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On the Fault Detection and Isolation Systems using Functional Observers

이 기 상*, 류 지 수
(Kee-Sang Lee and Ji-Su Ryu)

Abstract : Two GOS (Generalized Observer Scheme) type Fault Detection Isolation Schemes (FDIS), employing the bank of unknown input functional observers (UIFO) as a residual generator, are proposed to make the practical use of the multiple observer based FDIS. The one is IFD (Instrument Fault Detection) scheme and the other is PFD (Process Fault Detection) scheme. A design method of UIFO is suggested for robust residual generation and reducing the size of the observer bank. Several design objectives that can be achieved by the FDI schemes and the design methods to meet the objectives are described. An IFD system is constructed for the Boeing 929 Jetfoil boat system to show the effectiveness of the propositions. Major contributions of this paper are two folds. Firstly, the proposed UIFO approaches considerably reduce the size of residual generator in the GOS type FDI systems. Secondly, the FDI schemes, in addition to the basic functions of the conventional observer-based FDI schemes, can reconstruct the failed signal or give the estimates of fault magnitude that can be used for compensating fault effects. The schemes are directly applicable to the design of a fault tolerant control systems.

Keywords : fault detection isolation systems, unknown input functional observer, observer based FDI systems, instrument fault detection, process fault detection

I. Introduction

In all control systems, sensors and actuators are the most important components because they provide important information for monitoring and control input generation. Therefore, these components are usually implemented by the use of hardware or software redundancy, so that any fault can be promptly detected and appropriate remedies can be applied to maintain the desired level of system reliability and safety. With the remarkable growth of computer technology, analytical redundancy methods have been developed in the name of Instrument Fault Detection (IFD) or Fault Detection and Isolation (FDI) where state estimators such as Kalman filters or Luenberger observers are used for residual generation [1][2].

After an IFD scheme, Dedicated Observer Scheme (DOS), was proposed by Clark [1], many research results have been reported to enhance the performances of the IFD system [3]. And many modifications that can be used for instrument fault detection and for process fault detection and isolation have been reported [4][5]. Among them, development of robust design methods of residual generator against disturbances, parameter variations and unmodelled dynamics have been prime importance [6]. And the development of FDI systems for linear process seems to be completed.

Unfortunately, almost all of these schemes cannot be implemented by the use of limited performance microprocessors that are normally used in automatic control systems for commercial processes. There is a need to develop the FDI system that can be implemented by the use of microprocessors at a low cost, and some research activities have been started recently [7]. In the FDI systems based on the DOS or the Generalized Observer Schemes (GOS) that require multiple observers, a large bulk of differential or difference equations must be driven in real time. And it requires fast computing capability and large memory space to find out the faults in their mission time.

In this paper, two FDI schemes using functional observers are proposed to make the practical use of observer based fault detection system possible. In order to design such an FDI system with a reasonable performance, a design method of an unknown input functional observer (UIFO) for the systems with slowly varying disturbances is presented first. Then, various design aspects of the proposed FDI system are described. The FDI system can be designed in different ways according to the design objectives.

In the case of Instrument Fault Detection, the design objectives are:

- Sensor fault detection and isolation of failed sensor
- Sensor fault detection, isolation of failed sensor and generation of failed signal
- Sensor fault detection, isolation of failed sensor and output/state feedback control input generation without external controller

In the case of Process Fault Detection Isolation (PFDI), the design objectives are:

- Process fault detection and isolation (classification)
- Process fault detection, isolation and estimation of fault magnitude
- Process fault detection, isolation, control input generation, and fault compensation

It is noteworthy that the FDI systems can reconstruct the failed signal or give the estimates of fault magnitude that can be used for compensating fault effects. The organization of this paper is as follows. In section 2, the problem and a simple design method of the UIFO are described. The details of the proposed GOS type IFD system and PFDI system are described in section 3 and 4, respectively. In the development of the IFD/PFDI schemes, it is assumed that a fault occurs at a time. In order to show the effectiveness, a proposed FDI scheme is applied to a model of the Boeing 929 Jetfoil boat system for instrument fault detection in section 5. The design objective is selected as sensor fault detection, isolation of failed sensor, generation of failed signal, and compensation.

* 책임저자(Corresponding Author)
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이기상 : 단국대학교 전기전자컴퓨터공학부(keesang@dku.edu)
류지수 : 단국대학교 대학원 전기공학과(jsryu@dku.edu)
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II. An unknown input functional observer

1. Description of UIFO design problem

Consider a linear time invariant system with following dynamic equation.

