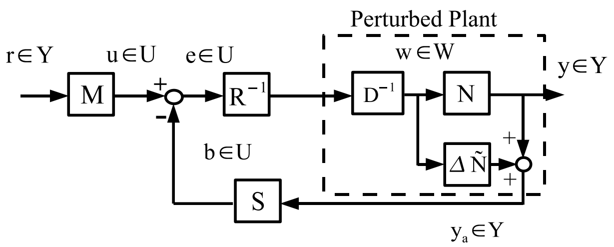

Fig. 4. Tracking system (Deng et al., (2007))

Eventually, operators S, R and M are designed as follows

$$S(y_a)(t) = K_p(1 - B)[\frac{dy(t)}{dt} + Ay(t)] \quad (19)$$

$$R(u_d)(t) = \frac{K_pB - K_p + 1}{cm}u_d(t) \quad (20)$$

$$M(r)(t) = Ar + (1 - A)re^{-t}, \quad (21)$$

where K_p is the proposal gain and B is a design parameter.

4. ALGORITHM OF THE FAULT DETECTION SYSTEM

In the previous paper (Deng et al., (2007)), fault detection system in regards to the tracking operator M was proposed. One advantageous point of the method is that the fault signal in the tracking operator can be obtained without using a large number of sensors. The fault detection system can be meaningful provided that the tracking operator works on hardware. Besides, the fault detection system in this paper may be more useful than that in Deng et al., (2007), since it is applied to an actuator fault and does not depend on what kind of the operators are, i.e. software or hardware.

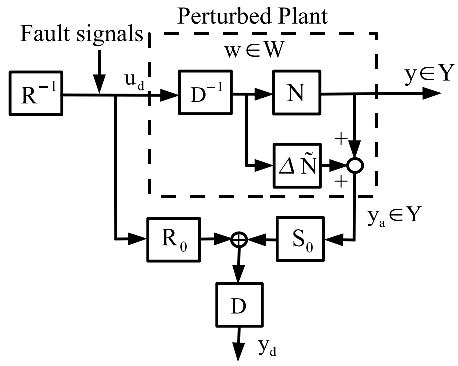

Fig. 5. Fault detection system

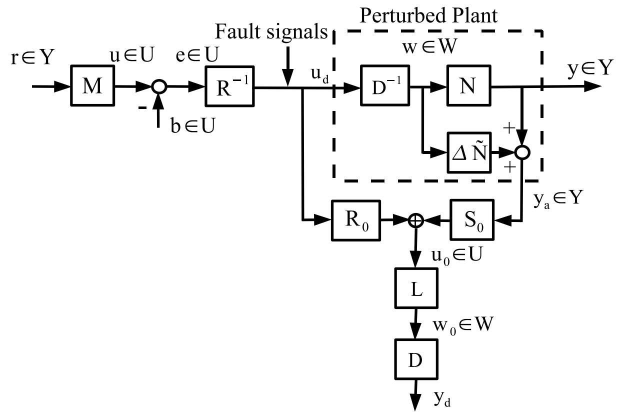

Fig. 6. Detailed fault detection system

For detecting fault signal, firstly three operators R_0, S_0 and D represented in Fig. 5 and Fig. 6 are designed. In Fig. 4, three sorts of Bezout identities, which are in (22)-(24), are satisfied.

$$(SN + RD)(w)(t) = I(w)(t) \quad (22)$$

$$(S(N + \Delta N) + RD)(w)(t) = I(w)(t) \quad (23)$$

$$(S(N + \Delta\tilde{N}) + RD)(w)(t) = I(w)(t) \quad (24)$$

When R_0 and S_0 are composed to satisfy the following Bezout identity:

$$(S_0N + R_0D)(w)(t) = I(w)(t). \quad (25)$$

Where, S_0 and R_0 are obtained as follows

$$S_0(y_a)(t) = (1 - K_0)(\frac{dy(t)}{dt} + Ay(t)) \quad (26)$$

$$R_0(u_d)(t) = \frac{K_0}{cm}u_d(t), \quad (27)$$

where K_0 is a constant. Assume that sum of the output of S_0 and that of R_0 is a mapping from space W to U as

Maximum power of heater	40[W]
Reference input	$r = 1.5$
Constant	$B = 0.7$
Proposal gain	$K_p = 3.2$
Gain for fault detection	$K_0 = 0.95$
Simulation time	1800[s]

Table 1. Parameters for experiment

Desired temperature	28.3[C]
Initial temperature	26.8[C]

