Proceedings of the International Conference on Aerospace Science and Technology
26 - 28 June 2008, Bangaloire, India

INCAST 2008-027

ADAPTIVE NEURO-FUZZY BASED CONTROL SURFACE FAULT DETECTION AND RECONFIGURATION

Shobha. R. Savanur [1], Sudesh K. Kashyap [2] and J. R. Raol (Retd.) [3]

[1] Asst. Prof. Dept of E & E, B.L.D.E.A's College of Engineering and Technology, Bijapur, India,
[2,3] Scientists, Flight Mechanics and Control Division, National Aerospace Laboratories, Bangalore, India

ABSTRACT: The aircraft becomes unstable due to fault in actuator or if there is a loss of control surface effectiveness due to damaged or blown surfaces. One of the popular methods to detect and reconfigure the surface fault is model based approach e.g. Extended Kalman filter (EKF). Using EKF, the parameters of control distribution matrix are estimated as augmented states of the system which are subsequently used to compute feedback gain to reconfigure the impaired system In this paper, detection and reconfiguration of surface fault in elevator of an aircraft is demonstrated using ***Adaptive Neuro - Fuzzy Inference System*** ANFIS . Under this approach, i) ANFIS is trained using time history of i/o data i.e. inputs as errors between nominal (healthy) states of aircraft and its faulty states (noise free) for different fault conditions and output as parameters of control distribution matrix and ii) trained ANFIS is subsequently used to estimate the parameters of control distribution matrix for the actual fault condition and the reconfiguration is carried out by computing new feedback gain using pseudo-inverse technique.

1. INTRODUCTON

A Fault Tolerant Control System (FTCS) is a control system that possesses the ability to accommodate system component (actuator, control surface, mechanical link, etc.) faults automatically. Such a control system is capable of maintaining overall closed loop stability and performance in the event of faults. In this paper, the effect of impaired control surfaces is measured by the amount of deviation of control effectiveness factors from their normal values. This is achieved by multiplying the components of the control distribution matrix of the state model by a factor of effectiveness. Model based techniques are commonly used techniques and the most popular method to detect and reconfigure the surface fault is using Extended Kalman filter (EKF) [1]. In the method using EKF, the state matrix is augmented The true parameters, estimated parameters and feedback gain (computed using Linear Quadratic Regulator (LQR) algorithm - under healthy condition) are then used to compute feedback gain to reconfigure the impaired system. The limitation of this approach is that the model of the system should be known accurately which is not always the case for e.g. some times models are very complex to be mathematically formulated and may be highly non-linear and time varying. In such situation, the better option would be to follow the non-model or data driven methodology. One such method is ***Adaptive Neuro - Fuzzy Inference System*** (ANFIS)[2] wherein Fuzzy logic is used to predict or estimate the system states used in control law to achieve desired system response. The performance of Fuzzy logic is totally based on how accurately the rules are known and they can be either obtained from experts or fetched from the input/output data of plant. In ANFIS approach rules are automatically generated using i/o data and parameters defining the membership functions are tuned using Neural Network (NN). In this paper, detection and reconfiguration of surface fault in elevator of an aircraft is demonstrated using ANFIS (see fig. 1 for proposed architecture). In ANFIS scheme, data at present instant is smoothened by averaging the previous samples over a selected window length. ANFIS is trained using inputs as errors between nominal states of aircraft and its faulty states and it is then used to estimate factor of effectiveness and hence the elements of control distribution matrix under faulty condition. The reconfiguration is then carried out by computing new feedback gain using Pseudo inverse technique [3]. In section 2.1 identification of the control distribution matrix using EKF is dealt with. In section 2.2 control reconfiguration algorithm is discussed. Section 3 deals with surface fault detection and accommodation using ANFIS. Simulation results are presented in section 4.

2. EXTENDED KALMAN FILTER IMPEMENTATION

Here an actuator surface fault detection algorithm based on EKF is used for estimation of elements of control matrix [3].The state space equation of the longitudinal motion of an aircraft is considered which is of the form:

$$\dot{x} = Ax + Bu + \Gamma w \tag{1}$$

where $x = [u', w', q', \theta]$, $u = \delta_E$, w is a white Gaussian process noise with zero mean and covariance Q, Γ is a perturbation noise transition matrix. The state vector 'x' is obtained by integrating eq. (1) using runge-kutta fourth order integration method. Then measurement equation is obtained as:

$$z = H x + v \tag{2}$$

where, z is measurement vector and v is a white Gaussian measurement noise with zero mean and covariance R.