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) + Qw(t) \\ y(t) &= Cx(t). \end{aligned} \tag{1}$$

where $x(t)$, $u(t)$, $y(t)$, and $d(t)$ are the n-dimensional state vector, l-dimensional input vector, p-dimensional output vector and q-dimensional disturbance vector, respectively. A, δA, B, δB, Q, and C are appropriate dimensional matrices. Without loss of generality, the parameter variations and disturbances can be considered at the same time by defining

$$Qw(t) = \delta Ax(t) + \delta Bu(t) + \hat{Q}d(t)\,. \tag{2}$$

Assume that $w(t)$ also is a q-dimensional vector for convenience. Then the familiar equations are obtained as

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) + Qw(t) \\ y(t) &= Cx(t). \end{aligned} \tag{3}$$

Now, the problem is to design a functional observer that can generate the estimate of an arbitrary linear functional of the state variables, even in the cases where unknown time varying disturbances are injected. The reason of employing functional observers in FDIS is that the maximum order of a functional observer is limited to the number of functions to be estimated times the observability index of the system. Although there have been many research results on the design of an unknown input observer (UIO), only a few results on the unknown input functional observer can be found [8-10]. In the UIFO design, there may be two kinds of approaches. The one is the algebraic canceling method and the other is the disturbance modeling approach [11]. The second approach is taken here because the UIFO designed by using the approach provides the fault information and because the algebraic approach may lead to difficult existence conditions.

2. Mathematical models for unknown disturbances and faults

The performance of the UIFO, designed by the disturbance modeling approach, largely depends on the quality of the mathematical model of the disturbances. And the disturbance should be modeled so that the resultant UIFO gives the functional estimates with reasonable accuracy. Without loss of generality, let us assume slowly varying disturbances. Then the disturbance can be modeled by (4), because the disturbances that occur in physical process frequently possess waveform structure such as jump (step), ramp and exponential function etc..

$$w_i(t) = \sum_{i=1}^{m_i} c_i \phi_i(t) \tag{4}$$

where the $\phi_i(t)$'s are basis functions and the c_i's are unknown coefficients, and m_i is a finite number which can be determined. The dynamic representation corresponding to (4) may be obtained by following two approaches.

CASE (1): If sufficient experimental data or waveform is given, a set of basis functions can be determined and (4) can be considered as a primitive of the differential equation

$$\frac{d^{m_i} w_i}{dt^{m_i}} + a_m \frac{d^{m_i-1} w_i}{dt^{m_i-1}} + \cdots + a_1 w_i = \delta(t)\,. \tag{5}$$

CASE (2): If the selection of the basis function set is difficult due to the lack of information, the disturbances may be modeled as a Taylor series expansion in time.

$$w_i(t) = c_0 + c_1 t + c_2 t^2 + \cdots + c_{m_i-1} t^{m_i-1} \tag{6}$$

Equation (5) and (6) can easily be represented as an observable canonical form,

$$\begin{aligned} \dot{z}_i(t) &= D_i z_i(t) + E_i \delta(t) \\ w_i(t) &= h_i z_i(t) \end{aligned} \tag{7a}$$

where D_i, h_i, and E_i are (m_i, m_i), $(1, m_i)$, and $(m_i, 1)$ dimensional matrices with following structures

$$D_i = \begin{bmatrix} -a_m & 1 & 0 & \cdots & 0 \\ -a_{m-1} & 0 & 1 & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ -a_2 & 0 & 0 & \cdots & 1 \\ -a_1 & 0 & 0 & \cdots & 0 \end{bmatrix}, \quad h_i^T = \begin{bmatrix} 1 \\ 0 \\ \vdots \\ 0 \\ 0 \end{bmatrix}, \text{ and}$$

$$E_i = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 1 \end{bmatrix}. \tag{7b}$$

In case (1), the coefficients a_i's have to be identified and a parameter identification algorithm such as recursive least square can be employed to get the a_i's from experimental (operation) data. In case (2), m_i=1 is chosen for step disturbance, $m_i = 2$ for ramp disturbances. Note that there is no need to know the values of coefficients in (6) because (7) with all a_i's equal zero is the exact dynamic model for all signals that can be represented by (6), regardless of the coefficient values. The model (6) is simple but provides reasonable results in many applications. If there are several disturbances to be considered, the overall disturbance vector can be represented as

$$\begin{aligned} \dot{z}(t) &= Dz(t) + E\delta(t) \\ w(t) &= Hz(t) \end{aligned} \tag{8}$$

where $z(t)$ is $m(=\sum_{i=1}^{q} m_i)$ dimensional vector and D, E, and H are matrices with

$$\begin{aligned} D &= diag\begin{bmatrix} D_1 & D_2 & \cdots & D_q \end{bmatrix}, \\ E &= diag\begin{bmatrix} E_1 & E_2 & \cdots & E_q \end{bmatrix}, \text{and} \quad . \\ H &= diag\begin{bmatrix} H_1 & H_2 & \cdots & H_q \end{bmatrix}\,. \end{aligned} \tag{9}$$

Remember that the disturbance model (8) and (9) provides an effecttive model not only for disturbances but also for process/sensor faults with the assumption that they are slowly varying.

