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Model-based fault detection and control design – Applied to a pneumatic Stewart-Gough platform

K.S.Grewal ^{a*}, R. Dixon ^a, J. Pearson ^b

^a Control Systems Group, Loughborough University, Loughborough, Leicestershire, UK.

^b SEIC, BAE Systems, Holywell Park, Loughborough, Leicestershire, UK.

Abstract: This paper discusses research carried-out on the development and validation of a model-based fault detection and isolation (FDI) system for a pneumatically actuated Stewart platform arrangement. The FDI scheme is based on combining parity-equation and Kalman filter based techniques. The parity and Kalman filter equations are formulated and used to generate residuals that, in turn, are analysed to determine whether faults are present in the system. Details of the design process are given and the experimental results are compared. The results demonstrate that both approaches when combined can successfully detect and isolate and in some cases accommodate faults associated with the sensors, actuators (servo-valves and piping) and the pneumatic system itself. The work is part of a BAE SYSTEMS' sponsored project to demonstrate advanced control and diagnosis concepts on an industrial application.

Keywords: Fault detection; modelling; isolation; residuals; pneumatic; parity equation; Kalman filter; Stewart-Gough platform.

Introduction

The problem of fault detection and isolation (FDI) in dynamic processes has received great attention, and a large variety of methodologies have been studied and developed based upon both physical and analytical redundancy. In the first case, the system is equipped with redundant physical devices, like sensors and actuators, so that if a fault occurs, the redundant device replaces the functionality of the faulty one.

Model-based Fault Detection and Isolation (FDI) utilizes the principles of analytical redundancy to first detect deviations from normal behaviour in a system, and then to isolate the particular component that has a fault. Useful surveys of these and other useful FDI methods can be found in Patton, (1997) and Venkatasubramaniam et al, (2003). Fig.1 depicts a schematic structure of a typical FDI procedure using analytical redundancy. The analytical approach requires that a residual generator perform a validation of the nominal relationships of the system, using the actual input, u , and the measured output, y .

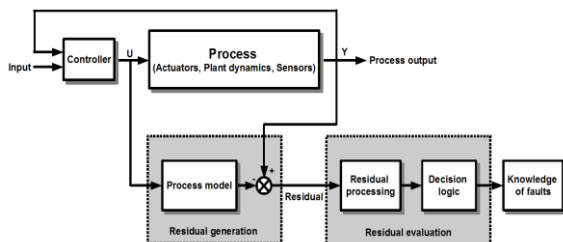


Fig.1: Schematic structure of a FDI procedure

This is usually achieved by expressing the normal

system operation in terms of system models. This modelling procedure is necessary to have relationships between various known or measured variables. The work described in this paper aims to demonstrate FDI as part of a fault tolerant control system on a Stewart-Gough platform comprising six pneumatic actuators. The FDI scheme is designed to detect and isolate pneumatic and sensor faults using model-based fault detection and isolation. As far as the authors are aware no such work has been carried out on a pneumatic system.

2. Experimental set-up

Stewart-Gough platforms (Fig.2) are generally of a mechanical design used mainly for position control. The design is a parallel mechanism consisting of a rigid body mobile plate, connected to a fixed base plate and is defined by at least three stationary points on the fixed (grounded) base connected to six independent legs. The six variable length legs are connected to both the base and top plate by universal/ball joints in parallel located at both ends of the six legs. This allows for the length of each leg to be varied. The linear extension and retraction of the six cylinders gives the platform six degrees of freedom positioning capabilities.

The design concept of the FDI scheme for the full Stewart-Gough platform is first developed using a single cylinder set-up. This modular approach is adopted so that a robust fault tolerant control scheme can be developed off-line (i.e. not attached to the Stewart-Gough platform). This modular approach is made possible as the Stewart-Gough platform design uses six identical pneumatic cylinders. The single

actuator set-up is illustrated schematically in Fig.3. Initial work was reported in Grewal, (2008).

Flow from the air supply is governed by the servo valve which gives a flow into each of the cylinder chambers that is proportional to the voltage applied. This results in a differential pressure across the cylinder piston causing it to move. The pressures are measured via pressure sensors located between the valve and cylinder chambers. The overall aim is position control, so this is measured via two Linear Resistive Transducers (LRT) mounted in the cylinder. The second position sensor provides a means of redundancy if the primary position develops a fault or fails. The schematic also shows the xPC Target coupled with Matlab/Simulink, which provides a real-time environment for running the control and fault detection algorithms. The faults considered for this paper are position/pressure sensor faults, leaks in pneumatic system, blockages in pneumatic system and actuator faults.



