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Reference Model Based Maintenance of Control System Performance for Industrial Processes

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Abstract—In the last decade, fault tolerant controls (FTC) have enjoyed tremendous success to effectively accommodate defects in sensors, actuators, or plants. However, little of them considered what should be done once a control system performance is degraded during the operation. The aim of this paper is to maintain the performance of a control system at an acceptable level based on a pre-defined reference model. A maintenance approach is proposed and experimented in this paper. The method is to insert a compensator into the faulty control system and make the compensator and the faulty open loop system working together to track the pre-defined reference model. The proposed method is illustrated by reference to a mini process rig and shows the potential to industrial processes.

Keywords: Reference model; compensator; maintenance; control system performance.

I. INTRODUCTION

Controller software maintenance is to keep controller software in an optimal state for the purpose of maintaining a healthy performance of control systems. In details, it consists of three stages (Dai and Yang, 2003):

- Controller performance assessment. It is mainly concerned with quantification of controller performance. Usually, one uses some measures – whether achievable or ideal, subjective or objective – to determine control performance. Some of these measures are the steady-state offset, integrated absolute error (IAE), integrated squared error (ISE), and mean squared error (MSE). Performance measure is used to decide if the performance of a control system is satisfactory or not.
- Controller fault detection. When the controller performance is inadequate, it is important to identify if the degraded performance is caused by a failure in controller software or other parts of the system.
- Controller failure maintenance. If the degradation of the performance is caused by a failure in the controller software, the faulty controller software must be compensated and the degraded control performance needs to be recovered.

Failure may occur in any system, especially in complex systems. Defects in sensors, actuators, process, or within the controller, can be amplified by closed-loop control systems,

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and faults can develop into malfunctions of the loop (Blanke et al, 2001). The malfunctions can cause disastrous damages; the damages range from those affecting the qualities of final products to those involving dangers to property or loss of human life. The malfunctions must be mitigated and control systems should be maintained under any fault scenario.

In the last decade, Fault Tolerant Controls (FTCs) have enjoyed tremendous successes in effectively accommodating defects in sensors or actuators. A number of theoretical results as well as application examples (Rizzoni and Min, 1991; Niemann and Stoustrup, 2003) have been described in the literature. The FTCs are usually based on a re-configurable controller. The purpose of controller reconfiguration is to compensate for the effects of the failed component. The existing methods for the re-configurable controller design such as the quadratic regulator (Zhang and Jiang, 2001) often assume that a perfect fault detection and diagnosis (FDD) scheme is available and the post-fault model of the system is known completely, and the reconfiguring algorithm is then developed according to the post fault model. Karsai et al (2002) used the fault adaptive control to manage the fault recovery, in which the plant is modeled as hybrid bond graph. An observer is developed to track system behavior and the controller reconfiguration relies on a pre-developed controller library. Zhang and Jiang (2003) proposed an active fault tolerant control system, which explicitly incorporates with allowable system performance degradation in the event of partial actuator faults in the design process. This control system is based on model-following and command input management techniques and the degradation in dynamic performance is accounted for through a degraded reference model.

In the rest of this paper we propose and demonstrate a reference model based performance maintenance approach for faulty controller software. The paper is arranged as follows. Section 2 designs the compensator. Section 3 illustrates the case study of applying the compensator into a mini-process unit rig. Section 4 is the conclusions.

II. COMPENSATOR DESIGN

The compensation in the case of the controller failure can be also achieved by the application of model following technique to design a compensator. Suppose a faulty open loop of a

Fig. 1. Compensator in the faulty control loop

system, which can be described by the following representation as:

$$\begin{aligned}\dot{x} &= \mathbf{F}x + \mathbf{G}e + q^x \\ y &= \mathbf{H}x + \mathbf{D}e\end{aligned}\quad (1)$$

where $\mathbf{F}$, $\mathbf{G}$, $\mathbf{H}$ and $\mathbf{D}$ are proper matrices. x is the system state, e the difference between the setpoint and process outputs, y the output, q^x is a zero mean white Gaussian sequence with covariance Q^x .