3. UIFO design procedure

The UIFO design procedures consist of two stages. In the first stage, system equation (3) and the disturbance model are combined to construct an augmented system:

$$\begin{aligned} \dot{\underline{x}}(t) &= \underline{A}\underline{x}(t) + \underline{B}u(t) + \underline{E}\delta(t) \\ y(t) &= \underline{C}\underline{x}(t) \end{aligned} \tag{10}$$

where $\underline{x}^T = \left[x^T\, x_1^T \cdots z_q^T\right]$ is $(n+m)$ dimensional augmented state vector and the matrices in (10) are as follows.

$$\begin{aligned} &\underline{A} = \begin{bmatrix} A & QH \\ O & D \end{bmatrix},\ \underline{B} = \begin{bmatrix} B \\ O \end{bmatrix},\ \underline{E} = \begin{bmatrix} O \\ E \end{bmatrix}, \text{and} \\ &\underline{C} = [C\ \vdots\ O] \end{aligned} \tag{11}$$

The existence condition of the UIFO is lenient. Assume that the pair $[C\ \vdots\ A]$ is completely observable. Then the pair $[\underline{C}\ \vdots\ \underline{A}]$ of the augmented system is also observable, if and only if, the rank of $\begin{bmatrix} A & Q \\ C & O \end{bmatrix}$ equals $(n+q)$. This is due to the mathematical model of each disturbance can always be represented by an observable canonical form.

In the second stage, a UIFO should be constructed to estimate the linear functions that are predetermined by the FDI system or IFD system designer according to his design purpose. Let us assume q independent linear functions,

$$v(\underline{x}) = K\underline{x} \tag{12}$$

where K is a $(q, n+m)$ dimensional matrix. Then a UIFO, which can estimate (12), is described by the following equations.

$$\begin{aligned} \dot{s}(t) &= Fs(t) + Jy(t) + Gu(t) \\ \hat{v}(\underline{x}) &= Ly(t) + Ps(t) \end{aligned} \tag{13}$$

In (13), the dimension of vector s, i.e., the order of UIFO, should be selected so as to meet the conditions in following theorem.

Theorem: For the pre-selected F that has left half plane eigenvalues, if there exits a T such that

$$\begin{aligned} FT - T\underline{A} &= J\underline{C} \\ K &= PT + L\underline{C} \\ G &= T\underline{B} \end{aligned} \tag{14}$$

and if the pair $[P\ \vdots\ F]$ is completely observable, then $\hat{v}(\underline{x})$ is an asymptotic estimate of $v(\underline{x})$.

Proof of this theorem is well known and is omitted here.

The theorem provides necessary and sufficient conditions for the existence of the functional observer with order less or equal to q times the observability index of the pair $[\underline{C}\ \vdots\ \underline{A}]$. Since there is no simple method to determine the minimal order of the observer and there is no unified design procedure, the design algorithm must be selected among several existing methods by considering the number of functions to be estimated, the number of measurement outputs, and the required order of the resultant observer. A design algorithm is given in [12].

III. GOS type IFD system using UIFOs

In this section, the IFD problem is described. A fault of ith sensor can be defined as the addition of a disturbance to the true output and/or a scale change of the measurement matrices.

$$y(t) = Cx(t) + Q_f w_f \quad \text{or} \quad y(t) = (C + \delta C)x(t) \tag{15}$$

The sensor fault detection problem is to detect the occurrence of the fault and to identify the failed sensor promptly following the occurrence of the fault. The proposed GOS type IFD system can be constructed so as to meet various design objectives such as sensor fault detection, isolation of failed sensors, failed signal regeneration, correct control input generation, and the combinations of these by selecting the functions to be estimated. The selection of functions is the most important part of the design procedure. The functions must be selected so that the resultant IFD system satisfies the given design objectives, so that estimation of the functional is guaranteed and the detection of an instrument fault can be performed by simple decision logic. In order to reduce the order of each functional observer in the IFD system, the observability index of the pair $[C_i\ \vdots\ A]$ should be minimized by introducing the maximum number of independent measurement outputs as the inputs to the UIFO. In this section, a simple approach to choosing the observer inputs (measurement outputs) that gives the minimum size estimator bank is described. Then, some functions with which each design objective can be satisfied are suggested. In addition, related decision functions and logic are given. Throughout this section, it is assumed that a single fault occurs at a time.

In GOS type IFD systems [13], the number of UIFOs should be the same as the number of sensors in order to detect and isolate every sensor fault. It is desirable that the IFD system can be constructed so that the isolation of the failed sensor can be performed by a predetermined logic. For detailed explanation of the IFD system design, a system with 5 measurement outputs is considered. In table 1, a relation between UIFOs and measurement outputs is constructed. The relationship guarantees simple and predetermined isolation logic. It also gives the minimum size estimator bank because the maximum number of outputs are used as the inputs to the observers.

Table 1. A UIFO-output relation for IFDS.