Fig.2. Stewart-Gough platform set-up

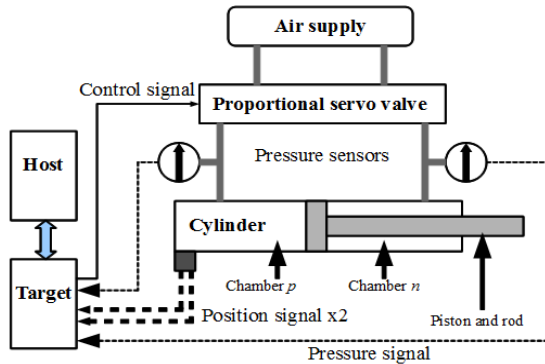


Fig.3. Schematic of experimental set-up

3. Modelling of pneumatic system

The relationship between the air mass flow and the pressure changes in the chambers is obtained using energy conservation laws (first law of thermodynamics), and the force equilibrium is given by Newton's second law. The overall pneumatic

system can be approximated by equations (1-3), see for example Grewal *et al* (2008). Where P_p is the pressure in chamber p , P_n is the pressure in chamber n , V_p is the air volume in chamber p , V_n is the air volume in chamber in n , T_s is the operating temperature, γ is the ratio of specific heat, and R is the universal gas constant. M is the piston mass, A is the bore area, x is the position of the piston, and F_f represents the frictional forces. K is the servo valve constant and v is the voltage input.

$$\dot{P}_p = -\frac{\gamma A^2 P_p}{V_p} \dot{x} + K \frac{\gamma R T_s}{V_p}, \dot{P}_n = -\frac{\gamma A^2 P_n}{V_n} \dot{x} + K \frac{\gamma R T_s}{V_n} \quad (1)$$

$$\dot{x} = \frac{A}{M} (P_p - P_n) - \frac{F_f}{M} \dot{x} \quad (2)$$

4. Design of FDI scheme

Fig.1 shows the generic structure of the model-based fault detection scheme. The method consists of detecting faults on the process which includes actuators, components and sensors, based on measuring the input signal $U(t)$ and the output signal $Y(t)$. The detection method uses models to generate residuals $R(t)$. The residual evaluation examines the residuals for the likelihood of faults and a decision rule is applied to determine if faults have occurred. In this paper the process model can be based on either parity equations or Kalman filters. The main function of the FDI scheme is to detect faults typical in pneumatic system. Once these faults are detected the FDI scheme isolates the fault. The two approaches are discussed below.

4.1 The Parity Equation Method

The idea of the parity approach is to rearrange the model structure to achieve the best fault isolation (i.e. so that the effect of faults is far greater than that of the other uncertainties). The desired properties for the residual signal are $R(t) \neq 0$ if $f(t) \neq 0$. Where R is the residual and f is the fault. The pneumatic control loop (Fig.4) scheme, which contains the following elements: The controller $C(s)$, the proportional valve $GA(s)$, the pneumatic actuator $GP(s)$, and the sensor $GS(s)$. The proportional valve fault $Fa(s)$ and the sensor fault $FS(s)$ can have dynamics, which are modelled by the transfer functions $Ha(s)$, and $HS(s)$. In addition to the position (feedback) sensor, pressure sensors are included in the system to read pressure from each chamber of the actuator. These are not included in the closed loop system, and are shown as $Pp(s)$ and $Pn(s)$ respectively. With the pressure sensor faults, shown as $FPp(s)$ and $FPn(s)$, again having dynamics modelled by the transfer functions $HPp(s)$ and $HPn(s)$. The following relationships (equations) can be derived.

$$XS(s)=[GS(s)+HS(s)FS(s)][GA(s)U(s)GP(s)+Ha(s)Fa(s)GA(s)GP(s)] \quad (3)$$

$$Pn_{act}=[U(s)GA(s)+Ha(s)Fa(s)][Pn(s)+HPn(s)FPn(s)] \quad (4)$$

$$Pp_{act}=[U(s)GA(s)+Ha(s)Fa(s)][Pp(s)+HPp(s)FPp(s)] \quad (5)$$

$$U(s)=C(s)(V(s)-XS(s)) \quad (6)$$

Residuals are formulated from equations (3) to (5) as follows

$$R_1=XS(s)-GS(s)GP(s)GA(s)U(s)=HS(s)FS(s)+Ha(s)Fa(s) \quad (7)$$

$$R_2=Pn_{act}-U(s)GA(s)Pn(s)=Ha(s)Fa(s)+HPn(s)FPn(s) \quad (8)$$

$$R_3=Pp_{act}-U(s)GA(s)Pp(s)=Ha(s)Fa(s)+HPp(s)FPp(s) \quad (9)$$

Where, $GA(s)$ is modelled by the equations (1) and $GP(s)$ by equation (2). It is assumed that the fault and sensor transfer functions are all instantaneous.

