'88 韓國自動制御學術會議論文集 1988. 10. 21~22

# A new Fault Detection and Accomodation Scheme in Estimator based Control Systems

Kee Sang Lee, Eui Sung Park* and °Seung Yub Park**

* Dep. of Electrical Eng., Dankook Univ.
** Dep. of Electronics, Changwon Nat'l Univ.

ABSTRACT

A reliable Analytical Redundancy(AR) based Fault Detection Scheme(FDS) that can detect, discriminate sensor fault and process fault is presented. And a Fault Tolerant Control System ( FTCS ) with the FDS that performs original control objective without considerable loss of control performance in the face of sensor/process faults is constructed. These propositions are valuable in the sense that it resolves the well known sensitivity problem and that sensor/process faults can be detected, discriminated so that effects of any fault can be promptly accomodated by reconfiguring control system structure automatically.

## 1. Introduction

In order to maintain desired level of reliability and safety of control systems possible but unexpected faults must be promptly detected and appropriated remedial actions have to be applied. A conventional hardware redundancy method(HRM) can be used for fault detection, the method is with following penalties;

- component cost, volume, power consumption and weight
- difficulty of minor fault detection
- operator's responsibility to fault diagnosis and remedial actions

Due to remarkable growth of computer technology, various software methods for fault detection and diagnosis have been developed to alliviate the difficulties of HRM since middle of the 1970's. Among available techniques, the most promissible fault detection method is the use of Analytical Redundancy (AR) in which input/output behavior of a system is utilized analytically to recognize possible changes cause by faults. Most of the ARM available nowdays were well presented in survey papers by Willsky[1], Merrill[2], Clark[3] and Upadhyaya[4] and can be classified as following according to residual generation method.

- detection filter [5]
- Multiple filter scheme/Dedicated observer scheme [3],[6]
- Kalman filter innovation based scheme [3],[7]
- Parity relation approach [8],[9]

One of critical problems with ARM is sensitivity; Detection performance of sensor fault detection system(process fault detection system) is significantly deteriorated by parameter variation, unknown input diturbance (measurement noise, sensor bias) etc.. Although a few schemes to remove the difficulty have been suggested by using parameter insensitive observer, unknown input observer , the schemes can not give complete solution because the schemes are designd to detect only one type of fault.

Another problem to be further investigated is to design Fault Tolerant Control System including AR based FDS to increase system reliability.

The purpose of this paper therefore is twofolds:

- develope an innovation based FDS that detect and discriminate sensor fault and process fault even when operating environment of control system change to some degree.
- propose a FTCS including the FDS that can be performs original control objectives in the face of sensor/process faults.

## 2. Basic structure of estimator based control system and effects of faults

### 2.1 structure of estimator control systems

Consider a controlled process driven by following discrete equation.

$$X(k+1)=AX(k)+BU(k) + n(k) \qquad (1.a)$$
$$Y(k)=CX(k) + v(k) \qquad (1.b)$$

Kalman filter is given by the equations

$$\bar{X}(k+1)=A\bar{X}(k)+BU(k)+G(k)r(k) \qquad (2)$$
$$r(k)=Ym(k)-C\bar{X}(k) \qquad (3)$$

where Ym(k) is measured output and G(K), P(k) are computed from eq.(4)(5).

$$G(k)=P(k)C'[CP(k)C'+R(k)] \qquad (4)$$
$$P(k+1)=A[I-G(k)C]P(k)A'+Q(k) \qquad (5)$$

The control input (gain) K(k) can be obtained according to desired control objective in following form.

$$U(k)=K(k)\bar{X}(k) \qquad (6)$$

And the overall structure of estimator based control system containing controlled process, Kalman filter and controller is shown in Fig.1.

### 2.2 Effects of process(sensor) fault

In all state feedback control systems that contain state estimator, control performance is largely dependent on the accuracy of state estimates provided by estimator such as kalman filter since control inputs are generated by using these estimates.

Although the kalman filter, if properly designed,gives very good state estimates in normal operating condition, some unexpected change of operating conditions due to sensor (process) faults cause errorneous estimates. The estimation errors are fedback to controlled system via controller and badly deteriorate control performance.