Consider that a desired reference model is represented by:

$$\begin{aligned}\dot{x}^m &= \mathbf{F}^m x^m + \mathbf{G}^m u^m \\ y^m &= \mathbf{H}^m x^m + \mathbf{D}^m u^m\end{aligned}\quad (2)$$

where $\mathbf{F}^m$, $\mathbf{G}^m$, $\mathbf{H}^m$ and $\mathbf{D}^m$ are proper matrices, x^m is the reference model state, y^m is the process output of the reference model and u^m is the control signal of the reference model.

Assume that a compensator is inserted into the faulty control loop as shown in Fig. 1(a), and then the faulty open loop model in Equation 1 is rewritten as:

$$\begin{aligned}\dot{x}^{com} &= \mathbf{F}x^{com} + \mathbf{G}u^{com} + q^x \\ y &= \mathbf{H}x^{com} + \mathbf{D}u^{com}\end{aligned}\quad (3)$$

where u^{com} is the compensator signal and x^{com} is the system state under the compensator control.

The problem of determining the perfect tracking solution is formulated as follows: design a compensator and make the compensator control signals u^{com} to drive the tracking error $\mathcal{E}$ to zero asymptotically. The error $\mathcal{E}$ is defined as follows:

$$\mathcal{E} = y - y^m = [\mathbf{H} \quad \mathbf{D}] \begin{bmatrix} x^{com} \\ u^{com} \end{bmatrix} - [\mathbf{H}^m \quad \mathbf{D}^m] \begin{bmatrix} x^m \\ u^m \end{bmatrix}$$

When perfect tracking occurs, the resulting process output and THE system state are denoted as:

$$\dot{x}^{com} = \mathbf{F}x^{com} + \mathbf{G}u^{com} + q^x \quad (4)$$

$$y^{com} = [\mathbf{H} \quad \mathbf{D}] \begin{bmatrix} x^{com} \\ u^{com} \end{bmatrix} = [\mathbf{H}^m \quad \mathbf{D}^m] \begin{bmatrix} x^m \\ u^m \end{bmatrix} \quad (5)$$

The ideal control signal u^{com} generating perfect output tracking and the ideal state trajectories x^{com} are assumed to be a linear combination of the model states and model input (Ozcelik and Kaufman, 1999):

$$\begin{bmatrix} x^{com} \\ u^{com} \end{bmatrix} = \begin{bmatrix} \mathbf{S}_{11} & \mathbf{S}_{12} \\ \mathbf{S}_{21} & \mathbf{S}_{22} \end{bmatrix} \begin{bmatrix} x^m \\ u^m \end{bmatrix} \quad (6)$$

where $\mathbf{S}_{i,j}$ are proper matrices

Matrices $\mathbf{S}_{i,j}$ satisfy an algebraic matrix equation by determining expression for $\begin{bmatrix} \dot{x}^{com} \\ y^{com} \end{bmatrix}$ (Broussard and O'Brien, 1980). Differencing x^{com} in Equation 6, and using $\dot{x}^m$ in Equation 2, y^{com} in Equation 5, we have:

$$\begin{bmatrix} \dot{x}^{com} \\ y^{com} \end{bmatrix} = \begin{bmatrix} \mathbf{S}_{11}\mathbf{F}^m & \mathbf{S}_{11}\mathbf{G}^m \\ \mathbf{H}^m & \mathbf{D}^m \end{bmatrix} \begin{bmatrix} x^m \\ u^m \end{bmatrix} + \begin{bmatrix} \mathbf{S}_{12}\dot{u}^m \\ 0 \end{bmatrix} \quad (7)$$

Using $\dot{x}^{com}$ in Equation 3 and y^{com} in Equation 5, and x^{com} and u^{com} in Equation 6 we have:

$$\begin{bmatrix} \dot{x}^{com} \\ y^{com} \end{bmatrix} = \begin{bmatrix} \mathbf{F} & \mathbf{G} \\ \mathbf{H} & \mathbf{D} \end{bmatrix} \begin{bmatrix} \mathbf{S}_{11} & \mathbf{S}_{12} \\ \mathbf{S}_{21} & \mathbf{S}_{22} \end{bmatrix} \begin{bmatrix} x^m \\ u^m \end{bmatrix} + \begin{bmatrix} q^x \\ 0 \end{bmatrix} \quad (8)$$