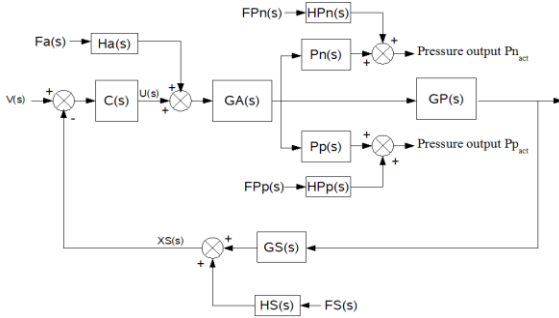


Fig.4. Pneumatic closed loop scheme with intended faults

4.2. Observer approach (Kalman filter)

The fundamental idea of the observer approach is to reconstruct the outputs of the system from the measurements or subsets of measurements with the aid of observers or Kalman filters using the estimation error or innovation (Frank, 1990). This estimation error or innovation is used as a residual for the detection and isolation of faults. Given a system:

$$\dot{x} = Ax + Bu + Gw \text{ (State eq)} \quad (10)$$

$$y = Cx + Du + Hw + v \text{ (Measurement eq)} \quad (11)$$

Where u is the input, w is the process noise, v is the measurement white noise with $E(w w^T) = Q$, and $E(v v^T) = R$. It is also assumed that the state and measurement noise is uncorrelated, that is, $E(w v^T) =$

0. An optimal estimate of y , \hat{y} can be provided by the Kalman filter equations:

$$\dot{\hat{x}} = A\hat{x} + Bu + L(y - C\hat{x} - Du) \quad (12)$$

$$\hat{y} = C\hat{x} + Du \quad (13)$$

Where in practice the weightings for process and measurement noise (Q and R respectively) are chosen heuristically using engineering judgement to provide a trade-off between sensitivity to faults, and the likelihood of false alarms. The steady-state Kalman filter gain L is determined by solving an algebraic Riccati equation. This estimator uses the known inputs u and the measurement y to generate the output and state estimates \hat{y} and \hat{x} .

$$\begin{bmatrix} \dot{\hat{P}}_d \\ \dot{\hat{x}} \\ \dot{\hat{x}} \end{bmatrix} = \begin{bmatrix} 0 & 0 & a-b \\ 0 & 0 & 1 \\ \frac{A}{M} & 0 & -\frac{F_f}{M} \end{bmatrix} \begin{bmatrix} \hat{P}_d \\ x \\ \dot{x} \end{bmatrix} + \begin{bmatrix} c-d \\ 0 \\ 0 \end{bmatrix}$$

$$y_{pos} = [0 \quad 1 \quad 0] \begin{bmatrix} \hat{P}_d \\ x \\ \dot{x} \end{bmatrix}$$

$$y_{pd} = [1 \quad 0 \quad 0] \begin{bmatrix} \hat{P}_d \\ x \\ \dot{x} \end{bmatrix}$$

Where

$$P_d = P_p - P_n, \quad a = -\frac{\gamma AP_p}{V_p}, \quad b = \frac{\gamma AP_n}{V_n}, \quad c = K \frac{\gamma RT_s}{V_p}, \quad d = -K \frac{\gamma RT_s}{V_n}$$

In designing the Kalman filter approach only the sensed outputs are considered. These are position and pressure difference outputs. The residual equations are:

$$R_4 = y_{pos} - C_{pos} \hat{x}_1 \quad (15)$$

$$R_5 = y_{pd} - C_{pd} \hat{x}_2 \quad (16)$$

Where

$$C_{pos} = [0 \quad 1 \quad 0], \quad C_{pd} = [1 \quad 0 \quad 0]$$

A voter scheme is used to minimize switching transients since the isolation of faulty signals is achieved through a continuous numerical weighting (Broen, 1975). The voter scheme continuously determines the output in a manner which discriminates against the erroneous signal in favour of the other channels. The general form (Fig. 5) of the voter scheme is determined using a weighted average of its inputs.