UIFOs	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5
UIFO 1	X	0	0	0	X
UIFO 2	X	X	0	0	0
UIFO 3	0	X	X	0	0
UIFO 4	0	0	X	X	0
UIFO 5	0	0	0	X	X

In the table, the character "0" means that the measurement is an input to the corresponding functional observer(s) and "X" means that it is not included in the observer inputs. Since each functional observer generates a functional estimate, the functional observer bank provides five estimates for a functional. Fault detection and isolation of the failed sensor can be performed by the simple comparison of each estimate to the other estimates. For example, if UIFO 1 and UIFO 2

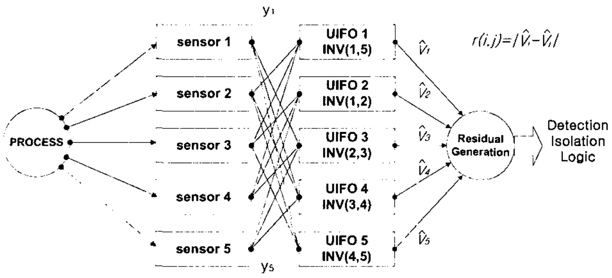

Fig. 1. The structure of IFD system using UIFOs.

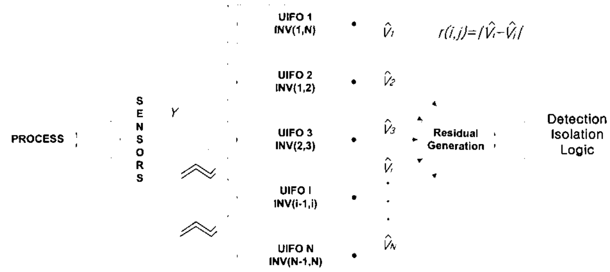

Fig. 2. An FDI system for process fault using UIFOs.

generate different estimates from those of three other functional observers, then sensor 1 is malfunctioning. Further, UIFO 1 and UIFO 2 provide the correct estimates of the functional. It is noteworthy that the maximum number of inputs (measurement outputs) for each UIFO is 3. The IFDS structure in Fig.1 is the realization of the UIFO-output relation given in table 1. Note that each UIFO provides the estimate ($\hat{v}_i$) of single functional $v(x)$.

Design objective (1): Detection of sensor fault and isolation of failed sensor

This objective is a quite general one. With this objective, any single functional that is independent of all measurement outputs can be selected as the functional to be estimated.

Let's define a residual as $r(i,j)=\left|\hat{v}_i(\underline{x})-\hat{v}_j(\underline{x})\right|$. Then there are a total of $p(p-1)/2$ residuals. Remember that p is the number of outputs. The occurrence of any sensor fault can be easily detected by applying the following simple logic.

If $r(i,i+1)<$ threshold for $i=1$ to $p-1$, then no fault

else if $v_i(t)=\sum^{m_i} c_i\phi_i(t)$ >threshold, then ($i-1$)th sensor is faulty

In order to reduce the false alarm rate of the IFDS, following isolation logic may be applied. The isolation logic conforms the ($i-1$)th sensor fault by testing all the residuals that may be increased by the sensor fault.

If $r(i-1,j)$ >threshold for $\hat{v}_i(y)$ to p , $(j \neq i-1, i)$,

then ($i-1$)th sensor is faulty.

Design objective (2): Detection of sensor fault, isolation of failed sensor, and regeneration of the failed signal

With these objectives, some degree of freedom exists in choosing the functions to be estimated. However, an increase in the number of functions leads to an increase of the UIFO order. It is desired to select only p functions, one for each UIFO. One of the useful candidates is a function that is an equally weighted linear combination of sensor outputs.

$$v_i(y)=\sum_{i=1}^{p} y_i \tag{16}$$

Each UIFO in the IFD system estimates only one function. A detection logic that is the same as that of the case (1) should be applied.

In order to generate the failed signal, say y_i, one of two correct estimates $\hat{v}_i(y)$ or the average of them may be used together with all normal sensor outputs.

$$y_{re}(i)=\hat{v}_i(y)-(y_1+y_2+\cdots+y_{i-1}+y_{i+1}+\cdots+y_p) \tag{17}$$

In (19), $y_{re}(i)$ is the regenerated value of the failed signal y_i and the other y_i's are normal sensor outputs. With this objective, the IFDS has the ability to feed the regenerated output values to the controller so that the controller generates accurate control inputs in spite of the sensor fault.

Design objective (3): Detection of sensor fault, isolation of failed sensor and output/state feedback control input generation without external controller

This objective is also a special case of design objective (1) when it is applied to single input systems. With this objective, IFD system can be used for fault detection and also for correct control input generation in the face of a sensor fault. Since it also is a controller and therefore simplifies the overall control system. In this case, estimation of the control input $u(t)=Kx(t)$ or $Ky(t)$ is all that is required for generating the direct redundancy to detect a fault and to actuate the feedback control system. Fault detection logic can be set up in the same manner as for design objective (1).

