

Fault Detection and Isolation Scheme Based on Parity Space Method for Discrete Time-Delay System

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1. Introduction

In recent years, fault detection and isolation (FDI) problem in dynamic system has been paid more and more attention. A great number of methods for FDI have been proposed (Chow & Willsky, 1984; Frank & Ding, 1997; Chen & Patton, 1999; Patton et al., 2000; Venkatasubramanian et al., 2003). All of the FDI schemes are concerned with a core stage: the generation of the residual signals. The difference between the measurement of the system and its estimation is called residual, whose values are zero or near to zero when no fault occurs while differ distinctly from zero otherwise. Appropriate decisions such as the occurrence, magnification, type, location, etc. of the faults are called fault isolation, which are achieved by residual evaluation.

In the field of analytical model-based FDI techniques, the analytical redundancy relations of the system are used to create residual signal. The approaches can be roughly classified into observer-based approaches and parameter estimation approaches. Parity space approaches have been proved to be structurally equivalent to the observer-based though the design procedures differ (Gertler, 1991). However, the parity space methodology using the temporal redundancy has its advantages, especially in the discrete system. This method was firstly generalized by the (Chow & Willsky, 1984).

Time delays are inherent in many real physical processes (i.e. mechanical and chemical processes, long transmission lines in pneumatic systems, power and water distribution networks, air pollution systems etc.) Over the past two decades, analysis and synthesis of dynamic time-delay systems have attracted a great deal of interests (Dugard & Verriest, 1997; Yang & Saif, 1998). However, there are relative fewer research results on FDI of time-delay systems (KRATZ et al., 1998; Zhong et al., 2004).

This paper proposes a method to deal with the FDI problem for the linear discrete-time systems with delays. The results in (KRATZ et al., 1998) are extended. Both fault detection and fault isolation method are proposed. The occurrence of the fault can be detected timely and the position of the fault can be located exactly. A numerical example is given to illustrate the design method at the end.

2. Mathematical Preliminaries

A time delay operator ∇ is defined according to (KRATZ et al., 1998). $\nabla f(k) = f(k-1)$ for any discrete-time function f . It is easy to understand that $\nabla \nabla f(k) = \nabla^2 f(k) = f(k-2)$, $\nabla^w f(k) = f(k-w)$.

Consider a linear discrete time-delay system described by

$$\begin{cases} \mathbf{x}(k+1) = \sum_{i=0}^{\nu} \mathbf{A}_i \mathbf{x}(k-i) + \mathbf{B}[\mathbf{u}(k) + \mathbf{f}_a(k)] + \mathbf{E}_d \mathbf{d}(k) \\ \mathbf{y}(k) = \mathbf{C}\mathbf{x}(k) + \mathbf{F}_d \mathbf{d}(k) \end{cases} \quad (1)$$

where $\mathbf{x}(k) \in R^n$ is the state vector, $\mathbf{u}(k) \in R^p$ is the control vector, $\mathbf{y}(k) \in R^m$ is the output vector, $\mathbf{f}_a(k) = [f_{a1}(k), \dots, f_{ap}(k)]^T$ stands for the actuator faults. $f_{ai}(k)$, $i=1, \dots, p$ is corresponding to the i th actuator fault. $\mathbf{d}(k) \in R^l$ is disturbance vector, $\|\mathbf{d}(k)\| < \bar{d}$. \mathbf{A}_i ($i=0, \dots, \nu$), \mathbf{B} , \mathbf{C} , \mathbf{E}_d and \mathbf{F}_d are constant matrices with appropriate dimensions. Integers $\nu \geq 0$ denotes the number of time delays in the state.

Using the operator ∇ , the system (1) can be rewritten as

$$\begin{cases} \mathbf{x}(k+1) = \mathbf{A}(\nabla)\mathbf{x}(k) + \mathbf{B}[\mathbf{u}(k) + \mathbf{f}_a(k)] + \mathbf{E}_d \mathbf{d}(k) \\ \mathbf{y}(k) = \mathbf{C}\mathbf{x}(k) + \mathbf{F}_d \mathbf{d}(k) \end{cases} \quad (2)$$

where,

$$\mathbf{A}(\nabla) = \mathbf{A}_0 + \mathbf{A}_1 \nabla + \dots + \mathbf{A}_\nu \nabla^\nu \quad (3)$$

