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Tytuł: Wykrywanie uszkodzeń w układach dynamicznych przy użyciu obserwatorów - część I

Artykuł recenzowany

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Observer-based fault detection in dynamical systems - part II

Abstract

The paper is the second part of a survey of observer-based fault detection and isolation (FDI) methods. Observer-based FDI schemes are presented, both for standard and singular systems. The applications of unknown input observer (UIO) as well perfect observers to FDI are shown. Basic ideas and concepts underlying much of model-based FDI, as well a general introduction to FDI have been given in the first part of this survey.

Streszczenie

Artykuł jest drugą częścią przeglądowej pracy nt. użycia obserwatorów do wykrywania uszkodzeń izolacji uszkodzeń (ang. *FDI*) w układach dynamicznych. Zaprezentowano schematy wykrywania i izolacji uszkodzeń przy użyciu obserwatorów zarówno dla układów standardowych jak i singularnych. Przedstawiono zastosowanie obserwatorów o nieznanym wejściu jak również obserwatorów doskonałych dla celów FDI. Podstawowe idee i pojęcia metod FDI opartych na modelu, jak również ogólne wprowadzenie w tematykę FDI zawiera pierwsza część pracy.

1. Observer-based FDI schemes

1.1. FDI schemes based on UIOs

The main requirement for fault detection is to generate a residual signal which is robust to the system uncertainty. On the other hand to detect a particular fault, the residual has to be sensitive to this fault. In this section we present several FDI observer-based schemes.

The results concerning FDI observer-based schemes for standard systems have been given in [1]. We present some generalizations of theses results for singular systems. We also try to apply perfect observers (they have been discussed in the first part of this survey [5]) to observer-based FDI.

According to [1], a system with possible sensor and actuator faults can be described as

$$\dot{x}(t) = Ax(t) + Bu(t) + Ed(t) + Bf_a(t), \tag{1a}$$
$$y(t) = Cx(t) + f_s(t), \tag{1b}$$

where $f_a \in R^r$ and $f_s \in R^m$ are vectors of actuator and sensor faults, respectively. Our task is to generate a disturbance decoupled residual, using the following UIO

$$\dot{z}(t) = Fz(t) + TBu(t) + Ky(t),$$
$$\hat{x}(t) = z(t) + Hy(t),$$

where $\hat{x} \in R^n$, $z \in R^n$, F, T, K and H are real matrices of appropriate dimensions. These matrices must satisfy additional conditions guaranteeing the convergence to zero of estimation error. More details can be found in [5]. If the state estimation is available, the residual can be generated as

$$r(t) = y(t) - C\hat{x}(t) = (I - CH)y(t) - Cz(t). \tag{2}$$

Applying the above residual generator to the system described (1), we obtain the following equations governing the state estimation error $e(t)$

$$\dot{e}(t) = (A_1 - K_1C)e(t) + TBf_a(t) - K_1f_s(t) - H\dot{f}_s(t), 6a \tag{3a}$$
$$r(t) = Ce(t) + f_s(t), 7b \tag{3b}$$

From the above one can see that the disturbance effects have been decoupled from the residual. To make detection of actuator faults possible, one has to guarantee, that condition $TB \neq 0$. holds true. Considering the issue more precisely, the necessary and sufficient condition for detection of a fault in the i-th actuator is following $Tb_i \neq 0$,
where b_i denotes the i-th column of the matrix B. It is rather straightforward that the sensitiveness of residual to $f_s(t)$ must be guaranteed to make detection of sensor faults possible. As one can see, the sensor fault vector $f_s(t)$ affects directly the residual $r(t)$, and therefore the above mentioned condition is usually fulfilled. The disturbance-decoupled residual can be used to detect faults according to the following threshold logic

$$\begin{cases} \|r(t)\| < Threshold & \text{for fault-free case} \\ \|r(t)\| \geq Threshold & \text{for faulty case} \end{cases} \tag{4}$$

The determination in which sensor (or actuator) a fault has occurred is the main issue of fault isolation. To accomplish this task Gertler [2] proposed to design a so called structured residual set [2, 1], where by *structured* one understands that each residual is sensitive to a certain group of the faults and insensitive to others. These properties of the sensitivity and insensitivity, respectively, are the ones allowing fault isolation. Unfortunately, this ideal situation is usually difficult, or even impossible, to attain. [4] Moreover, even if it is possible, there is usually no freedom left to guarantee disturbance decoupling. To make a disturbance decoupling maximally effective, Patton [4] proposed to make each residual sensitive to faults in all but one sensors (or actuators). This approach is called a generalized residual set.