(a) process fault: If some process fault such as parameter variation, actuator fault occurred, actual plant dynamic equation becomes as follows.

$$X(k+1)=AX(k)+BU(k)+DpWp(k)+n(k) \quad (8)$$

In these cases, the residual r(k) is not zero mean process but has a mean that can be represented by eq.(9).

$$r(k)=Sp\ Ex(k)+e(k) \quad (9)$$

In this equation, Ex(k) is state estimation error vector which can be defined as

$$Ex(k)=X(k)-\bar{X}(k)=VpWp \quad (10)$$

Therefore, the control input generated by using the kalman filter estimates include unknown error of K(k)Ex(k) and it deteriorate the control performance of overall system. Another important problem with process fault is the fact that original control objective cannot be achieved even when corrected estimate is used for input generation as far as the effects of process fault was not considered in the design stage. A viable method to perform the objective is drive an additional fault accomodating controller in order to remove the effects of fault.

(b) sensor fault:When sensor fault is considered,measurement equation becomes as eq. (11)

$$Ym(k)=CX(k)+DsWs(k)+v(k) \quad (11)$$

Kalman filter estimation error and residual can be represented by eq.(12)(13), respectively

$$r(k)=SsEx(k)+e(k) \quad (12)$$

$$Ex(k)=X(k)-\bar{X}(k)=VsWs(k) \quad (13)$$

In this case, control input includes the error of G(k)Ex(k). And it is neccessary to compensate the errorneous estimate in order to perform original control objective.

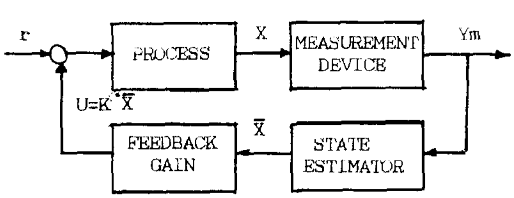


Fig.1 Structure of estimator based control system

3.The proposed structure of FTCS

The proposed FTCS structure is shown in Fig.2. The structure is new one in a view point that the system detect, discriminate, diagnose and compensate process fault and sensor fault, simultaneously, while almost all of the conventional FTCS treat only one type of faults.

3.1 Fault detection

The innovation sequence of the kalman filter that is a basic component of state feedback control system is very useful information that can be used for detecting fault symptoms. And fault detection is made from the information by mean test, variance test with preselected threshold values.

The thrèshold values that are compared with computed mean or variance must be selected by considering false alram probability,miss probability, detection probability, measurement cost and computational burden etc..If threshold values are selected, then computed mean and/or variance are compared with the threshold. And fault is declared when any one (or more) of mean and/or variance is (are) larger than corresponding threshold values.

3.2 Estimation of fault magnitude

When any fault symptom is detected, the kind of fault must be promptly identified. It is also necessary to estimate the fault magnitude. Although a few schemes have been developed to estimate fault magnitude, two bias estimation schemes based on GLRT and MLE are expected to be useful for estimator based control systems because these bias estimators are driven by kalman filter innovation sequence inherently and give good estimates of fault magnitude that can be used for correcting the errorneous state estimates provided by kalman filter.

The bias estimation algorithm adopted in this study is as follows.

$$\hat{W}(k)=[I-L(k)S(k)]\hat{W}(k-1)+L(k)r(k)$$
$$L(k)=M^{-1}(k+1)[CV(k)+Es(k)]'R(k)$$
$$M^{-1}(k+1)=M^{-1}(k)+S(k)'[CP(k)C'+R(k)]^{-1}S(k)$$

In above equation,$\hat{W}(k)$ is estimate of fault magnitude, and related parameter matrices are computed by recursive equations described below.

$$S(k)=CU(k)+Ds$$
$$V(k)=U(k)-G(k)S(k)$$
$$U(k+1)=AV(k)+Dp$$

The estimation algorithm can be applied to estimate both process faults and sensor faults by following simple modification.