IV. GOS type process FDI system using UIFOs

The UIFO can be applied to the detection, isolation and estimation of process faults, including actuator faults by simply replacing/adding the expected faults to the process equation (1), (3). In such cases, (3) may be rewritten in (18)

$$\begin{aligned}\dot{x}(t)&=Ax(t)+Bu(t)+Q_d w_d(t)+Q_f w_f(t)\\ y(t)&=Cx(t)\end{aligned} \tag{18}$$

However, (18) may be reduced to (3) because w_d and w_f are not known in advance, so all of them can be treated as unknown variables regardless of their actual meaning. It is noteworthy that there has been considerable research effort to design robust residual generators (robust state observers) so that the resultant observer estimates are insensitive to disturbances while sensitive to faults [14]. Unfortunately, almost algebraic design approaches fail to design such observer whenever the range space of disturbance transfer matrix includes that of assumed fault transfer matrix. Assume (3') can be reduced to (3) with an additional assumption $RS(Q_d) \cap RS(Q_f) = \Phi$, so rank$Q$ = rankQ_d + rankQ_f. Here, Φ represents a null matrix.

The concepts of GOS can also be applied to the process fault detection and isolation. The structure of a GOS using UIFOs for process fault detection is shown in Fig. 2. Other than IFDS, all the measurement outputs can be employed as the input to each UIFO. In the structure, the number of UIFOs is the same as the number of faults to be considered. We consider a system with 5 process faults for more detailed explanation. Among the five observers, there should be two

Table 2. A UIFO-fault relation for PFDS.

UIFOs	Fault 1	Fault 2	Fault 3	Fault 4	Fault 5
UIFO 1	inv	0	0	0	inv
UIFO 2	inv	inv	0	0	0
UIFO 3	0	inv	inv	0	0
UIFO 4	0	0	inv	inv	0
UIFO 5	0	0	0	inv	inv

observers invariant to each fault while others are sensitive to the corresponding fault as shown in following table.

In the table "inv" means, for example, UIFO 1 has to be designed so as to be invariant or robust against fault 1 and fault 5, simultaneously. And the roust design will be accomplished by modeling the faults, expanding the process dynamic equation by attaching these fault models, and designing a functional observer as described in section 2. There are some degrees of freedom in choosing functions to be estimated. It means that several design objectives can be achieved with this FDI structure.

Design objective (1): Fault Detection and Isolation

In this case, the selection of all the functions to be estimated and the detection/isolation logic are very similar to the design objective (1) for IFD. Define residuals as $r(i,j)=\left|\hat{v}_i(\underline{x})-\hat{v}_j(\underline{x})\right|$, then a fault can be detected and isolated by the following logic:

If $r(i,i+1)$ <threshold for $i=1$ to $q-1$, then no fault

else if $r(i,i+1)>$ threshold, then ($i-1$)th fault occurred.

When the reliability of the PFDS is important, following logic may be employed to reduce the false alarm rate. Note that the logic takes successive threshold tests for the residuals that are increased by the ($i-1$)th fault.

If $r(i-1,j)>$ threshold for $j=1$ to q, $(j\neq i-1,i)$,

then ($i-1$)th fault occurred.

Design objective (2): Fault detection, isolation and estimation of fault magnitude

In this case, each UIFO has to estimate functions carrying information about the magnitude of fault. Remember that each UIFO is designed so as to have a robust property against two faults. For example, UIFO 1 produces an accurate function estimate even in the case of fault 1 or fault 5. This means the corresponding UIFO is designed by using the augmented model in which two fault models are included. In other words, the fault variables, linear combination of fault variables, or linear combination of fault variables and state variables may be chosen as the functions to be estimated. A simple method to achieve this objective is to choose two functions for each UIFO, one for detection and isolation of any process fault and the other for estimation of fault magnitude. The first function must be a function of state variables whose dynamics are considered in the design stage of all the UIFOs included in FDI system. And the second function is the fault variable w_{fi} for *i*th UIFO.

Design objective (3): Fault detection, isolation, control input generation and fault compensation

The first three items in this objectives are considered as a special case of design objective (1) and (2). The control input $u(t)=Kx(t)$ may be a useful candidate whenever FDI system and a control algorithm have to be implemented by using a single processor. For the fault compensation, the feedback control input with two components, one for primary control objective and the other for fault compensation, should be designed. The composite control input may be represented by

$$u(t)=u_0(t)+u_f(t)\,. \tag{19}$$

By substituting the control input into (3), we obtain

$$\dot{x}=Ax+B(u_0+u_f)+Q_f w_f\,. \tag{20}$$

In (20), the disturbance term is neglected for brevity. But it can be cancelled by the same method described here. Two simple methods for synthesizing u_f are as follows.

CASE (1): If rank(B $\vdots$ Q_f) = rank(B), then there exists L such that $Q_f=BL$, the fault compensation input can be obtained as

$$u_f=-L\hat{w}_f \tag{21}$$

where $\hat{w}_f$ is the estimate of a fault magnitude.