Therefore, we have:

$$\begin{bmatrix} \mathbf{F} & \mathbf{G} \\ \mathbf{H} & \mathbf{D} \end{bmatrix} \begin{bmatrix} \mathbf{S}_{11} & \mathbf{S}_{12} \\ \mathbf{S}_{21} & \mathbf{S}_{22} \end{bmatrix} \begin{bmatrix} x^m \\ u^m \end{bmatrix} + \begin{bmatrix} q^x \\ 0 \end{bmatrix} = \begin{bmatrix} \mathbf{S}_{11}\mathbf{F}^m & \mathbf{S}_{11}\mathbf{G}^m \\ \mathbf{H}^m & \mathbf{D}^m \end{bmatrix} \begin{bmatrix} x^m \\ u^m \end{bmatrix} + \begin{bmatrix} \mathbf{S}_{12}\dot{u}^m \\ 0 \end{bmatrix} \quad (9)$$

One of possible solution for Equation 9 is to let (Broussard and O'Brien, 1980):

$$\begin{bmatrix} \mathbf{F} & \mathbf{G} \\ \mathbf{H} & \mathbf{D} \end{bmatrix} \begin{bmatrix} \mathbf{S}_{11} & \mathbf{S}_{12} \\ \mathbf{S}_{21} & \mathbf{S}_{22} \end{bmatrix} = \begin{bmatrix} \mathbf{S}_{11}\mathbf{F}^m & \mathbf{S}_{11}\mathbf{G}^m \\ \mathbf{H}^m & \mathbf{D}^m \end{bmatrix} \quad (10)$$

Suppose the two matrices $\begin{bmatrix} \mathbf{S}_{11}\mathbf{F}^m & \mathbf{S}_{11}\mathbf{G}^m \\ \mathbf{H}^m & \mathbf{D}^m \end{bmatrix}$ and $\begin{bmatrix} \mathbf{F} & \mathbf{G} \\ \mathbf{H} & \mathbf{D} \end{bmatrix}$

are square and non-singular, i.e. $\begin{bmatrix} \mathbf{S}_{11}\mathbf{F}^m & \mathbf{S}_{11}\mathbf{G}^m \\ \mathbf{H}^m & \mathbf{D}^m \end{bmatrix} \neq 0$

and $\begin{bmatrix} \mathbf{F} & \mathbf{G} \\ \mathbf{H} & \mathbf{D} \end{bmatrix} \neq 0$

Let

$$\begin{bmatrix} \tau_{11} & \tau_{12} \\ \tau_{21} & \tau_{22} \end{bmatrix} = \begin{bmatrix} \mathbf{F} & \mathbf{G} \\ \mathbf{H} & \mathbf{D} \end{bmatrix}^{-1} \quad (11)$$

Therefore

$$\begin{bmatrix} \tau_{11} & \tau_{12} \\ \tau_{21} & \tau_{22} \end{bmatrix} = \begin{bmatrix} \mathbf{S}_{11} & \mathbf{S}_{12} \\ \mathbf{S}_{21} & \mathbf{S}_{22} \end{bmatrix} \begin{bmatrix} \mathbf{S}_{11}\mathbf{F}^m & \mathbf{S}_{11}\mathbf{G}^m \\ \mathbf{H}^m & \mathbf{D}^m \end{bmatrix}^{-1} \quad (12)$$

Equation 12 is re-written as:

$$\begin{bmatrix} \tau_{11} & \tau_{12} \\ \tau_{21} & \tau_{22} \end{bmatrix} \begin{bmatrix} \mathbf{S}_{11}\mathbf{F}^m & \mathbf{S}_{11}\mathbf{G}^m \\ \mathbf{H}^m & \mathbf{D}^m \end{bmatrix} = \begin{bmatrix} \mathbf{S}_{11} & \mathbf{S}_{12} \\ \mathbf{S}_{21} & \mathbf{S}_{22} \end{bmatrix} \quad (13)$$