1.1.1. Sensor fault isolation scheme

Our task is to design disturbance decoupled sensor fault isolation schemes. We assume that all actuators are fault-free and the system is governed by the following equations [1].

$$\dot{x}(t) = Ax(t) + Bu(t) + Ed(t), \tag{5a}$$
$$y_j(t) = C_jx(t) + f_s^{[j]}(t), \tag{5b}$$
$$y_{[j]}(t) = c_{[j]}x(t) + f_{s[j]}(t), \quad j = 1,2,\ldots,m, \tag{5c}$$

where $c_{[j]} \in R^{1\times n}$ denotes the j-th row of the matrix C, $C_j \in R^{(m-1)\times n}$ is obtained from the matrix C by deleting j-th row $c_{[j]}$, $y_{[j]}$ denotes the j-th entry of y and $y_j \in R^{m-1}$ is obtained from the vector y by deleting its j-th entry. $f_{s[j]}$ is the j-th entry of f_s and $f_s^{[j]} \in R^{m-1}$ is obtained from the vector f_s by deleting its j-th entry. According to this description, an UIO-based residual generators of the following form is proposed

$$\dot{z}_j(t) = F_jz_j(t) + T_jBu(t) + K_jy_j(t), \tag{6a}$$
$$r_j(t) = (I - C_jH_j)y_j(t) - C_jz_j(t), \tag{6b}$$

where $j = 1,2,\ldots,m$, and the parameter matrices must satisfy

$$\begin{cases} E &= H_jC_jE \\ T_j &= I - H_jC_j \\ F_j &= T_jA - K_{1,j}C_j \quad j = 1,2,\ldots,m, \\ K_{2,j} &= F_jH_j \\ K_j &= K_{j,1} + K_{2,j} \end{cases} \tag{7}$$

and $\sigma(F_j) \subset C^-$, $j = 1,2,\ldots,m$.

Thus each residual generator is driven by all inputs and all but one outputs. When all actuators are fault-free (which was assumed) and a fault occurs in the j-th sensor, the residual will satisfy the following isolation logic

$$\begin{cases} \|r_j(t)\| < T_{SFI}^j & \text{for fault-free case} \\ \|r_k(t)\| \geq T_{SFI}^k & \text{for faulty case} \end{cases} \quad k = 1,\ldots,j-1,j+1,\ldots,m \tag{8}$$

where T_{SFI}^j is the j-th isolation threshold. An UIO-based sensor fault isolation scheme is shown in the fig. 1.

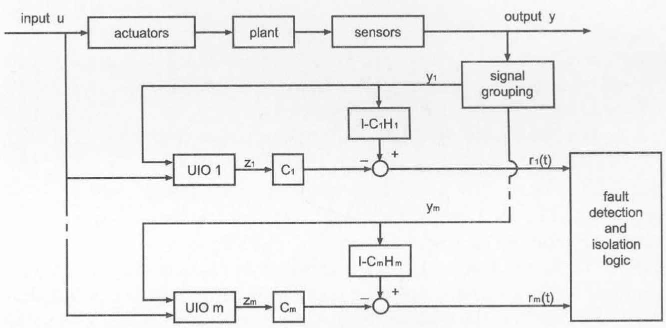

Fig. 1. A disturbance decoupled sensor fault isolation scheme

1.1.2. Actuator fault isolation scheme

Our task is to design disturbance decoupled actuator fault isolation schemes, we assume that all sensors are fault-free and the system is governed by the following equations [1]

$$\begin{aligned} \dot{x}(t) &= Ax(t) + B_iu^{[i]}(t) + B_if_a^{[i]}(t) \\ &\quad + b_i\left[u_i(t) + f_{a[i]}(t)\right] + Ed(t) \\ &= Ax(t) + B_iu^{[i]}(t) + B_if_a^{[i]}(t) + E_id_i(t), \\ y(t) &= Cx(t), \qquad i = 1,2,\ldots,r, \end{aligned}$$