CASE (2): If the rank condition cannot be met, the compensation input may be chosen to minimize the vector norm of the equation

$$\mathrm{Min}\left\|Bu_f+Q_f w_f\right\| \tag{22}$$

and the resultant input is given by

$$u_f=-B^{+}Q_f\hat{w}_f \tag{23}$$

where B^+ denotes pseudo-inverse of B.

V. Application to Instrument Fault Detection in the Boeing 929 Jetfoil boat

1. Autopilot system dynamics

In order to show the effectiveness of the proposed FDI scheme, it is applied to the Boeing 929 Jetfoil boat. The boat itself is unstable and must have an autopilot when it is foilborne. The autopilot has a pitch axis channel and a lateral axis channel. Only the lateral axis is considered here, with the boat in a cruise condition. A thorough description of that system is described in [15]. The state variables as well as the system input vector are selected as follows:

$x_1(t)=P(t)=\dot{\phi}(t)$: roll rate, degree/sec

$x_2(t)=\phi(t)$: roll angle, degree

$x_3(t)=R(t)$: yaw rate, degree/sec

$x_4(t)=v(t)$: lateral velocity, ft/sec

$x_5(t)=\delta_A(t)$: horizontal flap deflection, degree

$x_6(t)=\delta_R(t)$: rudder deflection, degree

$u_1(t)=\bar{\delta}_A(t)$ and $u_2(t)=\bar{\delta}_R(t)$

The deflection δ_A (t) and δ_R (t) are the outputs of two actuators. Thus the input to the actuator-boat system are the inputs $\bar{\delta}_A(t)$ and $\bar{\delta}_R(t)$ to the actuators that are modeled as first order systems. There are six measurement outputs in this system.

$y_1(t) = a_p(t)$: port acceleration, ft/sec^2

$y_2(t) = \phi(t)$: roll angle , degree

$y_3(t) = R(t)$: yaw rate, degree/sec

$y_4(t) = a_L(t)$: lateral acceleration, ft/sec^2

$y_5(t) = \delta_A(t)$: ailerons deflection, degree

$y_6(t) = \delta_R(t)$: rudder deflection, degree

The overall system dynamic relationships *x(t)*, *u(t)*, and *y(t)* valid for moderate maneuvers about a nominal cruise condition are

Plant $\dot{x} = Ax + Bu + Qw$

Autopilot $\dot{q} = F_A q + G_A y + H_A \theta_h$

$u = J_A q + L_A y + M_A \theta_h$

Sensors $y = Cx + y_f$

where *t* is dropped for brevity. The exact parameter values of this system can be found in [15]. Let us assume that is a side wind disturbance that produces moments about the roll and yaw axes, and a side force. Then the Q matrix is of the form:

$$Q = \begin{bmatrix} 1 & 0 & 1 & 1 & 0 & 0 \end{bmatrix}^T$$

2. Design of IFD system

Different from all other IFD schemes, the first stage of the proposed FDI system design is the selection of design objective. Then, the function to be estimated by the UIFOs has to be chosen, with which the design objectives can be achieved. In this example, the following design objective is considered:

Sensor fault detection,
Identification of failed sensor and
Regeneration and compensation of failed signal

The function of (18) is a useful candidate in this case.

$$v(y) = \sum_{i=1}^{p} y_i \ , \ p = 6$$

It can be represented by a linear function of states

$v(x) = Kx$ with

K= [3.107 1.737 -0.47 -8.147 -1.4142 6.747].

The second step of IFD system design is the design of UIFOs. As mentioned in section 3, the maximum number of independent outputs gives minimum size observer bank. With the assumption of "one fault at a time", four outputs can be taken to be the inputs to each UIFO. For example, the first observer must driven by the output set $\{y_2, y_3, y_4, y_5\}$, the second observer by the set $\{y_3, y_4, y_5, y_6\}$, and the sixth observer by the set $\{y_1, y_2, y_3, y_4\}$, etc.. In order to guarantee the robustness against a side wind disturbance, the disturbance model (7a) with following parameters is introduced.

$$D = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, \ H = \begin{bmatrix} 1 & 0 \end{bmatrix}, \text{and } E = \begin{bmatrix} 0 \\ 1 \end{bmatrix}.$$

The term $E\delta(t)$ can be neglected in the UIFO design procedure since it physically means nonzero initial conditions. The effects of the initial condition mismatch disappear after short transient period of the UIFO.

Six UIFOs are designed and the eigenvalues of each UIFO are selected as -1 and -5. All observers have same eigenvalues, so that they have similar convergence characteristics. The design parameters of the UIFOs are given in Appendix. For the detection and isolation of any fault, the following logic is employed.

