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Research issue:

Our objective is to develop algorithms for faults detection and isolation coming from actuators and sensors. For this purpose a model based method will be developed by using the continuous model of the non linear process.

Objectives:

The industrial systems have become more and more complex with the automation of the control feedback (Fig.1). A strong need has appeared for the reliability of these systems. This particular interest was firstly focused on the great systems like those of aerospace, the nuclear power plants and petrochemical plants. The reasons for which we were interested in the reliability of these systems are (human and environmental) safety and the need for increasing the productivity. So this necessity leads us to develop new specific monitoring methods for the fault detection and isolation (FDI) of this kind of process.

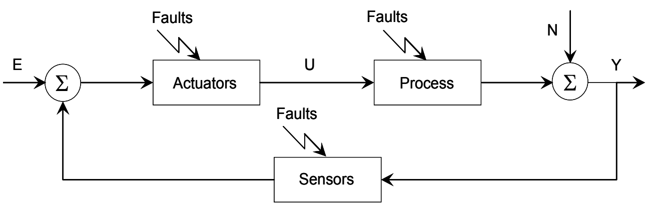

Figure.1 Closed loop system

Our objective is to study the faults coming from actuators and sensors. The proposed methodology will treat not only simple faults but also multiple and simultaneous faults.

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Background and positioning:

The methods based on observers are rather well developed especially for the linear systems. Various types of observers were created according to the nature of the problems of interest. More recent work treats theoretical development for fault detection and isolation methods of non linear systems [1]. For example, one finds the sliding mode observers [2, 3] and the adaptive observers [4, 5] which are the most known methods in the literature for non linear systems. In these methods, a residual is built by using the difference between the nonlinear system's output and the observer's output. In this report we treat with constant actuator faults and the fault isolation for single and multiple faults.

Firstly we will present the class of nonlinear system that we will study. Then we propose a fault isolation scheme where all the system's states are available and we give the sufficient conditions for the fault isolation. After that we will present briefly a mathematical model of an activated sludge process. Finally we give some simulation results that illustrate the effectiveness of the method for single and simultaneous actuator faults.

Research progress:

A bibliographical study has been done on various methods of fault detection and isolation. It enabled us to focus our research towards the model based approaches. Among these approaches, one can mention: the parity space method which was studied for linear systems [6, 7] but also for non linear systems [8, 9]. Other observers were developed in the linear and non linear case [5], like the extended Luenberger observers [10, 11], the unknown input observers (UIO) [8, 9], the sliding mode observers [2, 3] and the adaptive observers [12, 13].

For our research, we will consider the following class of nonlinear systems:

$$\begin{aligned} \dot{x} &= f(x) + g(x)u \\ y &= h(x) \end{aligned} \quad (1)$$

where $f(x)$ is a non linear vector function from R^n to R^n, $g(x) \in R^{n \times m}$ is a matrix function whose elements are non linear functions and $u \in R^m$ is the input vector (the output of actuators). The vector $h(x) \in R^p$ is a non linear or linear function of the output (the output of the sensors).

Firstly, we assume that only constant actuator faults can occur, that is $u_j^f \equiv \theta_j$ for $t \geq t_f$, $j \in 1, 2, \cdots m$, and $\lim_{t \to \infty} |u_j(t) - \theta_j| \neq 0$, where θ_j is a constant and u_j^f is the actual output of the j^{th} actuator when it is faulty, while $u_j(t)$ is the expected output when it is healthy. The corresponding faulty model is:

$$\dot{x} = f(x) + \sum_{j \neq l} g_j(x) u_j + g_l(x)\theta_l \quad (2)$$

where we have a fault in the l^{th} actuator and $g(x) = (g_1(x) \cdots g_m(x))$. A bank of m observers for fault isolation will be given in the following equations [14]:

$$\begin{cases} \dot{\hat{x}}_i = H(\hat{x}_i - x) + f(x) + \sum_{j \neq l} g_j(x) u_j + g_i(x)\hat{\theta}_i \\ \dot{\hat{\theta}}_i = -2\gamma(\hat{x}_i - x) P g_i(x), \ 1 \leq i \leq m \end{cases} \quad (3)$$

Where H is a Hurwitz matrix that it can be chosen freely, γ is a design constant and P is a positive definite matrix. We can calculate the matrix P with the help of the following equation:

$$H^T P + PH = -Q \tag{4}$$

Where Q is a positive definite matrix that it can be chosen freely [14].