2. 1. Identification of The Control Distribution Matrix

Fig.1 shows the block diagram structure of the identification algorithm. The $b_{i,j}\ (i = 1,n ; j = 1,m)$ elements of the control distribution matrix B are identified using EKF to detect the actuator surface faults. For this purpose, the state vector x is augmented as follows:

$$x_a = [x_1, x_2, ..., x_n, b_{11}, b_{12}, ..., b_{ij}, ..., b_{nm}] \tag{3}$$

and the augmented dynamic system can be represented by

$$x_a(k+1) = \tilde{F}(k+1,k)x_a(k) + \tilde{\Gamma}(k+1,k)w(k) \tag{4}$$

and the measurement eq. turns out to be

$$\tilde{z}(k) = \tilde{H}(k)x_a(k) + v(k) \tag{5}$$

where x_a is an (n+nm) dimensional augmented system state vector, $\tilde{F}(k+1,k)$ is a (n + nm) by (n +nm) augmented system matrix, $\tilde{\Gamma}(k+1,k)$ is an (n + nm) by (n + nm) augmented perturbation noise transition matrix, $\tilde{z}(k)$ is an s by nm dimensional system measurement matrix. The matrix $\tilde{F}$ is the discrete form of the system matrix $\tilde{A}$. where,

$$\tilde{A} = \begin{bmatrix} A_{nxn} & \begin{bmatrix} u_1 \ldots u_m\, 0 \ldots\ldots\ldots\ldots 0 \\ 0 \ldots 0 \quad u_1 \ldots u_m\, 0 \ldots 0 \\ \ldots\ldots\ldots\ldots\ldots\ldots \\ 0 \ldots 0 \quad \ldots 0\, u_1 \ldots u_m \end{bmatrix} \\ 0_{nm\,x\,n} & I_{nm\,x\,nm} \end{bmatrix}$$

The discrete form of $\tilde{A}$ is computed as :

$$\tilde{F} = e^{\tilde{A}T} \tag{6}$$

The Extended Kalman Filter estimation algorithm is as follows:

State and Covariance Propagation

$$\hat{x}_a(k,k-1) = \int \tilde{A}\hat{x}_a(k-1,k-1) \tag{7}$$

$$P(k,k-1) = \tilde{F}(k,k-1)P(k-1/k-1)\tilde{F}^T(k,k-1) + \tilde{\Gamma}(k,k-1)Q(k-1)\tilde{\Gamma}^T(k,k-1) \tag{8}$$

Measurement Update

$$\hat{x}_a(k,k) = \hat{x}_a(k,k-1) + K(k)\gamma(k) \tag{9}$$

where, $\gamma(k) = \tilde{z}(k) - \tilde{H}(k)\hat{x}_a(k,k-1)$ is innovation sequence

$$K(k) = P(k/k-1)\tilde{H}^T(k)\,[\,\tilde{H}(k)P(k/k-1)\tilde{H}^T(k) + R(k)]^{-1} \tag{10}$$

$$P(k/k) = [\,I - K(k)H(k)]\,P(k/k-1) \tag{11}$$

2.2 Control Reconfiguration Algorithm

State feedback [4] can be used to improve the stability properties of the control system as follows: Consider the state eq.

$$\dot{x} = Ax + Bu \tag{12}$$

Then the state feedback control law is given by

$$u = -Kx \tag{13}$$

where $K = [\,k_1\,k_2\,,...,k_n\,]$ is a constant state feedback gain matrix. If this state feedback control law is connected to the eq. (12), the close loop system is described by the state eq.:

$$\dot{x} = (A - BK)x \tag{14}$$

Once the feedback control law is designed for fault free system, then under actuator fault condition, control reconfiguration can be realized for the impaired aircraft control system. There are several approaches for reconfiguration such as linear quadratic regulator (LQR), Eigen structure assignment (EA), pseudo inverse, neural networks and fuzzy logic etc. Pseudo inverse technique [3] is adopted here. The technique can be stated as follows:
Let the dynamics of the closed system be:

$$\dot{x}_0 = (A - B_0K_0)\,x_0 \tag{15}$$

After an actuator surface fault occurs, the dynamics may be represented as:

$$\dot{x}_i = (A - B_iK_i)\,x_i \tag{16}$$

To ensure the closed loop dynamics is the same, as before, the following condition must be satisfied:

$$B_0\,K_0 = B_iK_i \tag{17}$$

where, B_0 is unimpaired control distribution matrix, K_0 is gain matrix for unimpaired system and

B_i is estimated (EKF) impaired control distribution matrix and K_i is gain matrix for impaired system.