i) set Ds=0 for process fault
ii) set Dp=0 for sensor fault

With estimation result W(k), state estimation error of normal mode kalman filter caused by faults can be corrected by

$$\hat{X}(k)=\bar{X}(k)+V(k)\hat{W}(k)$$

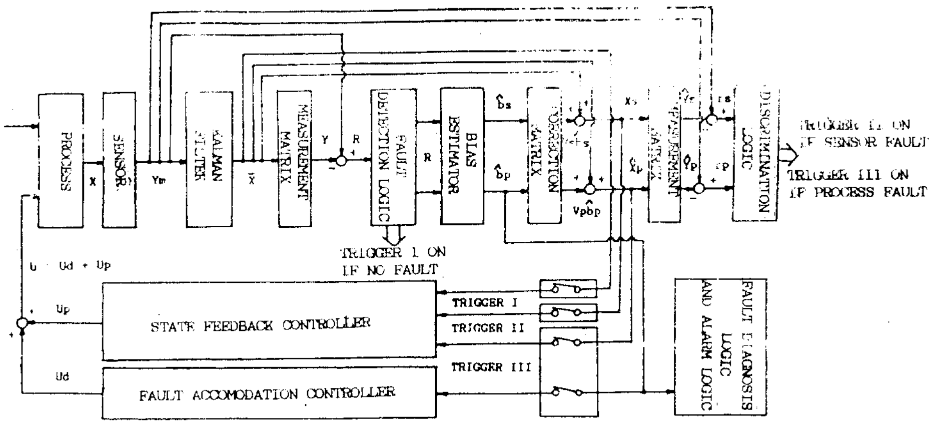


Fig.2 Proposed FTCS structure

### 3.3 Discrimination of process fault and sensor fault

The problem of detection,estimation and accomodation for process fault and sensor fault have been treated separately in all previous studies.However,performance deterioration of process(sensor) fault detection system due to small perturbation of sensor signal(process parameter) is inevitable.

Although a few process(sensor) fault detection schemes that are insensitive w.r.t. sensor (process) fault have been suggested, the problem still make its practical application very restrictive.

In this paper, the difficulty is removed by using the proposed FTCS structure.In the system shown in Fig.2 two bias estimator, one for process fault and the other for sensor fault, are deriven by innovation sequence of a kalman filter.The PFBEST(process fault bias estimator) estimates bias with the assumption that the detected fault symptoms are generated by process fault and the SFBEST( sensor fault bias estimator) estimate bias with assumption that the symptoms are generated by sensor fault. Then, errorneous state estimates are corrected by using these informations are reconstruct the Yp and Ys,When $\hat{Y}p(\hat{Y}s)$ is corrected output estimates with the assumption that process (sensor) fault is occured. Finally,$\hat{Y}p$ and $\hat{Y}s$ are compared with measured output value Ym.

And discrimination logic can be designed by considering the following with assumption that process fault and sensor fault can not be occured at the same instant.

1. If the detected symptoms are generated by any sensor fault,remaining measured output value are approximately equal to reconstructed output $\hat{Y}s$ while all the elements of $\hat{Y}p$, the reconstructed output provided by PFBEST,are quite different from Ym.
2. If the detected symptoms are generated by any process fault, reconstructed output values ( $\hat{Y}pi$,i=1,----,p) are approximately equal to Ym, while elements of Ys are quite different from Ym due to the fact that sensor fault assumption is false.
3. In the transient period, considerable overshoots may be contained in the bias estimates,since the overshoots increase the rate of invalid discrimination,it is desirable that the decision time is delayed until admissible informations can be obtained from the bias estimators.

According to above facts,an efficient reliable fault discrimination logic is suggested as follow.

if $\underset{i}{\mathrm{MIN}}[\mathrm{abs}(Ymi-\hat{Y}si)] > 1/p\sum_{i=1}^{p}\mathrm{abs}(Ymi-\hat{Y}pi)$,
 then process fault
if $\underset{i}{\mathrm{MIN}}[\mathrm{abs}(Ymi-\hat{Y}si)] < 1/p\sum_{i=1}^{p}\mathrm{abs}(Ymi-\hat{Y}pi)$,
 then sensor fault

where p is number of sensors, $\hat{Y}si$ is estimated value of Yi corrected by SFBEST and $\hat{Y}pi$ is estimated value of Yi corrected by PFBEST.

### 3.4 Compensation of fault effects

The compensation of sensor fault effects is quite simple. And it can be completed by sending the corrected state estimats $\hat{X}s=\bar{X}+Vs\hat{W}s$ instead of $\bar{X}$, state estimates provided by kalman filter,to the feedback channel.

In the cases of process fault, only the use of corrected state estimates $\hat{X}p=\bar{X}+Vp\hat{W}p$ instead of $\bar{X}$ is insufficient to completely remove the fault effects since the process fault means that undisirable (input) disturbance are introduced to actual plant. And it is inevitable to reconfigure the control system structure by introducing an additional fault accomodating controller or by actuating the stand-by component, if possible.