3. Parity Space Residual Generation for Fault Detection and Isolation

The task of FDI is to design a residual signal which is zero or near to zero in a fault free case and non-zero when a fault occurs in the monitored system. Time delay implies that the state of the system for the next time step is not only determined by the current state but also concerned with the state of the former intervals. The recursion of equation (2) from time instant $k-L$ to time instant k yields

$$\mathbf{y}_L = \mathbf{H}_{o,L} \mathbf{x}(k-L) + \mathbf{H}_{u,L} \mathbf{u}_L + \mathbf{H}_{d,L} \mathbf{d}_L + \mathbf{H}_{fa,L} \mathbf{f}_{aL} \quad (4)$$

where

$$\mathbf{y}_L(k) = \begin{bmatrix} \mathbf{y}(k-L) \\ \mathbf{y}(k-L+1) \\ \vdots \\ \mathbf{y}(k) \end{bmatrix} = \underbrace{\begin{bmatrix} \underbrace{\begin{bmatrix} \Delta^L & & \\ & \ddots & \\ & & \Delta^L \end{bmatrix}}_m & & \\ & \underbrace{\begin{bmatrix} \Delta^{L-1} & & \\ & \ddots & \\ & & \Delta^{L-1} \end{bmatrix}}_m & & \\ & & \ddots & & \\ & & & \underbrace{\begin{bmatrix} 1 & & \\ & \ddots & \\ & & 1 \end{bmatrix}}_m \end{bmatrix}}_{\triangleq \Delta_{Lm}} \begin{bmatrix} \mathbf{y}(k) \\ \mathbf{y}(k) \\ \vdots \\ \mathbf{y}(k) \end{bmatrix} \in R^{(L+1)m},$$

$$\mathbf{u}_L(k) = \begin{bmatrix} \mathbf{u}(k-L) \\ \mathbf{u}(k-L+1) \\ \vdots \\ \mathbf{u}(k) \end{bmatrix} = \Delta_{Lp} \begin{bmatrix} \mathbf{u}(k) \\ \mathbf{u}(k) \\ \vdots \\ \mathbf{u}(k) \end{bmatrix} \in R^{(L+1)p}, \mathbf{f}_{aL}(k) = \begin{bmatrix} \mathbf{f}_a(k-L) \\ \mathbf{f}_a(k-L+1) \\ \vdots \\ \mathbf{f}_a(k) \end{bmatrix} = \Delta_{Lp} \begin{bmatrix} \mathbf{f}_a(k) \\ \mathbf{f}_a(k) \\ \vdots \\ \mathbf{f}_a(k) \end{bmatrix} \in R^{(L+1)p},$$

$$\mathbf{d}_L(k) = \begin{bmatrix} \mathbf{d}(k-L) \\ \mathbf{d}(k-L+1) \\ \vdots \\ \mathbf{d}(k) \end{bmatrix} = \Delta_{Ll} \begin{bmatrix} \mathbf{d}(k) \\ \mathbf{d}(k) \\ \vdots \\ \mathbf{d}(k) \end{bmatrix} \in R^{(L+1)l}, \mathbf{H}_{o,L} = \begin{bmatrix} \mathbf{C} \\ \mathbf{CA}(\nabla) \\ \vdots \\ \mathbf{CA}^L(\nabla) \end{bmatrix} \in R^{(L+1)m \times n},$$

$$\mathbf{H}_{d,L} = \begin{bmatrix} \mathbf{F}_d & & & \\ \mathbf{CE}_d & \mathbf{F}_d & & 0 \\ \mathbf{CA}(\nabla)\mathbf{E}_d & \mathbf{CE}_d & \mathbf{F}_d & \\ \vdots & \vdots & \vdots & \ddots \\ \mathbf{CA}^{L-1}(\nabla)\mathbf{B} & \mathbf{CA}^{L-2}(\nabla)\mathbf{B} & \vdots & \dots & \mathbf{CE}_d & \mathbf{F}_d \end{bmatrix} \in R^{(L+1)m \times (L+1)l}, \mathbf{H}_{fa,L} = \mathbf{H}_{u,L}$$

Define the following parity space:

$$\mathbf{P}_L = \{ \mathbf{v}_L \mid \mathbf{v}_L \mathbf{H}_{o,L} = 0 \} \tag{5}$$

where $\mathbf{v}_L \in R^{1 \times (L+1)m}$ is row vector. Vectors belong to parity space are called parity vectors. Residual signals can be created by the following equation:

$$\mathbf{r}_L(k) = \mathbf{v}_L [\mathbf{y}_L(k) - \mathbf{H}_{u,L} \mathbf{u}_L(k)] \in \mathbf{R} \tag{6}$$