where $b_i \in R^n$ denotes the i-th column of the matrix B, $B_i \in R^{n\times(r-1)}$ is obtained from the matrix B by deleting the i-th column b_i, u_i is the i-th entry of u, $u^{[i]} \in R^{r-1}$ is obtained from the vector u by deleting its i-th entry, $f_{a[i]}$ is the i-th entry of f_a, $f_a^{[i]} \in R^{r-1}$ is obtained from the vector f_a by deleting its i-th entry and

$$E_i = \begin{bmatrix} E & b_i \end{bmatrix}, \quad d_i(t) = \begin{bmatrix} d(t) \\ u_i(t) + f_{a[i]}(t) \end{bmatrix},$$

where $i = 1,2,\ldots,r$. According to this description, an UIO-based residual generators of the following form is proposed

$$\dot{z}_i(t) = F_iz_i(t) + T_iB_iu_i(t) + K_iy(t),$$
$$r_i(t) = (I - CH_i)y(t) - Cz_i(t), \quad i = 1,2,\ldots,r.$$

The parameter matrices must satisfy

$$\begin{cases} H_iCE_i &= E_i \\ T_i &= I - H_iC \\ F_i &= T_iA - K_{1,i}C \quad i = 1,2,\ldots,r \\ K_{2,i} &= F_iH_i \\ K_i &= K_{i,1} + K_{2,i} \end{cases}$$

and $\sigma(F_i) \in C^-$ for $i = 1,2,\ldots,r$.

Thus each residual generator is driven by all outputs and all but one inputs. When all sensors are fault-free and a fault occurs in the i-th actuator, the residual will satisfy the following isolation logic

$$\begin{cases} \|r_i(t)\| < T_{AFI}^i & \text{for fault-free case} \\ \|r_k(t)\| \geq T_{AFI}^k & \text{for faulty case} \end{cases} \quad k = 1,\ldots,i-1,i+1,\ldots,r \tag{9}$$

where T^i_{AFI} is the i-th isolation threshold. An UIO-based actuator fault isolation scheme is shown in the fig. 2.

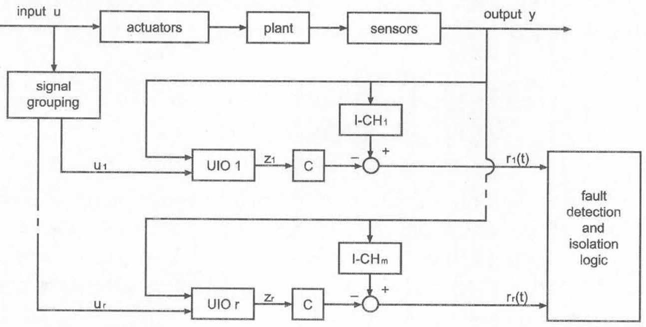

Fig. 2. A disturbance decoupled sensor fault isolation scheme

1.2. FDI schemes for singular systems using standard observers

Let us consider a singular system with possible sensor and actuator faults

$$E\dot{x}(t) = Ax(t) + Bu(t) + Bf_a(t), \quad (10a)$$
$$y(t) = Cx(t) + f_s(t), \quad (10b)$$

where $f_a \in R^r$ and $f_s \in R^m$ are the vectors of actuator and faults, respectively. Matrix E is in general singular, $\det E = 0$. As a residual generator we use a standard observer for singular systems. More details on such observer can be found in [5].

$$\dot{z}(t) = Fz(t) + Gu(t) + Ky(t), \quad (11a)$$
$$\hat{x} = Mz + Ny, \quad (11b)$$

where z, $\hat{x}$, F, G, K, M and N are real matrices of appropriate dimensions, satisfying additional conditions to guarantee the convergence of estimation error to zero. More details can be found in [5]. If the state estimation is available, the residual can be generated as

$$r(t) = y(t) - C\hat{x}(t) = (I - CN)y(t) - CMz(t). \quad (12)$$

Applying the above residual generator to the system described by (1), we obtain the following equations governing the state estimation error $e(t) := x(t) - \hat{x}(t)$

$$E\dot{e}(t) = (A - KC)e(t) + Bf_a(t) - Kf_s(t), \quad (13a)$$
$$r(t) = Ce(t) + f_s(t), \quad (13b)$$

Thus that residual is sensitive to both actuator and sensor faults. Therefore it can be used to detect faults according to the threshold logic (4).