Therefore, matrices $\mathbf{S}_{ij}$ can be obtained in terms of the following equations:

$$\mathbf{S}_{11} = \tau_{11}\mathbf{S}_{11}\mathbf{F}^m + \tau_{12}\mathbf{H}^m \quad (14)$$

$$\mathbf{S}_{12} = \tau_{11}\mathbf{S}_{11}\mathbf{G}^m + \tau_{12}\mathbf{D}^m$$

$$\mathbf{S}_{21} = \tau_{21}\mathbf{S}_{11}\mathbf{F}^m + \tau_{22}\mathbf{H}^m \quad (15)$$

$$\mathbf{S}_{22} = \tau_{21}\mathbf{S}_{11}\mathbf{G}^m + \tau_{22}\mathbf{D}^m$$

It is clear that once $\mathbf{S}_{11}$ is determined all the other $\mathbf{S}_{ij}$ can be obtained. Actually, the solution for $\mathbf{S}_{11}$ in Equation 14 is a well-known matrix problem (Bartels and Stewart, 1972). Equation 14 can be rewritten as:

$$-\tau_{11}\mathbf{S}_{11} + \mathbf{S}_{11}\mathbf{F}^{m-1} = \tau_{12}\mathbf{H}^m\mathbf{F}^{m-1} \quad (16)$$

where the solution of $\mathbf{S}_{11}$ is subject to the matrix $\mathbf{F}^{m-1}$, which exists when $\mathbf{F}^m$ is square nonsingular and $|\mathbf{F}^m| \neq 0$.

Set $\tilde{\mathbf{A}} = -\tau_{11}$, $\tilde{\mathbf{B}} = \mathbf{F}^{m-1}$, $\tilde{\mathbf{C}} = \tau_{12}\mathbf{H}^m\mathbf{F}^{m-1}$, and $\mathbf{X} = \mathbf{S}_{11}$

Therefore Equation 16 can be re-written as:

$$\tilde{\mathbf{A}}\mathbf{X} + \mathbf{X}\tilde{\mathbf{B}} = \tilde{\mathbf{C}} \quad (17)$$

Equation 17 has a unique solution if and only if the eigenvalues $a_1, a_2, \dots, a_m$ of $\tilde{\mathbf{A}}$ and $b_1, b_2, \dots, b_n$ of $\tilde{\mathbf{B}}$ satisfy (Bartels and Stewart, 1972).

$$a_i + b_j \neq 0, (i=1,2,\dots,m; j=1,2,\dots,n) \quad (18)$$

Considering the implementation issue of the compensator the compensator linked with the existing control system in series shown in Fig. 1(a) is re-formatted to the one linked in parallel as shown in Fig. 1(b). The compensator control output $\tilde{u}^{com}$ is given as Equation 19 in terms of the second part of Equation 6:

$$\tilde{u}^{com} = \mathbf{S}_{21}x^m + \mathbf{S}_{22}u^m - e \quad (19)$$

where e is defined in Equation 1 as the difference between the setpoint and process output.

III. CASE STUDY

In order to demonstrate the designed compensator, a process control unit (PCU) in our Networks and Control Laboratory is chosen as a test-bed. The details of implementation are discussed in this section.

3.1 Experimental set-up

Fig. 2. PCU Rig

PCU shown in Fig. 2 consists of a process rig, a computer control module, power supply and an external interface card, together with comprehensive interactive control software. The process rig comprises a process tank and a sump tank as well as connecting pipes, a heater, and an alternative flow path through a cooler. Flow rate through the pipes, fluid temperature in the process tank and pipes, and liquid level in the process tank are all measured. The liquid level is controlled by a PID controller. The I/O interface manages the data acquisition and signal conversion from analogue to digital and from digital to analogue. The PID controller measures the liquid level of the process tank and regulates the flow rate of the pump to maintain the liquid level of the process tank at a desired value. In the normal operation, the outlet flow rate of the water tank is constant. In order to set up a faulty environment in the experiment, the outlet flow rate is

suddenly increased manually at the instant 300. As a result, the original balance between the inlet flow rate controlled by the PID controller and the outlet flow rate is broken. The PID controller fails to keep the water level at the desired value with the pre-tuned PID parameters. The water level is significantly below the desired value (50% in this case) as shown in Fig. 3.