Substituting equation (6) to equation (4) yields:

$$\mathbf{r}_L(k) = \mathbf{v}_L \mathbf{H}_{d,L} \mathbf{d}_L(k) + \mathbf{v}_L \mathbf{H}_{fa,L} \mathbf{f}_{aL}(k) \tag{7}$$

It should be noted that the parity vectors v_L satisfying equation (5) are not unique, and the corresponding residual signals $r_L(k)$ are not unique. The freedom of the v_L can be used to creat specific residual signals, so as to fulfill specific design purpose.

The parity vectors v_L can be described as $v_L = [v_1, v_2, \dots, v_{(L+1)m}]$. Substituting it to equation (7), the terms corresponding to disturbance $v_L H_{d,L} d_L(k)$ and faults $v_L H_{fa,L} f_{al}(k)$ can be respectively expanded as follows:

$$v_L H_{d,L} d_L(k) = \psi_1 d_1(k) + \psi_2 d_2(k) + \dots + \psi_p d_p(k) \tag{8}$$

$$v_L H_{fa,L} f_{al}(k) = \omega_1 f_{a1}(k) + \omega_2 f_{a2}(k) + \dots + \omega_p f_{ap}(k) \tag{9}$$

Where $\psi_1, \psi_2, \dots, \psi_p, \omega_1, \omega_2, \dots, \omega_p$ are polynomials corresponding to $v_1, v_2, \dots, v_{(L+1)m}$ and ∇ .

The successful detection of a fault is followed by the fault isolation procedure which will distinguish (isolate) a particular fault from others. While a single residual signal is sufficient to detect faults, a set of residuals (or a vector of residual) is usually required for fault isolation. According to (Chen & Patton, 1999), a commonly used scheme in designing the residual set is to make each residual sensitive to all but one fault, i.e.

$$\begin{cases} r_1 = R(f_{a2}, \dots, f_{ap}) \\ \vdots \\ r_i = R(f_{a1}, \dots, f_{ai-1}, f_{ai+1}, \dots, f_{ap}) \\ \vdots \\ r_p = R(f_{a1}, \dots, f_{ap-1}) \end{cases} \tag{10}$$

where $R(\cdot)$ denotes some functional relation, which works as the residual generator. This is defined as a generalized structured residual set. The isolation can be performed by the following logic:

$$\left. \begin{cases} \|r_i\| \leq th^i \\ \|r_j\| > th^j \text{ for } j = 1, \dots, i-1, i+1, \dots, p \end{cases} \right\} \Rightarrow f_{ai} \neq 0 \tag{11}$$

where th^i means the fault isolation threshold to the corresponding fault.

To achieve the so called generalized structured residual set, let $\omega_1, \omega_2, \dots, \omega_p$ satisfy the folowing equatinos:

$$\begin{cases} \omega_1 \neq 0 \\ \vdots \\ \omega_{i-1} \neq 0, i = 1, 2, \dots, p \\ \omega_i = 0 \\ \omega_{i+1} \neq 0 \end{cases} \tag{12}$$

Solving the equations (12) respectively can achieve a set of parity vecters v_{Lfa_i} $i = 1, 2, \dots, p$, witch lead to a set of residual signals $r_{Lfa_i}(k)$, $i = 1, 2, \dots, p$ by equation (6). When the i th actuator fault occurs ($f_{ai}(k) \neq 0$), the corresponding residual signal $r_{Lfa_i}(k)$ is not affected, while the other residual signals $r_{Lfa_1}(k), r_{Lfa_2}(k), \dots, r_{Lfa_{i-1}}(k), r_{Lfa_{i+1}}(k), r_{Lfa_p}(k)$ are affected. The isolation can be fulfilled by equaton (11).