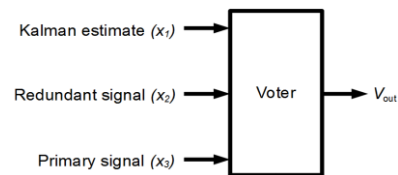


Fig.5. Voter scheme

Where V_{out} is defined as

$$V_{out} = \frac{w_1 x_1 + w_2 x_2 + w_3 x_3}{w_1 + w_2 + w_3} \quad (17)$$

The numerical properties of the voting scheme is given by letting

$$\hat{w}_j = \frac{w_j}{w_1 + w_2 + w_3}, \quad j = 1, 2, \text{ and } 3$$

Where w_j is given by

$$w_1 = \left[1 + \left(\frac{x_1 - x_2}{a} \right)^2 \left(\frac{x_1 - x_3}{a} \right)^2 \right]^{-1} \quad (18)$$

$$w_2 = \left[1 + \left(\frac{x_2 - x_1}{a} \right)^2 \left(\frac{x_2 - x_3}{a} \right)^2 \right]^{-1} \quad (19)$$

$$w_3 = \left[1 + \left(\frac{x_3 - x_1}{a} \right)^2 \left(\frac{x_3 - x_2}{a} \right)^2 \right]^{-1} \quad (20)$$

Where a is the tolerance parameter and is the measure of allowable noise level in a given channel. It should be noted the above voting scheme deals with three sensor inputs. The Kalman filter estimate (x_3) and the redundant signal (x_2), the third signal is taken from the primary signal (x_1).

Table 1 shows the theoretical fault signatures using the parity equations and Kalman filter approaches of the pneumatic system for various faults. These signatures arise from the formulation of parity equations and the structure of the observer scheme. Where the parity equations residuals (R_1 , R_2 and R_3), are given in equations (7), (8), and (9). The Kalman filter residuals (R_4 and R_5) are given by equations (14), (15), and (16). From Equations (18), (19), and (20) further residuals can be generated. Basically, if no faults occur the weighted output is 1 and if a fault occurs in either of the three signals (x_1 , x_2 and x_3) (\hat{w}_j) $\rightarrow 0$. In order to comply with the Kalman and parity residuals the weighted average outputs are inverted (i.e. fault =1, and no fault = 0). The residuals are evaluated by processing the residual output to acquire the root mean square (RMS) of the value over a moving window of N samples (Dixon, 2004) as shown:

$$R_{i,RMS}(k) = \sqrt{\frac{\sum_{j=k-N}^k R_{ij}^2}{N}} \quad i = 1, 2, 3, 4, 5 \quad (21)$$

Where $R_i(k)$ is the value of the i^{th} residual at the k^{th} sample. Subsequently, the residual RMS value is compared with a predetermined fault detection threshold

5. Experimental results

In order to demonstrate the FDI scheme using parity equations and Kalman filter approaches a

number of experiments were carried out on the Stewart–Gough platform (Fig.3) However, for this paper only an actuator fault is considered. The demand input to the system is a series of motions that represent the 6-degrees of movement. When a fault occurs, appropriate (safe) actions need to be taken. For the position sensor fault, accommodation is possible. This is also the case for the pressure sensor. For the other faults the appropriate action is to shutdown the rig.

5.1 Actuator fault (control signal loss)

A fault $Fa(s)$ (see Fig.4) is applied to the proportional valve at 20s. The fault injected is that the control signal has been disconnected. This is physically achieved by means of a switch. Fig.6 shows the time histories of this experiment. Applying the disconnection fault to the control signal of the proportional valve has an effect on the parity residual (R_1), this raises the fault flag. The fault has an effect on the pressure sensor parity residuals (R_2 and R_3). Both position and pressure difference Kalman residuals (R_4 and R_5) are affected by the actuator fault and their fault flags are raised. Residuals w_1 , w_2 and w_3 are not affected and the respective fault flags remain low. This agrees with the fault signatures detailed in Table 1. With this particular fault accommodation is not available as the control signal to the servo valve of pneumatic cylinder 2 is lost. This means that the desired positional movement of the rig is inadequate. From here (21.62s) the safety sequence is activated and the platform is made safe (i.e. brought back to its rest position).

From both methods (Kalman and parity) the Kalman approach tracks the fault better with a faster fault detection response time. Overall, it is clear that the parity equations and the Kalman filter approach can detect an actuator fault.