Table 2. Desired and initial temperatures

well as (22) according to Fig. 4. That is, the sum $u_0 \in U$ is represented as follows

$$u_0 = R_0(u_d)(t) + S_0(y_a)(t). \qquad (28)$$

Moreover, process input u_d becomes

$$u_d = R^{-1}(e)(t) + fault. \qquad (29)$$

It may be understandable from (22) that signal w is equivalent to u, because the Bezout identity is identity mapping from $W \to U$. Similarly, (25) implies that signal w equals to u_0. However, we have not made sure whether $u = u_0$. If so, (25) can be written

$$(S_0N + R_0D)(w)(t) = M(w)(t), \qquad (30)$$

where $M(w)(t)$ is unimodular, though in this paper, $M(w)(t)$ is decided as $I(w)(t)$. As for operator D, it means a mapping from signal w to u_d from Fig. 4. Therefore, y_d in Fig. 5 equals to the signal in an actuator affected by fault signal as long as w is equivalent to w_0. However, connecting u_0 to D directly like Fig. 5 is impossible due to the difference of spaces that u_0 and w_0 belong to. One way to solve this problem is to design an space-change operator L shown in Fig. 6, which is required to be mapped from U to W. The operator is described

$$L(R_0D + S_0N) = I, \qquad (31)$$

where N, S_0 and R_0 are invertible. Eventually, the difference between the actuator's signal before affected by the fault signal, i.e. the output of operator R^{-1} and y_d results in the actuator faults. In other words, the following equation enables us to detect the fault signal.

$$Detected\ fault\ signal = \text{abs}\ (R^{-1}(e)(t) - y_d) \qquad (32)$$

Unless there are no actuator faults, the following equation is given

$$Detected\ fault\ signal = 0.$$

5. EXPERIMENTS AND DISCUSSIONS

5.1 Experimental results

An experiment to show the effectiveness of the fault detection system is conducted. Table 1 represents parameters utilized in the simulation, and initial temperature and desired temperature of the aluminum plate are in Table 2. Other detailed information is in Deng et al., (2007).

Fig. 7 shows process input and its output, and Fig.8 is a figure that expresses the output of R^{-1}, y_d and detected fault signal in $0 < t \leq 1800$[sec] (see Table 3). Moreover,

$0 < t \leq 400$	0[W]
$400 < t < 500$	5.0[W]
$500 \leq t \leq 1800$	0[W]

Table 3. Fault signal in the actuator

Fig. 9 and Fig. 10 show the comparison of y_d and u_d and detected fault signal respectively. Figs. 11 and 12 are magnified figures of the process input and the detected fault signal respectively. Finally, the output of tracking operator, u is compared with the sum of R_0 and S_0, u_0 in Fig. 13.

From Fig. 7, process output tracks to the almost desired temperature before the fault signal happened, and after actuator fault was fixed, the temperature is back to the desired temperature. Further, the designed fault detection system can detect similar fault signal added according to Fig.10 and Fig.12. Detailed discussion in regards to the simulation will be given in next subsection.

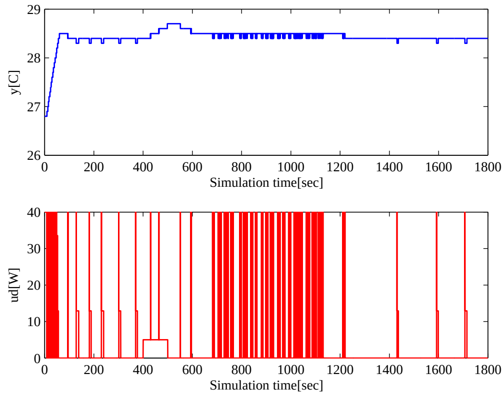

Fig. 7. y and u_d

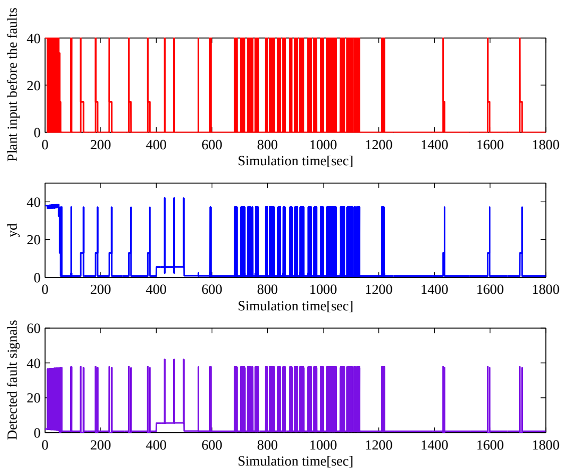

Fig. 8. Before fault, y_d and Detected faults

5.2 Discussions

From Fig.7 and Fig.11, process output y tracks to the desired temperature approximately 100[sec] and after adding the fault signal, its output is back to the desired temperature. As for process input u_d, when $400 < t < 500$, the value of its input increases owing to the influence