4. Numerical Example

To illustrate the design process of the proposed method and verify its effectiveness, the following numerical example is demonstrated. Consider a time delay system of the form (1),

$$\begin{cases} \begin{bmatrix} x_1(k+1) \\ x_2(k+1) \\ x_3(k+1) \end{bmatrix} = \begin{bmatrix} 0.15 & 0.324 & 0 \\ 0.102 & 0.258 & 0 \\ 0 & 0 & 0.412 \end{bmatrix} \begin{bmatrix} x_1(k) \\ x_2(k) \\ x_3(k) \end{bmatrix} + \begin{bmatrix} 0 & 0.265 & 0 \\ -0.406 & 0 & 0.308 \\ 0 & -0.252 & 0.124 \end{bmatrix} \begin{bmatrix} x_1(k-1) \\ x_2(k-1) \\ x_3(k-1) \end{bmatrix} \\ \quad + \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \left(\begin{bmatrix} u_1(k) \\ u_2(k) \\ u_3(k) \end{bmatrix} + \begin{bmatrix} f_{a1}(k) \\ f_{a2}(k) \\ f_{a3}(k) \end{bmatrix} \right) + \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} d(k) \\ \begin{bmatrix} y_1(k) \\ y_2(k) \\ y_3(k) \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_1(k) \\ x_2(k) \\ x_3(k) \end{bmatrix} + \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} d(k) \end{cases}$$

Where $d(k) = 0.01 \times randN(0,1)$, $randN(0,1)$ stands for zero mean, unit Gauss noise. Using the operator ∇ , the system (1) can be rewritten into the form (2), the system matrix is:

$$A(\nabla) = \begin{bmatrix} 0.15 & 0.324 + 0.265\Delta & 0 \\ 0.102 - 0.406\Delta & 0.258 & 0.308\Delta \\ 0 & -0.252\Delta & 0.412 + 0.124\Delta \end{bmatrix}$$

In order to fulfill the FDI, a parity space with $L = 2$ is established, the matrix $H_{o,L}$, $H_{u,L}$, etc. can be computed using the software MAPLE. Solving the equation (5) can get the parity vector:

$$v_L = \begin{bmatrix} t_1 \\ \begin{pmatrix} 1.767\nabla t_1 + 2.160t_1 - 0.03768t_2 - 0.7173\nabla^2 t_2 - 0.6968\nabla t_2 + 0.2520\nabla t_3 \\ -0.01221t_4 - 0.2357\nabla t_4 - 0.1901\nabla^3 t_4 - 0.4170\nabla^2 t_4 - 0.1074\nabla^2 t_5 - 0.009721t_5 \\ -0.1798\nabla t_5 + 0.1133\nabla t_6 + 0.2068\nabla^2 t_6 + 0.1807512\nabla^3 t_6 \end{pmatrix} \\ \begin{pmatrix} -0.308\nabla t_2 - 0.412t_3 - 0.124\nabla t_3 - 0.09979\nabla t_4 - 0.08162\nabla^2 t_4 - 0.2064\nabla t_5 - \\ 0.03819\nabla^2 t_5 + 0.06224\nabla^2 t_6 - 0.1023\nabla t_6 - 0.1697t_6 \end{pmatrix} \\ \begin{pmatrix} -6.667t_1 - 0.6800t_2 + 2.7067\nabla t_2 - 0.3703t_4 + 0.6968\nabla t_4 + 0.7173\nabla^2 t_4 + 1.104\nabla t_5 \\ -0.2774t_5 - 0.6821\nabla^2 t_6 + 0.1714\nabla t_6 \end{pmatrix} \\ t_2 \\ t_3 \\ t_4 \\ t_5 \\ t_6 \end{bmatrix} \tag{13}$$

Where $t_1, t_2, t_3, t_5, t_6 \in R$ and t_1, t_2, t_3, t_5, t_6 are not all zeros. v_L is a row 9 dimensions vector with 6 freedom.

In order to achieve fault detection and isolation, a generalized residual set consists in three residual signals should be created as show in Fig.1.

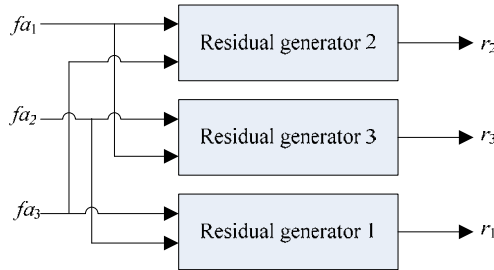


Fig. 1 Generalized residual set

In Fig.1, f_{ai} stands for the i th actuator fault. Residual signal r_1 is sensitive to f_{a2} and f_{a3} while insensitive to f_{a1} . The situation of r_2 and r_3 are the same with r_1 .