1.2.1. Sensor fault isolation scheme

We assume that all actuators are fault free and the systems equations are

$$E\dot{x}(t) = Ax(t) + Bu(t), 12a \quad (14a)$$
$$y_j(t) = C_j x(t) + f_s^{[j]}(t), 13b \quad (14b)$$
$$y_{[j]}(t) = c_{[j]}x(t) + f_{s[j]}(t),\ j = 1, 2, \ldots, m, 14c \quad (14c)$$

where $c_{[j]} \in R^{1\times n}$ is the j-th row of the matrix C, $C_j \in R^{(m-1)\times n}$ is obtained from the matrix C by deleting j-th row $c_{[j]}$, $y_{[j]}$ is the j-th entry of y and $y_j \in R^{m-1}$ is obtained from the vector y by deleting its j-th entry $y_{[j]}$. $f_{s[j]}$ is the j-th entry of f_s and $f_s^{[j]} \in R^{m-1}$ is obtained from the vector f_s by deleting its j-th entry. Based on this description, according to proceeding subsection residual generator of the following form is proposed

$$\dot{z}_j(t) = F_j z_j(t) + G_j u(t) + K_j y_j(t), \quad (15a)$$
$$r_j(t) = (I - C_j N_j)y_j(t) - C_j M_j z_j(t), \quad (15b)$$

where $j = 1, 2, \ldots, m,$.

Thus each residual generator is driven by all inputs and all but one outputs. When all actuators are fault-free and a fault occurs in the j-th sensor, the residual will satisfy the isolation logic (8) where T^j_{SFI} is the j-th isolation threshold. An appropriate sensor fault isolation scheme for singular systems is shown in the fig. 3.

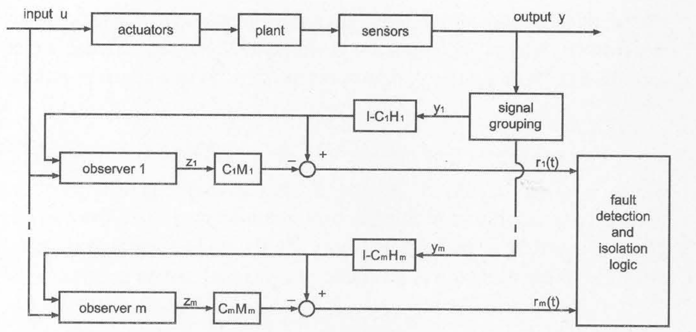

Fig. 3. A sensor fault isolation scheme for singular systems using standard observers

1.2.2. Actuator fault isolation scheme

To design actuator fault isolation schemes for singular system, all sensors are assumed to be fault free and the system is described by the following equations

$$\begin{aligned} E\dot{x}(t) &= Ax(t) + B_i u^{[i]}(t) + B_i f_a^{[i]}(t) \\ &\quad + b_i\left[u_i(t) + f_{a[i]}(t)\right] \\ &= Ax(t) + B_i u^{[i]}(t) + B_i f_a^{[i]}(t), \\ y(t) &= Cx(t), \qquad i = 1, 2, \ldots, r, \end{aligned}$$

where $b_i \in R^n$ is the i-th column of the matrix B, $B_i \in R^{n\times(r-1)}$ is obtained from the matrix B by deleting its i-th column, u_i is the i entry of u, $u^{[i]} \in R^{r-1}$ is obtained from the vector u by deleting its i entry, $f_{a[i]}$ is the i entry of f_a, $f_a^{[i]} \in R^{r-1}$ is obtained from the vector f_a by deleting its i entry. According to this description, a residual generators of the following form is proposed

$$\dot{z}_i(t) = F_i z_i(t) + G_i u_i(t) + K_i y(t),$$
$$r_i(t) = (I - CN_i)y(t) - CM_i z_i(t), \quad i = 1, 2, \ldots, r.$$

Thus each residual generator is driven by all outputs and all but one inputs. When all sensors are fault-free and a fault occurs in the i-th actuator, the residual will satisfy the isolation logic, where T^i_{SFI} denotes the i-th isolation thresholds, $i = 1, \ldots r$. An appropriate actuator fault isolation scheme is shown in the fig. 4.