The gain matrix for impaired system is obtained as:

$$K_i = B_i^{\#} B_0 K_0 \tag{18}$$

where the matrix $B_i^{\#}$ is the pseudo inverse of the matrix B_i.

3. SURFACE FAULT DETECTION AND RECONFIGURATION USING ANFIS

The concept of model based scheme for surface fault detection and accomodation is extended to non-model based approach -ANFIS. The architecture used to realize the entire scheme is shown in Fig. 2. Under this scheme, MATLAB based functions 'GENFIS' and 'ANFIS' [2] are used. The ANFIS scheme is broadly divided into two parts In the first part, ANFIS is trained using inputs as errors between nominal states of aircraft and its faulty states and output as factor of effectiveness for control surface. The state errors are computed using filtered measured data and nominal states. The filtering is carried out using moving average technique, wherein, the measured data at present instant is smoothened by averaging the previous samples over a selected window length. Then, in the second part the factor of effectiveness [5] for any fault condition is determined using the trained ANFIS. The elements of control distribution matrix under faulty condition are therefore determined by multiplying the factor of effectiveness with nominal B-matrix elements. The reconfiguration is then carried out with state feedback by computing new feedback gain using Pseudo inverse technique as in EKF method.

4. SIMULATION RESULTS

In the simulation, the longitudinal dynamics of a delta-4 [6] aircraft is considered. The state space matrices for the given model are:

$$A = \begin{bmatrix} -0.033 & 0.0001 & 0.0 & -9.81 \\ 0.168 & -0.367 & 260 & 0.0 \\ 0.005 & -0.0064 & -0.55 & 0.0 \\ 0.0 & 0.0 & 1.0 & 0.0 \end{bmatrix}; \quad B = \begin{bmatrix} 0.45 \\ -5.18 \\ -0.91 \\ 0.00 \end{bmatrix}; \quad C = I(4x4) \quad \Gamma = I(4x4)$$

The augmented state vector is given by $x_a = [u', w', q', \theta, b_1, b_2, b_3]^T$. where, control input $u = \delta_E$, and control matrix elements $b_1 = 0.45,\ b_2 = -5.18,\ b_3 = -0.91$. To simulate the fault, factor of effectiveness is changed to 60% of the normal value. Hence B-matrix elements are multiplied by 0.6.

$$\tilde{A} = \begin{bmatrix} -0.033 & 0.0001 & 0.00 & -9.81 & u & 0 & 0 \\ 0.168 & -0.387 & 260 & 0.00 & 0 & u & 0 \\ 0.005 & -0.0064 & -0.55 & 0.00 & 0 & 0 & u \\ 0.000 & 0.000 & 1.00 & 0.00 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}; \tilde{H} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix}; \tilde{\Gamma} = I(7x7)$$

Initial conditions:

$$x_a(0) = [0.0001\ \ 0.0001\ \ 0.0001\ \ 0.0001\ \ b_1\ \ b_2\ \ b_3\ ], \quad P(0) = \text{diag}\,[(x_a(0) - 0.9 * x_a(0))]^2$$

Fig 3 shows the actual and estimated control matrix elements by EKF and ANFIS schemes using noisy measured data In ANFIS scheme, state error is computed using filtered measured data and nominal states. The filtering is carried out using moving average technique with a window length of 20. It is seen that the estimated parameters are close to the true values for both the schemes. The delay in estimation is noticed in both the schemes but the estimated values settle to the true values much earlier in ANFIS scheme. Fig.4 shows the error in estimated states for the cases with and without reconfiguration. From the plots it can be interpreted that reconfigured aircraft states converge to the true states as desired and the error is less in ANFIS scheme. The proposed scheme of ANFIS as compared to EKF yields better estimate of parameters used for reconfiguration of impaired system.

ACKNOWLEDGMENT
First author acknowledges Mrs Padma Madhuranath, Head, Flight Mechanics and Control Division, National Aerospace Laboratories, Bangalore, for providing an opportunity to work in her division. Authors also acknowledge Dr Ambalal.V.Patel, Senior Scientist, IFCS, Directorate, Aeronautical Development Agencies, Bangalore for his technical inputs and discussions.