Detection Logic :

If $r(i, i+1) <$ th1 for $i = 1$ to 5 , then no fault

Otherwise a sensor failed

Isolation Logic :

If $r(i, i+1)$ < th1 and $\prod_{j=1}^{p} r(i, j)$ > th2, $(j \neq i+1)$

then i th sensor fault

Remember $r(i, j) = \left| \hat{v}_i(x) - \hat{v}_j(x) \right|$, where $\hat{v}_i(x)$ is an estimate of $v(x)$ provided by the ith UIFO. Threshold value is an important factor that affects IFD system performance. However, it is not discussed here since there are some well-known results about the threshold selection [16]. Only two threshold values, 0.1 for th1, and 10^{-4} for th2, are used for all sensor faults. The threshold values are determined by considering the fault simulation data for various operating conditions. To achieve the design objective, the IFD system must include an algorithm for the regeneration of the failed signal. When (16) is selected as the function to be estimated, (17) provides the simplest algorithm to regenerate the failed signal.

In simulation study, many tests are made for every sensor fault and it is found that the proposed IFD system works very well for all faults in the face of considerable wind disturbance with various frequency components. Simulation results show that the responses of the proposed IFD system for sensor 2 fault only. The time that fault occurs is taken to be 2 second in all the simulations. For the sensor fault, bias fault with magnitude 1.0 degree is considered. It is corresponds to about 30 percent of its normal value. An initial condition mismatch is assumed to show the convergence characteristics of each UIFO by introducing

$$x(0) = \begin{bmatrix} -1 & -1 & 0 & 0 & 0 & 0 \end{bmatrix} .$$

Fig. 3 shows the normal operating behavior of the overall system. The behavior of the overall autopilot system in case of sensor 2 fault is shown in Fig. 4. And Fig. 5 shows the same things when the fault effect is compensated by introducing the regenerated signal, $y_{re}(2)$, instead of the failed signal $y_{re}(2)$. The figures show the effect of corrective action following an abrupt fault. By comparing these figures with the normal operating behavior, it easily can be recognized that the effect of sensor fault is propagated by (feedback) autopilot, and deteriorates overall performance. With the proposed scheme, however, the normal operating behavior can be recovered completely in about one second after the fault. As a result, the IFD system with the design objective (2) can be considered as a type of fault tolerant control system.

VI. Conclusions

In this paper, two FDI schemes that employ the bank of UIFOs as

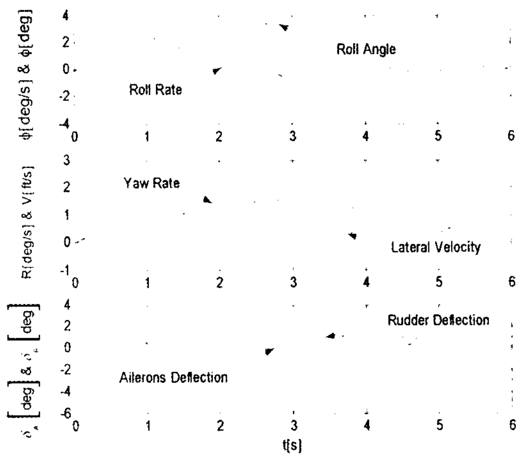

Fig. 3. Normal operating behavior of the overall system.

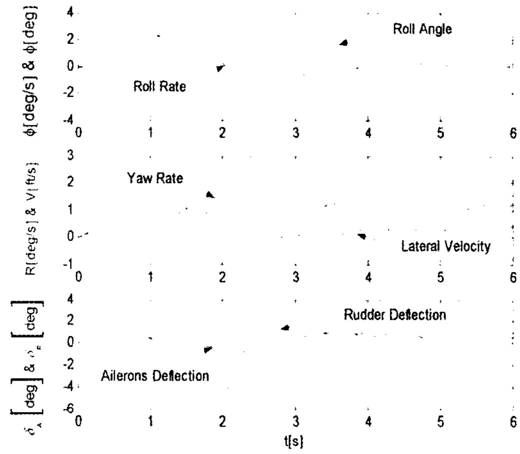

Fig. 4. Behavior of the boat system in case of sensor 2 fault.(uncompensated).

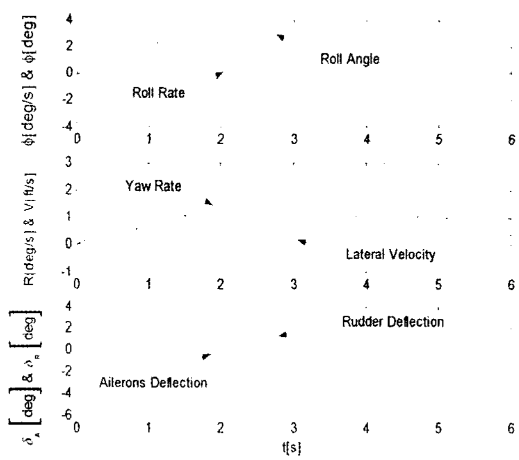

Fig. 5. Behavior of the boat system in case of sensor 2 fault(compensated by regeneration).

the residual generator are proposed to make the practical use of the GOS-type FDIS possible. The one is an IFD scheme and the other is PFDI scheme. In order to design such FDI systems, a design method of UIFO based on disturbance modeling approach is suggested. Different from the conventional FDI schemes, the proposed FDIS can be designed to meet several design objectives. And the design objectives that can be achieved by the schemes and the design methods to meet the objectives are described. Major contributions of this paper are two folds. First, by using UIFOs as the residual generator, the bulk of residual generator in the multiple observer based FDI systems is considerably reduced. Second, the FDI schemes, in addition to the basic functions of the conventional observer-based FDI schemes, can reconstruct the failed signal (IFD) or give estimates of fault magnitude that can be used for compensating fault effects. It means that the schemes are directly applicable to the design of fault tolerant control systems. A proposed FDI scheme is applied to a model of the Boeing Jetfoil boat system for IFD. Simulation results show the effectiveness of the IFD system.