Now, we assume that only constant sensor faults can occur. In order to apply the previous methodology for this type of faults it is necessary to apply the following filter:

$$\dot{\xi} = A_f \xi + B_f y \tag{5}$$

Where $A_f \in \Re^{p \times p}$ is a Hurwitz matrix and $B_f \in \Re^{p \times p}$ is an invertible matrix both of them has been chosen freely. We define the augmented state space $z^T = [x \quad \xi]$ and combine it with the equation (1) give us the following form:

$$\dot{z} = \tilde{f}(z) + \tilde{g}(z) w \tag{6}$$

Where $\tilde{f}(z) \in \Re^{n+p}$ is a vector with non linear and linear elements ($\tilde{f}^T(z) = [f(x) \quad A_f \xi]$). Also $\tilde{g} \in \Re^{(n+p)\times(m+p)}$ is a matrix of the following form ($\tilde{g}^T(z) = \begin{bmatrix} g(x) & 0_{n\times p} \\ 0_{p \times m} & B_f \end{bmatrix}$) and finally the vector $w \in \Re^{m+p}$ who is the new input vector, defined as $w^T = [u \quad y]$. Now this new system (6) can be reformulated to the faulty model (2) and the proposed bank of observers (3) can be applied for the sensor faults.

We apply the proposed methodology to the mathematical model of an activated sludge process. The equations, resulting from mass balance considerations, are computed for each of the reactant of the process applying the following principle:

Variation = ±Conversion + Feeding − Drawing off

The mass balance around the aerator in a fixed time interval gives the following equations [15]:

$$\frac{dS_I}{dt} = \frac{Q_{in}}{V_r}(S_{I,in} - S_I) \tag{7}$$

$$\frac{dS_S}{dt} = \frac{Q_{in}}{V_r}(S_{S,in} - S_S) - 1/Y_H \, \rho_1 + \rho_3 \tag{8}$$

$$\frac{dX_I}{dt} = \frac{Q_{in}}{V_r}(X_{I,in} - X_I) + \frac{Q_r}{V_r}(X_{I,rec} - X_I) + f_{X_I}\rho_2 \tag{9}$$

$$\frac{dX_S}{dt} = \frac{Q_{in}}{V_r}(X_{S,in} - X_S) + \frac{Q_r}{V_r}(X_{S,rec} - X_S) + (1 - f_{X_I})\rho_2 - \rho_3 \tag{10}$$

$$\frac{dX_H}{dt} = \frac{Q_{in}}{V_r}(X_{H,in} - X_H) + \frac{Q_r}{V_r}(X_{H,rec} - X_H) + \rho_1 - \rho_2 \tag{11}$$

$$\frac{dS_O}{dt} = \frac{Q_{in}}{V_r}(S_{O,in} - S_O) + Q_L(C_S - S_O) + -\frac{1 - Y_H}{Y_H}\rho_1 \tag{12}$$

$$\frac{dX_{H,rec}}{dt} = \frac{Q_{in} + Q_r}{V_{dec}} X_H - \frac{Q_r + Q_w}{V_{dec}} X_{H,rec} \tag{13}$$

$$\frac{dX_{I,rec}}{dt} = \frac{Q_{in} + Q_r}{V_{dec}} X_I - \frac{Q_r + Q_w}{V_{dec}} X_{I,rec} \tag{14}$$

$$\frac{dX_{S,rec}}{dt} = \frac{Q_{in} + Q_r}{V_{dec}} X_S - \frac{Q_r + Q_w}{V_{dec}} X_{S,rec} \tag{15}$$

$$\rho_1 = \mu_{\max} \frac{S_S}{(K_S + S_S)} \frac{S_O}{(K_O + S_O)} \tag{16}$$

$$\rho_2 = b_H X_H \tag{17}$$

$$\rho_3 = K_h \frac{X_S X_H}{(K_X X_H + X_S)} \frac{S_O}{(K_O + S_O)} \tag{18}$$

The process is a system with four input, nine states and six outputs. The inputs are the input flow rate Q_{in}, the air flow rate Q_L, the recycled sludge flow rate Q_r and the excess sludge flow rate Q_W.

Next we will illustrate only the results obtained from the developed observer for the additive actuator faults (a bank of four observers). We will present the outputs of the process and the four residuals from the four observers that we have developed for every actuator. In the begin we will give the case where an actuator has a single fault and then the results for simultaneous faults. In order to obtain results more realistic, we added to each input a Gaussian white noise of zero average and 0.5 standard deviation.