As a simple example,actuator fault can be compensated by adding the additional control input $\hat{U}=-B^{\#}Qp\hat{W}p$ to the original control input $U=K\hat{X}p$ where $\hat{W}p$ is the estimated fault magnitude provided by PFBEST.Any disturbance accomodation control scheme can be adopted for this purpose.

## 4. Appication

In order to show the performance of the proposed FTCS, it is adopted to 3 tank level control system.

Fig.3,4 show the bias fault estimates and the control system responses when actuator bias fault occured at 40 sec. And Fig.5,6 show the bias fault estimates and the responses of FTCS when sensor fault occurred at 40 sec.

As shown in the simulation results, effects of fault are effectively removed by introducing the proposed FTCS structure where performance of the conventional control system badly deteriorated by the fault. It should be noticed that the proposed FTCS has the ability to discriminate and to compensate the sensor fault and process fault automatically while almost all of the FDI system treats them separately.

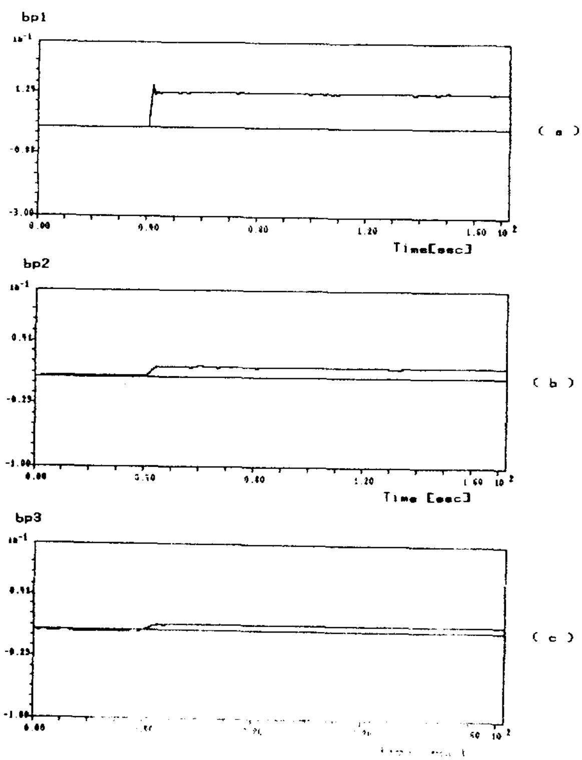


Fig.3 Estimation of fault magnitude when actuator 1 fault

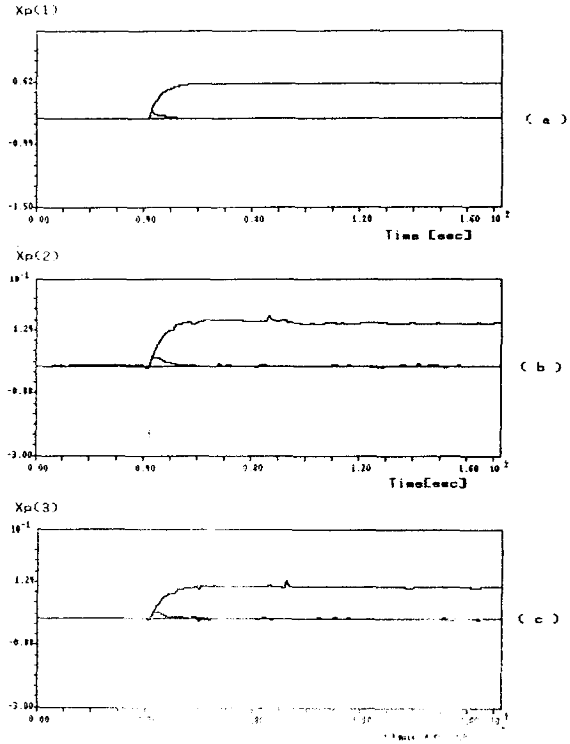


Fig.4 FTCS responces when actuator 1 fault

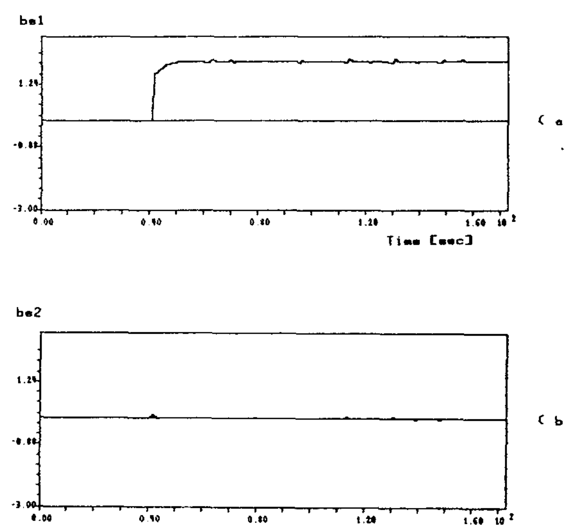


Fig.5 Estimation of fault magnitude when sensor 1 fault

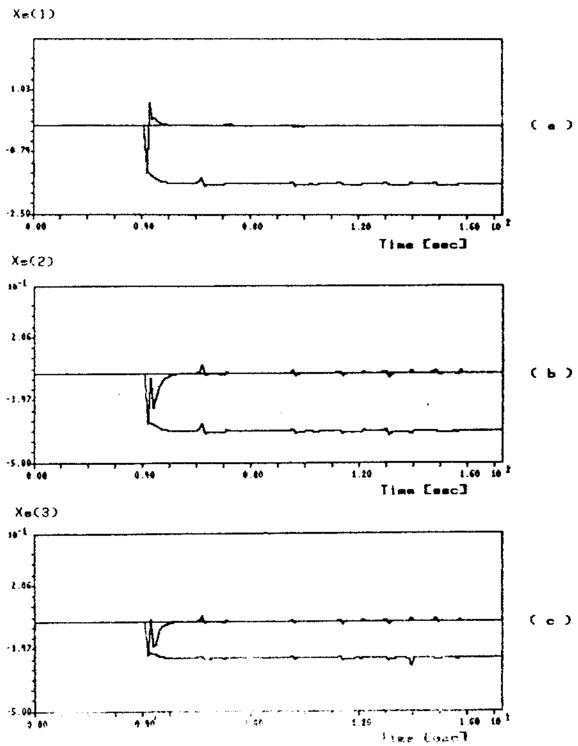


Fig.6 FTCS responces when sensor 1 fault

5.Conclusions

In this paper, a fault detection scheme and a FTCS that can be adopted for inhancing the functional reliability of estimator based state feedback control system are proposed.

The FTCS is composed of;

- kalman filter innovation based fault detection logic
- two bias estimator, one for sensor fault and the other for process fault,driven by kalman filter innovation sequence