Table 1: Residual fault signatures

Res	Potential faults						
	Act	Plant	(x_3)	(x_2)	(x_1)	Press sen (p)	Press Sens(n)
R_1	1	1	1	1	1	0	0
R_2	1	1	0	0	0	1	0
R_3	1	1	0	0	0	0	1
R_4	1	1	1	1	1	0	0
R_5	1	1	0	0	0	1	1
w_1	0	0	0	0	1	0	0
w_2	0	0	0	1	0	0	0
w_3	0	0	1	0	0	0	0

6. Conclusions

The paper has described the design, test and evaluation of fault detection in a closed loop system for an industrial standard pneumatic system. The pneumatic system model has been presented and manipulated. Parity equations and the Kalman filter

approach have been used to generate residuals for the purpose of fault detection. An actuator fault (control signal loss) scenario has been considered, which is typical for a pneumatic operating system. The results show that using the described parity equation and Kalman filter methods; including the weighted average voting scheme (for position sensor faults), fault detection and isolation was possible from the available measurements. An important reason for selecting the parity equation approach is that it is a relatively simple design approach. Basic equations of the system are used directly and compared to the system. The Kalman filter approach is more complex as the scheme takes into account noise variances. Other faults have been considered which include leak faults, air blockages, position sensor faults and pressure sensor faults. However, their results are not presented due to space limitations. The authors believe that applying the three schemes allows for better fault detection and fault isolation.

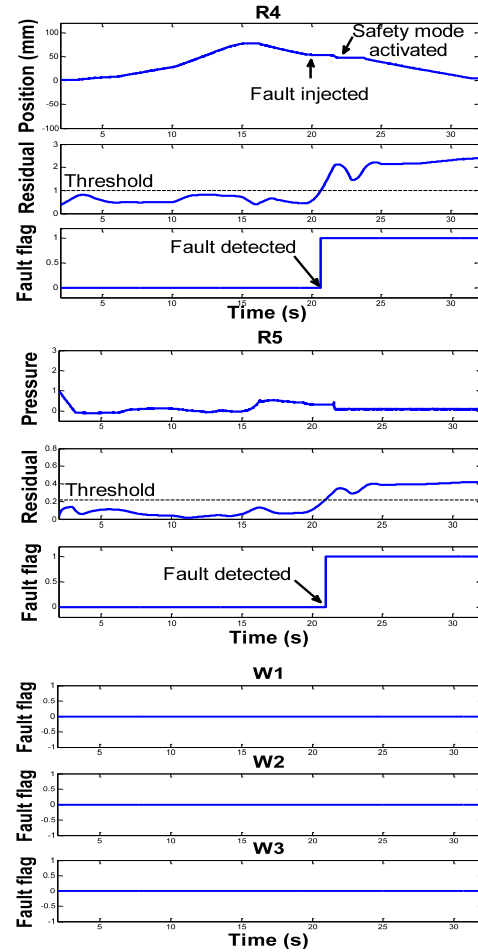
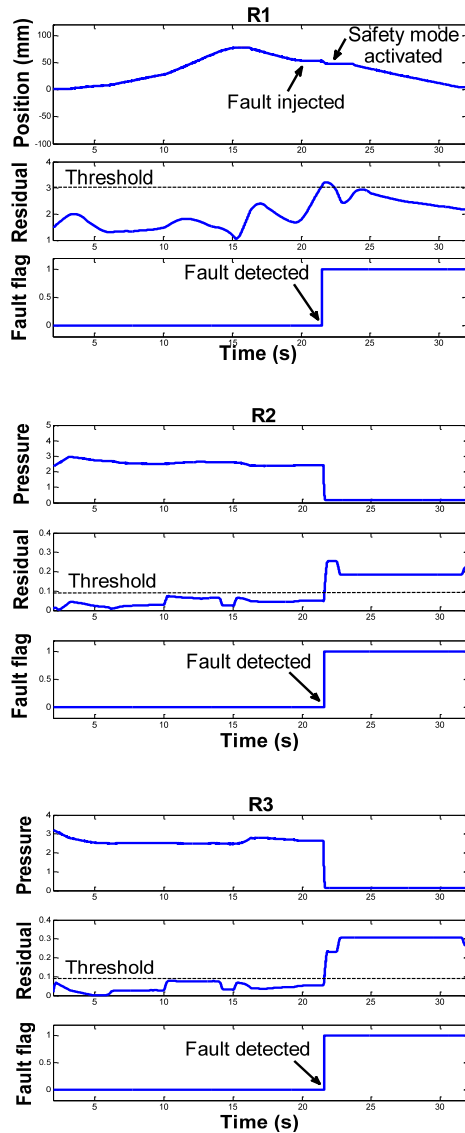


Fig.6. Actuator fault $F_a(s)$ (control signal loss)

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