Fig. 3. Water level

3.2 Compensator design

The faulty open loop model is identified and a reference model is pre-defined. The coefficient matrices in Equations 2 and 3 are shown as follows.

Reference model

$$F^m = \begin{bmatrix} 0.5134 & 0 \\ 0 & 0.6065 \end{bmatrix}, G^m = \begin{bmatrix} 0.3299 \\ 0.1740 \end{bmatrix},$$

$$H^m = \begin{bmatrix} 0.6667 & 1.2 \end{bmatrix}, D^m = 0$$

Faulty open-loop model

$$F = \begin{bmatrix} 1 & 0.0278 \\ 4 & 0 \end{bmatrix}, G = \begin{bmatrix} 0.0375 \\ 0 \end{bmatrix},$$

$$H = \begin{bmatrix} 0 & -0.23 \end{bmatrix}, D = 1.111$$

According to Equation 11 and the reference model shown above, $\tau_{11}, \tau_{12}, \tau_{21}, \tau_{22}$ are obtained as:

$$\tau_{11} = \begin{bmatrix} 0 & 0.2500 \\ 50.0835 & -12.5209 \end{bmatrix}, \tau_{12} = \begin{bmatrix} 0 \\ 1.6678 \end{bmatrix},$$

$$\tau_{21} = \begin{bmatrix} -10.5732 & 2.6433 \end{bmatrix}, \tau_{22} = -1.2521$$

Therefore, $S_{11}, S_{12}, S_{21}, S_{22}$ in Equations 14 and 15 are calculated as follows:

$$S_{11} = \begin{bmatrix} 0.0346 & 0.0793 \\ 0.2694 & 0.5227 \end{bmatrix}, S_{12} = \begin{bmatrix} 0.0450 \\ -0.9895 \end{bmatrix}$$

$$S_{21} = \begin{bmatrix} -0.6569 & -1.2354 \end{bmatrix}, S_{22} = 0.2089$$

The output of the compensator is given as

$$\tilde{u}^{com} = \begin{bmatrix} -0.6569 & -1.2354 \end{bmatrix} x^m + 0.2089 u^m - e \quad (20)$$

where x^m and u^m are the state and the input of the reference model; e is the deviation of the measured feedback from the desired set-point.

3.3 Experimental results

The control performance is measured by a performance index which is defined as:

$$\eta = \frac{J_{LQG}}{J_{act}} \quad (21)$$

where J_{LQG} is the cost function of the desired controller. The LQG benchmark controller is used here to referee the desired performance. J_{act} is the cost function of the actual PID controller.

Fig. 4. Performance index

Fig. 4 illustrates the change of the control performance before and after the fault is introduced into the system. In the normal operation, the performance is healthy and the index is around 0.86. When the fault is introduced at the instant 300, the performance is deteriorated and the index is down to 0.65. Implementing the compensator shown in Equation 20 into the existing control system as shown in Fig. 1, and activating the compensator at the instant 600, the control performance is clearly recovered and the water level returns back to the desired value (50% in the case) at about the instant 700 as shown in Fig. 3. The performance index returns to an acceptable value 0.82 at about the instant 800.

IV. CONCLUSIONS

Traditional methods addressing the control performance maintenance often focus on sensor/actuator failures. In this paper, we develop a maintenance approach for controller failure. The distinguishing feature of the approach is that it extends the range of traditional FTCs into the maintenance of controller failures. The proposed approach is based on the model following technique, where the compensator is

designed to make the new post fault control loop to exactly follow the desired reference model. Experimental results demonstrate the validity and effectiveness of the proposed approach.

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