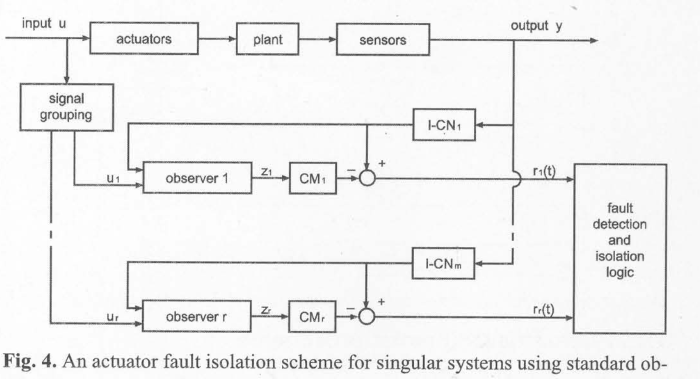

Fig. 4. An actuator fault isolation scheme for singular systems using standard observers

1.3. FDI schemes for singular systems using perfect observers

In this section we seek for FDI scheme for singular systems based on perfect observers. Let us consider a singular system with possible sensor and actuator faults given by (10)

$$E\dot{x}(t) = Ax(t) + Bu(t) + Bf_a(t),$$
$$y(t) = Cx(t) + f_s(t),$$

where $f_a \in R^r$ and $f_s \in R^m$ are vectors of actuator and sensor faults, respectively. Matrix E is in general singular, $\det E = 0$. We use a perfect observer for singular systems presented in [5] as a residual generator

$$E\dot{\hat{x}}(t) = (A - KC)\hat{x}(t) + Bu(t) + Ky(t), \quad (16)$$

where $\hat{x}$, y, u, E, A, K, C and B are real matrices of appropriate dimensions, satisfying additional conditions to guarantee the convergence of estimation error to zero; more details can be found in [5]. Assuming the state estimation is available, the residual can be generated as

$$r(t) = y(t) - C\hat{x}(t). \quad (17)$$

When this residual generator is applied to the system (10) the residual and the state estimation error $e(t) := x(t) - \hat{x}(t)$ are governed by the following equations

$$E\dot{e}(t) = (A - KC)e(t) + Bf_a(t) - Kf_s(t), \quad (18a)$$
$$r(t) = Ce(t) + f_s(t), \quad (18b)$$

Thus residual is sensitive to both actuator and sensor faults. Therefore it can be used to detect faults according to the threshold logic (4)

1.3.1. Sensor fault isolation scheme

We assume that all actuators are fault free and the systems equations are

$$E\dot{x}(t) = Ax(t) + Bu(t), \quad (19a)$$
$$y_j(t) = C_jx(t) + f_s^{[j]}(t), \quad (19b)$$
$$y_{[j]}(t) = c_{[j]}x(t) + f_{s[j]}(t), \quad (19c)$$

where $j = 1, 2, \ldots, m$, $c_{[j]} \in R^{1\times n}$ is the j-th row of the matrix C, $C_j \in R^{(m-1)\times n}$ is obtained from the matrix C by deleting j-th row $c_{[j]}$, $y_{[j]}$ is the j-th entry of y and $y_j \in R^{m-1}$ is obtained from the vector y by deleting its j-th entry. $f_{s[j]}$ is the j-th entry of f_s and $f_s^{[j]} \in R^{m-1}$ is obtained from the vector f_s by deleting its j-th entry. According to this description and to preceding section residual generators of the following form is proposed

$$E\dot{\hat{x}}_j(t) = (A - K_jC_j)\hat{x}_j(t) + Bu(t) + K_jy_j(t), \quad (20a)$$
$$r_j(t) = y_j(t) - C_j\hat{x}_j(t), \quad j = 1, 2, \ldots, m, \quad (20b)$$

Thus each residual generator is driven by all inputs and all but one outputs. When all actuators are fault-free (which is assumed) and a fault occurs in the j-th sensor, the residual will satisfy the isolation logic (8) where T_{SFI}^j is the j-th isolation threshold. An appropriate sensor fault isolation scheme for singular systems is shown in the fig. 5.