Firstly we have introduced a constant fault at time $t_f = 50$ hours in the first actuator Q_{in}. In Figure 2, we can see the effect of the fault in the six outputs of the system. As we can see, the input Q_{in} has a major influence at almost all the system outputs. In Figure 3, we present the residuals of the four observers. Here we define the residuals as $r_i(t) = \frac{d\|\hat{x}_i - x\|_2}{dt}$ for $1 \le i \le 4$. At time $t_f = 50$ hours we can see that the residual of the three observers remain equal to zero but the residual of the first observer that corresponds to the input Q_{in} leave the zero. Therefore, we isolate the faulty actuator correctly and fast enough.

Finally we illustrate the case where more than one fault occurs at the same time on the system or briefly the simultaneous faults. We have introduced two faults on the second Q_L and the third actuator Q_r at the same time $t_f = 20$ hours.

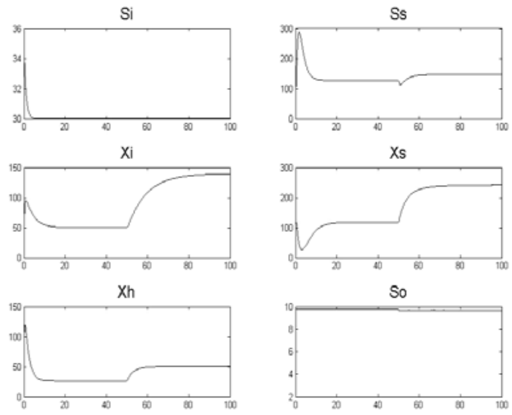

Figure.2 System's outputs with a fault on Q_{in}

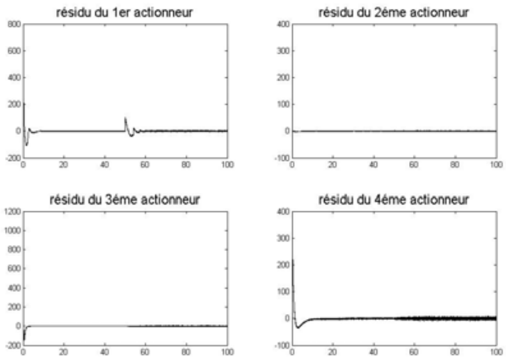

Figure.3 Residuals with a fault on Q_{in}

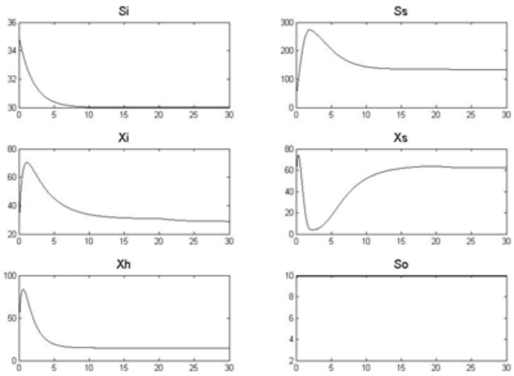

Figure.4 System's outputs with a fault on Q_L and Q_r

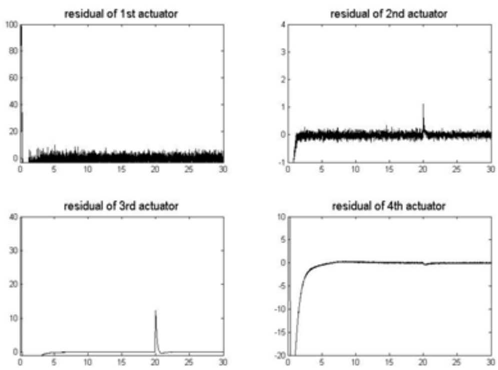

Figure.5 Residuals with a fault on Q_L and Q_r

In Figure 4 we have the system's outputs where we can see the influence of the two faults. Here we have to mention that the input Q_L does not have a major influence in the system and that we can see it also in the systems equations where appears in only one equation (12). In Figure 5 we give the residuals of the observers and we can see that their values are equal to zero until $t_f = 20$ hours where we have the two faults. At that time the residual of the second and third observer leaves zero and the other two residuals rest at zero. Therefore we isolate the two faulty actuators.

Publications:

Fragkoulis D. (2007). Détection et localisation de défauts au niveau des actionneurs dans un système non linéaire. 8ème Congrès des Doctorants de l'Ecole Doctorale Systèmes (EDSYS 07), Albi (France).

Fragkoulis D., Roux G. and B. Dahhou (2007). Actuator fault isolation strategy to a waste water treatment process. Conference on Systems and Control (CSC 07), Marrakech (Morocco).

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