Substituting v_L to equation (7), and expanding the terms corresponding to the actuator fault $v_L H_{fa,L} f_{al}(k)$ into equation (9) yields, $v_L H_{fa,L} f_{al}(k) = \omega_1 f_{a1}(k) + \omega_2 f_{a2}(k) + \omega_3 f_{a3}(k)$. Where $\omega_1, \omega_2, \omega_3$ are polynomials corresponding to t_1, t_2, t_3, t_5, t_6 and ∇ . Using equation (12), let

$$\begin{cases} \omega_1 = 0 \\ \omega_2 \neq 0 \\ \omega_3 \neq 0 \end{cases}$$

t_1, t_2, t_3, t_5, t_6 can be achieved by solving the above equation, and substituting them into (13) can get the parity vector corresponding to the first actuator fault f_{a1} :

$$v_{L,fa1} = \begin{bmatrix} 0 \\ 0.2520\Delta + 0.07762\Delta^2 \\ -0.4120 - 0.2509\Delta - 0.03819\Delta^2 \\ -0.1020 + 0.4060\Delta \\ -0.2580 \\ 1 \\ 0 \\ 1 \\ 0 \end{bmatrix}^T$$

Substituting $v_{L,fa1}$ to equation (6) can get generalized residual signal $r_{L,fa1}(k)$ corresponding to f_{a1} , denoted by r_1 .

$$r_1 = (-0.1020\Delta + 0.40600\Delta^2)y_1(k) + (1 - 0.2580\Delta + 0.2520\Delta^3 + 0.07762\Delta^4)y_2(k) + (\Delta - 0.4120\Delta^2 - 0.2509\Delta^3 - 0.03819\Delta^4)y_3(k) + (-\Delta)u_2(k) + (-\Delta^2 - 0.3080\Delta^3)u_3(k)$$

By the same process, let

$$\begin{cases} \omega_1 \neq 0 \\ \omega_2 = 0, \\ \omega_3 \neq 0 \end{cases} \begin{cases} \omega_1 \neq 0 \\ \omega_2 \neq 0 \\ \omega_3 = 0 \end{cases}$$

The residual signals correspond to f_{a2} and f_{a3} can be designed, denoted by r_2 and r_3 . Now, the design of the generalized residual set for actuator fault detection and isolation is accomplished. The result of the simulation is shown in Fig. 2 to Fig. 5.