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Appendix

A. UIFO parameters

F_{2x2}	P_{1x2}
DIAGONAL (-1, -5)	[1 1]

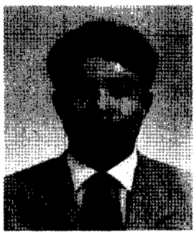
UIFOs	$G(1,1)$ / $G(2,1)$	$G(1,2)$ / $G(2,2)$
UIFO 1	4.5103292e+00	-2.2742420e+01
	5.6317696e+00	-2.0943000e+02
UIFO 2	-5.0563634e-04	-1.6107870e-00
	-1.1249580e+01	1.6031125e+02
UIFO 3	2.0521057e+00	-1.4571775e+01
	-4.3905487e+00	2.9554580e+02
UIFO 4	8.6781403e+00	-8.1456359e+00
	-9.1098515e-01	3.9379456e-01
UIFO 5	2.3461729e+00	-3.1284686e+00
	8.2300921e-01	1.7665412e+01
UIFO 6	1.9811482e+00	-1.9413643e+00
	4.3395041e-01	1.5308161e+01

UIFOs	$L(1,1)$ / $L(1,3)$	$L(1,2)$ / $L(1,4)$
UIFO 1	-4.1724268e+00	2.9821512e+01
	1.0709549e+01	-4.3215372e+00
UIFO 2	1.8806798e+01	7.3717570e+00
	2.6616602e+00	-4.3399034e+01
UIFO 3	-3.5943440e+00	5.1799357e+00
	-8.9243612e+00	-4.5437192e+01
UIFO 4	1.7142857e+00	1.6390078e+00
	5.9605417e-02	4.3915488e+00
UIFO 5	1.0424447e+00	7.4998247e-01
	-2.1633279e+00	2.5645554e+00
UIFO 6	9.2149316e-01	5.7447307e-01
	8.2286290e-02	7.9850858e-01

UIFOs	$J(1,1)$ / $J(1,3)$ / $J(2,1)$ / $J(2,3)$	$J(1,2)$ / $J(1,4)$ / $J(2,2)$ / $J(2,4)$
UIFO 1	4.4295139e-01	9.6991534e+00
	1.6327463e+00	2.1607686e+00
	-1.2742034e+01	4.4953833e+01
	1.7430685e+01	-2.1607686e+00
UIFO 2	-3.0802624e+00	-6.2100217e-01
	-1.3308301e+00	7.2331723e+00
	-6.0897119e+01	-2.1894617e+01
	1.3308301e+00	2.1699517e+01
UIFO 3	-1.3315641e+01	-3.8457087e+00
	4.4621806e+00	7.5728654e+00
	-3.2958028e+01	-1.6123292e+01
	-4.4621806e+00	2.2718596e+01
UIFO 4	1.3207217e+01	5.2362828e+00
	-2.9802708e-02	-7.3192479e-01
	-3.4223796e+00	-1.6821367e+01
	2.9802708e-02	-2.1957744e+00
UIFO 5	1.5176779e+00	8.4147909e+00
	8.6632309e-01	-4.2742590e-01
	-1.8671620e+00	1.0663158e+00
	2.8357779e+00	-1.2822777e+00
UIFO 6	8.7499660e-01	7.5569619e-01
	8.9479719e-02	-2.7974169e-01
	-1.6030037e+00	6.9939536e-01
	1.2517675e+00	-4.0375833e-01

이 기 상

1952년 10월 24일생. 1978년 고려대학교 전기공학과 졸업 (공학사). 1981년 동 대학원 전기공학과 졸업 (공학석사). 1984년 동 대학원 전기공학과 졸업 (공학박사). 1983년~현재 단국대학교 전기전자컴퓨터공학부 교수. 1995년~1996년 미국 University of Washington 방문교수. 관심분야는 고장진단, 퍼지 및 신경망 응용, 지능제어.



류 지 수

1968년 7월 28일생. 1990년 단국대학교 전기공학과 졸업 (공학사). 1996년 동 대학원 전기공학과 졸업 (공학석사). 2002년 동 대학원 전기공학과 졸업 (공학박사). 현재 단국대학교 전기전자컴퓨터공학부 강사. 관심분야는 고장진단, 전동기 제어, 마이크로프로세서 응용.