- discriminating logic for discriminating sensor fault and process fault by the use of information provided by bias estimators
- fault accomodating control structure for sensor/process faults

Main contribution of the proposition are as follows.

- The FDS not only resolves well known sensitivity problem that makes application of existing AR based FDS difficulty but also can detect and discriminate sensor/ process faults.
- The proposed FTCS can performs original control objectives without considerable loss of control performance in the face of sensor/process faults because the system promptly accomodate effects of faults by reconfiguring control structure, while all existing FTCS treat only one type of faults.

6.Reference

1.A.S.Willsky,"A survey of design methods for failure detection in dynamic systems", Automatica,Vol.12,1976

2.W.C.Merril,"Sensor failure detection for jet engines using analytical redundancy",J. Guidance,Vol.8,No.6,1985

3.R.N.Clark,"The dedicated observer approach to instrument failure detection", Proc. of 18th IEEE CDC. Florida,Dec.1979

4.B.R.Upadhyaya,"Sensor failure detection and estimation", Nucl. Safety, Vol.26,No.1, 1985

5.J.E.White and J.L.Speyer,"Detection filter design by eigensystem assignment,"American Control Conf.,1985

6.J.L.Tylee,"Real-time instrument failure detection in the LOFT pressurizer using functional redundancy,"EG&G Idaho,Inc.,1982

7.A.Madiwale and B.Friedland, "Comparison of innovation based analytical redundancy methods," Proc. American Control Conf.,1983

8.E.Y.Chow and A.S.Willsky,"Analytical redundancy and the design of robust failure detection systems", IEEE Trans.Auto.Contr., Vol.AC-29,No.7,1984

9.A.Ray and M.Desai," A redundancy management procedure for fault detection and isolation", Trans. ASME, J.Dynamic Sys.,Meas., Contr.,Vol.108,1986