REFERNCES

1. Chingiz. Hajiyev and Fikret Caliskan Fault Diagnosis and Reconfiguration in Flight Control Systems, Kluwer Academic Publishers Boston/Dordrecht/London, 2003.
2. Shobha R Savanur, Sudesh K Kashyap, J.R. Raol, Adaptive Neuro-Fuzzy Based Sensor Fault Detection, Isolation and Reconfiguration, Proceeding of National System Conference, MIT, Manipal, Nov. 14-15, 2007.
3. Ch. M. Hajiyev, F. Caliskan, Integrated sensor/actuator FDI and reconfigurable control for fault tolerant flight control system design, The Aeronautical Journal, Sept 2001
4. M. Gopal, Digital control and State Variable Methods, Tata McGraw-Hill publishing company Limited, New Delhi,2003.
5. N. Eva Wu, Youmin Zhang and Kemin Zhou, Detection, estimation, and accommodation of loss of control effectiveness, International Journal of Adaptive Control and Processing, 2000;14;775-795.
6. McLean .D.,Automatic Flight Control Systems, Prentice Hall International(UK),1990.

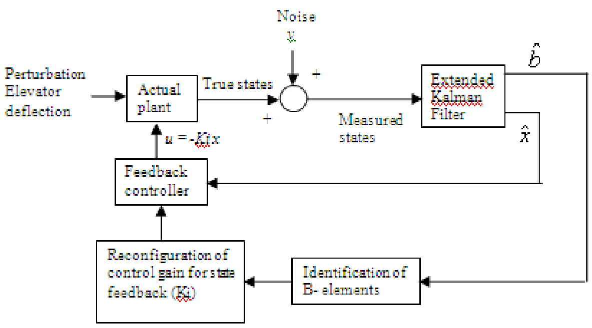

Fig. 1 Schematic for control surface fault detection and reconfiguration using EKF

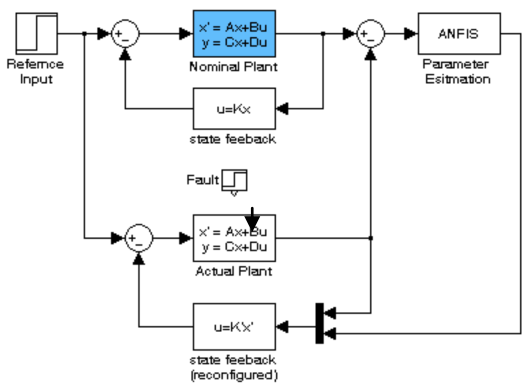

Fig. 2 Schematic for control surface fault detection and reconfiguration using ANFIS

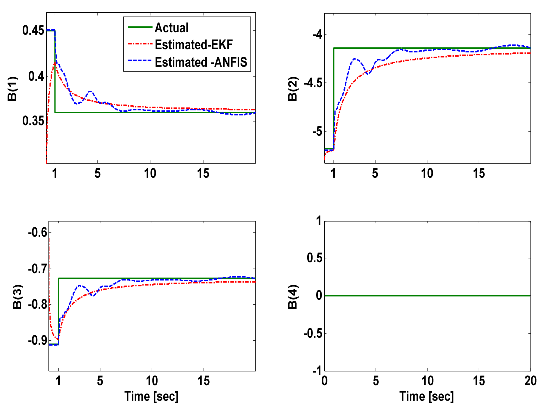

Fig. 3 Estimated and true values of control distribution matrix

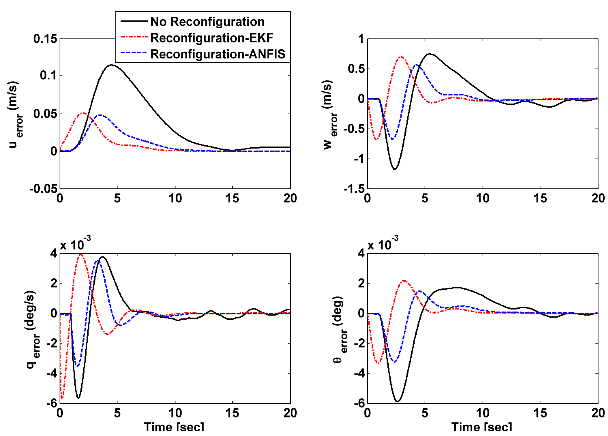

Fig. 4 Comparison of states errors