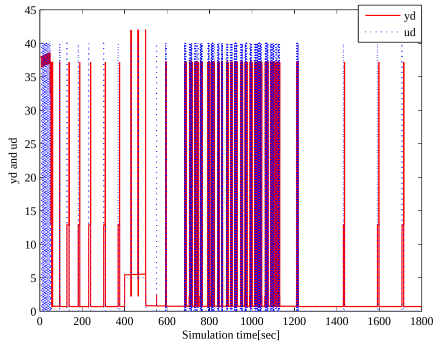

Fig. 9. y_d and u_d

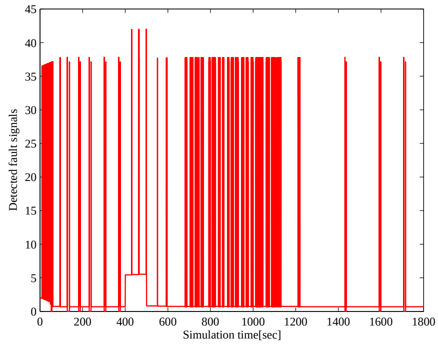

Fig. 10. Detected faults

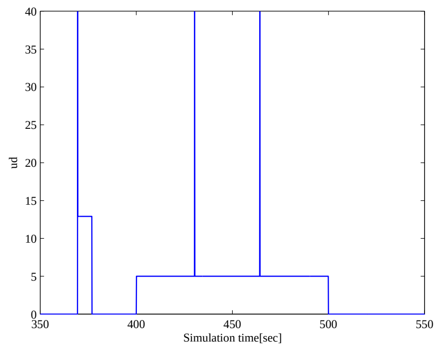

Fig. 11. u_d when $350 \leq t \leq 550$

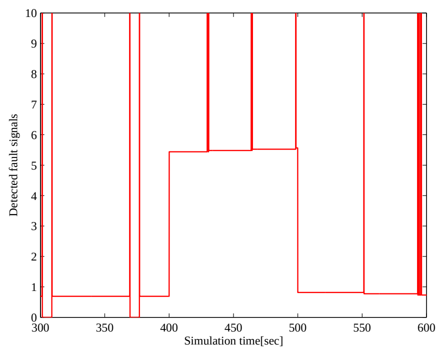

Fig. 12. Detected faults when $300 \leq t \leq 600$

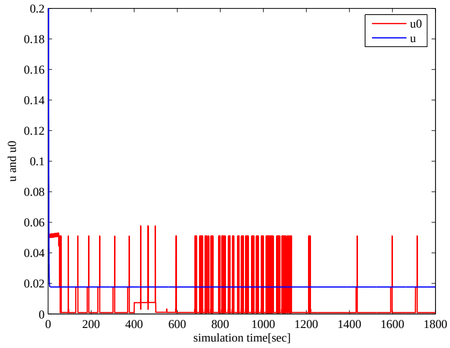

Fig. 13. u and u_0

from the fault signal, and its value is 5[W], though this is smaller than simulation result (2.8[W]). According to the simulation result, due to feedback from process output including an actuator fault, the impact from an actuator fault seems to be mitigated. However, the actuator fault affects on the actuator directly in this experiment. This may be because of process input constraints. Steady state value of process input is 0[W], which is equivalent to minimum input constraints. Consequently, the actuator faults cannot be reduced. Furthermore, a differentiator in the operator S affects on the signal whose size is 40[W] happening to the second graph from the top in Fig.7.

The third graph from the top in Fig.8 and Fig. 10 imply the effectiveness of the designed fault detection system, since the fault signal detected and that added are similar, though the former one is slightly larger (see Fig.12). This might be result from gain K_0 is not a proper number. Another possible reason will be appeared when we discuss the difference between y_d and u_d. From Fig. 8, the designed system can detect fault signal, as signal y_d could be as same as signal u_d if $w = w_0$ is satisfied. However, according to Fig. 9, these two signals are not exactly same. This is likely to come from the affect from process input constraints and (31). If the input constraints are considered somehow and if the equation is satisfied as $L(R_0D + S_0N) = I$, where L is unimodular, this problem would be solved.

Final argumentative point is in regards to the error between u and u_0. It is clear from Fig.6 that u_0 is the sum of $S_0(y)(t)$ and $R_0(u_d)(t)$. From Fig.13, signal u does not equal to signal u_0. The impulse signals happening when the temperature of the aluminum plate changes are created by a differentiator in operator S_0, which originally comes from low temperature resolution of CMOS sensors. Besides, the output of operator R_0 is restricted by process input constraints. For these two reasons, the value of u_0 is different from that of u, and this also could lead to data mismatching between y_d and u_d.

6. CONCLUSION

In this paper, using the method of an operator-based robust right coprime factorization approach, a fault detection system to an actuator was considered. The effectiveness of the proposed fault detection system is confirmed by the experimental result.

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