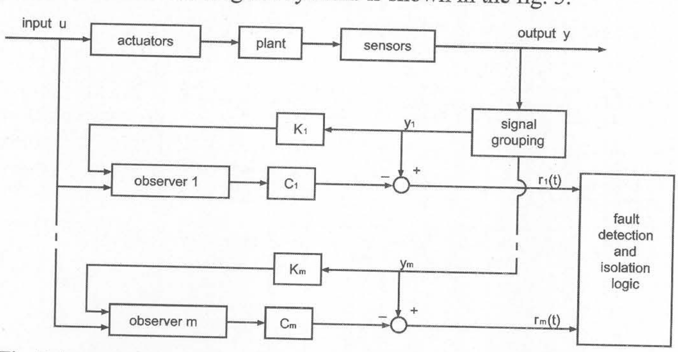

Fig. 5. A sensor fault isolation scheme for singular systems using perfect observers

1.3.2. Actuator fault isolation scheme

To design actuator fault isolation schemes for singular system, all sensors are assumed to be fault free and the system is described by the following equations

$$E\dot{x}(t) = Ax(t) + B_iu^{[i]}(t) + B_if_a^{[i]}(t)$$
$$+ b_i\left[u_i(t) + f_{a[i]}(t)\right]$$
$$= Ax(t) + B_iu^{[i]}(t) + B_if_a^{[i]}(t),$$
$$y(t) = Cx(t), \quad i = 1, 2, \ldots, r,$$

where $b_i \in R^n$ is the i-th column of the matrix B, $B_i \in R^{n\times(r-1)}$ is obtained from the matrix B by deleting the i-th column b_i, u_i is the i-th entry of u, $u^{[i]} \in R^{r-1}$ is obtained from the vector u by deleting its i-th entry, $f_{a[i]}$ is the i-th entry of f_a, $f_a^{[i]} \in R^{r-1}$ is obtained from the vector f_a by deleting its i-th entry. According to this, an perfect-observer-based residual generator of the following form is proposed

$$\dot{\hat{x}}_i(t) = (A - K_iC)z_i(t) + B_iu_i(t) + K_iy(t),$$
$$r_i(t) = y(t) - C\hat{x}_i(t), \quad i = 1, 2, \ldots, r.$$

Thus each residual generator is driven by all outputs and all but one inputs. When all sensors are fault-free and a fault occurs in the i-th actuator, the residual satisfies the isolation logic (9) where T_{SFI}^i denotes the i-th isolation thresholds, $i = 1, \ldots r$. An appropriate actuator fault isolation scheme is shown in the fig. 6.

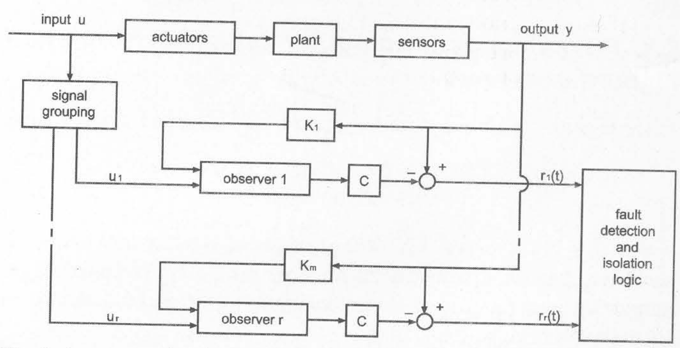

Fig. 6. An actuator fault isolation scheme for singular systems using perfect observers

2. Concluding remarks

Observer-based FDI schemes have been presented, both for standard and singular systems. The applications of perfect observers to FDI have been shown. The results concerning FDI observer-based schemes for standard systems have been presented after [1]. Some generalizations of these results for singular systems have been presented.

Application of to observer-based FDI was also demonstrated. FDI is very wide and complicated area of control theory and this short survey by no means claims to cover all its aspects. For more detailed study reader is referred to many monographs on the subject, an excellent one is, for instance, [3].

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Tytuł: Wykrywanie uszkodzeń w układach dynamicznych przy użyciu obserwatorów - część II

Artykuł recenzowany