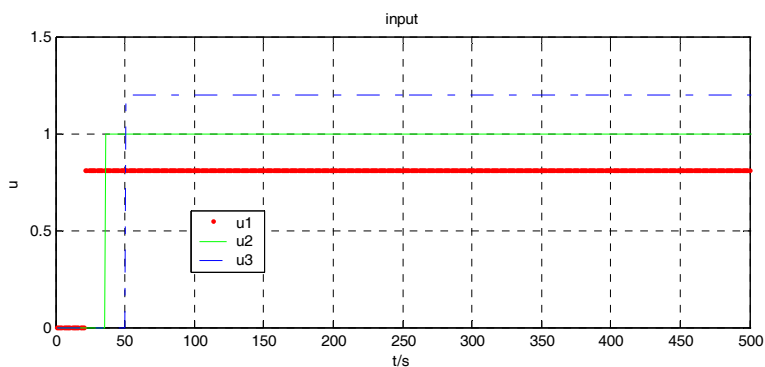


Fig. 2 System input signals

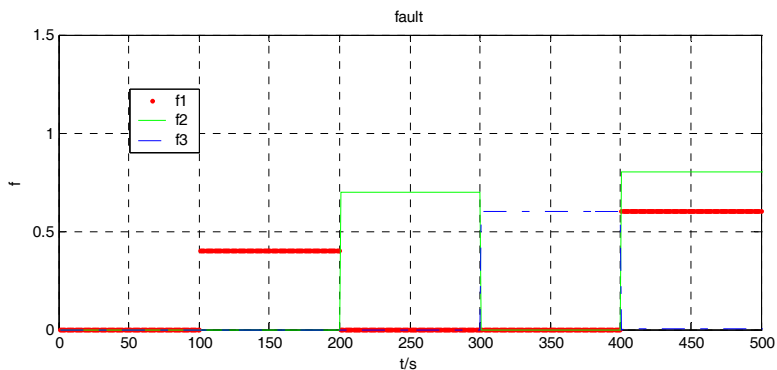


Fig. 3 Fault signals

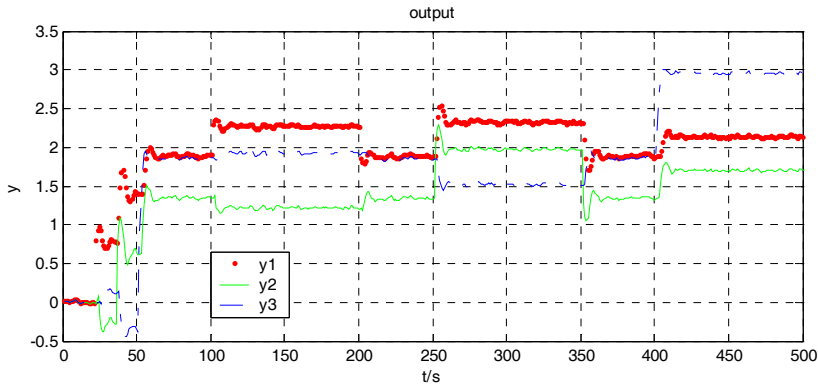


Fig. 4 System output signals

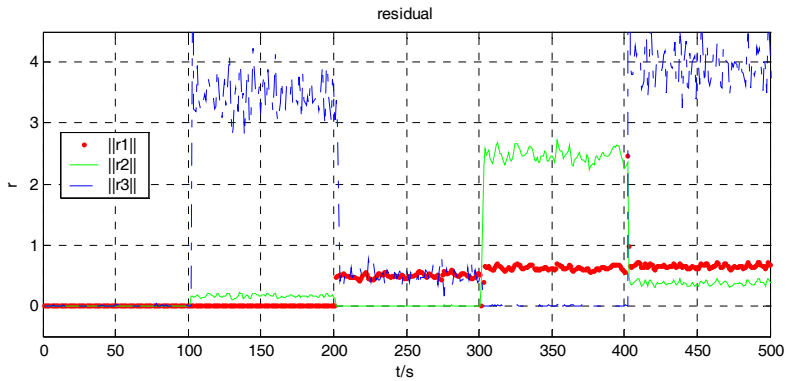


Fig. 5 Residual signals

There are 5 stages in the simulation process:

1. from time 0 second to time 100 second, the system works properly. $\|r_1\|$, $\|r_2\|$ and $\|r_3\|$ are near to zero.
2. from time 100 second to time 200 second, the actuator 1 suffers from fault, while actuator 2 and actuator 3 work properly. $\|r_2\|$ and $\|r_3\|$ differ from zero while $\|r_1\|$ keeps zero nearby.
3. from time 200 second to time 300 second, the actuator 2 suffers from fault, while actuator 1 and actuator 3 work properly. $\|r_1\|$ and $\|r_3\|$ differ from zero while $\|r_2\|$ keeps zero nearby.
4. from time 300 second to time 400 second, the actuator 3 suffers from fault, while actuator 1 and actuator 2 work properly. $\|r_1\|$ and $\|r_2\|$ differ from zero while $\|r_3\|$ keeps zero nearby.
5. from time 400 second to time 500 second, the actuator 1 and actuator 2 suffer from fault at the same time, while actuator 3 works properly. $\|r_1\|$, $\|r_2\|$ and $\|r_3\|$ differ from zero simultaneously.

It can be concluded that when there is one actuator goes into fault, the above generalize residual set based on parity space can detect the fault and isolate which actuator corrupted by the fault. However, when there are more than one actuators break into faults, the method can only detect the fault, while it have no idea that which actuators corrupted by the fault.

5. Conclusion

A fault detection and isolation scheme for discrete time-delay system has been proposed in this chapter. The scheme can not only detect the faults but also isolate (locate) the faults. To fulfill the FDI, a generalized residual set in form of parity space is designed by the recursion of the system equations. Each residual is sensitive to all but one actuator faults. The actuator with fault can be isolated from the normal ones exactly. A time delay operator is used to deal with the problem brought by the time-delay system. The effectiveness of the proposed method has been verified by a numerical example.

However, further studies are required which include the follow aspects:

1. To determine an optimal recursion step L . Such that the residuals can obtain a certain freedom to complete fault isolation, while the computation is minimized.
2. To extend the fault isolation result. The sensor faults and the actuator faults should be discerned.
3. To enhance the reliability and robust performance of the FDI system.

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