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Fault Detection and Isolation (FDI): Efficient Technique and Analysis

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ABSTRACT: *This paper deals extensively on Fault Detection and Isolation (FDI) techniques, using a three tank system with two inputs, three measured outputs and three States. And describes how the Fault detection and Isolation was carried out on each of the datasets provided. This report also describes how the simulation was developed to confirm the fault earlier detected and isolated. Finally the effects of complete failure of the sensor L3 and the ways of mitigating the adverse effects were carried out.*

KEYWORDS –*Fault detection,Fault isolation, Datasets, Components failure*

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I. INTRODUCTION

In today's industrial world, there is need for control and automation and its usefulness cannot be over emphasize. Everyday team of engineers are designing and manufacturing new equipment with more sophisticated technologies, in order to ease problems humans are encountering in the technological world. These new pieces of equipment, with their new technologies come with diverse complexity. In as much as the engineers are trying to solve problems, this will not be done at the expense of safety to the humans and the environment, which is also of great concern to the engineers. The engineers are also concern about the safety impact the equipment will create when in operation and when it fails. When equipment is in operation, they do not pose as much threat as compared to when they fail to function. This failure sometimes can be catastrophic. No equipment is design to last forever, as such failure is expected; equipment failure occurs as a result of use, wear and tear. Sometimes, it very difficult to identify the component that is malfunctioning or that has failed completely in a machine. This necessitates the study of Fault detection and Isolation in a system.

Fault Detection and Isolation (FDI) system uses diagnostic signals called Residuals caused by changes in the plant expected behaviour, based on the trending of the input commands and the measured outputs. Fault detection, is a rapid and spontaneous test carried out in a system to ascertain if a fault does exist. And if the fault does exist, the Fault Isolation process is use to identify the exact location of the fault(s) in the loop or equipment. [5]

II. OJECTIVES OF THE RESEARCH

The following are the aims of this research work:
- To identify the presence of a fault in the datasets provided
- To isolate the fault to a particular sensor affected
- To develop a simulation for the system, including the capability of injecting faults.
- Toinvestigate and analyse the effects of the faults identified in the datasets using the simulation.
- To mitigate the effects of the faults on the system

III. THE THREE TANK SYSTEM DESCRIPTION

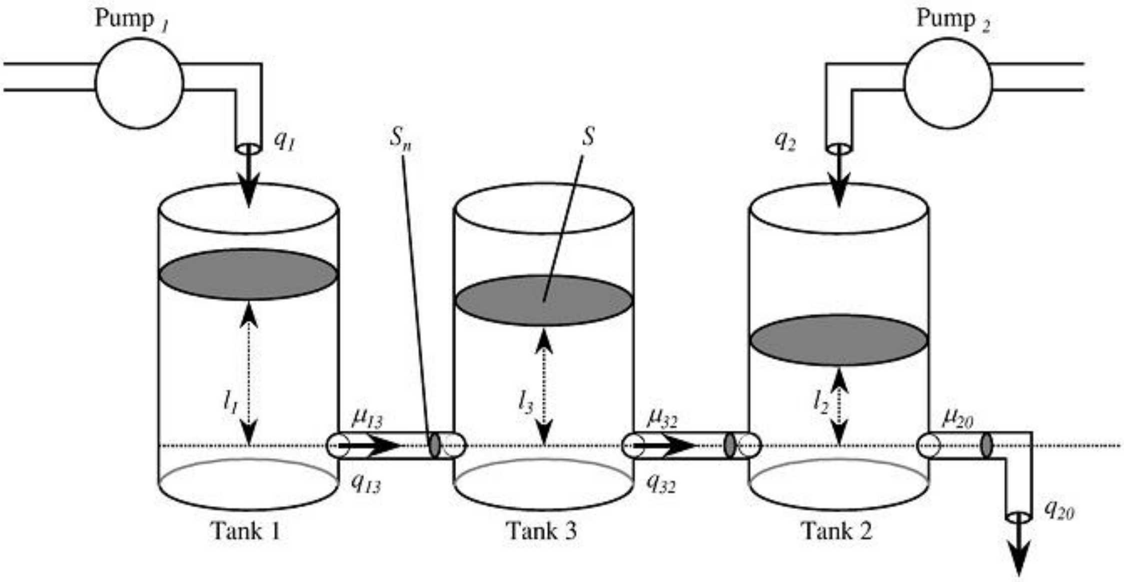

FIG 1: Diagram of the three-tank system

Figure 1 is the diagram of the three tank system, consisting of three cylindrical tanks coupled together by two cylindrical pipes. The nominal outflow is located at tank 2. The experimental plant is equipped with sensors and actuator that communicates with a personal computer through a data acquisition card. The two pumps (pump1 & pump 2) shown above are controlled by two (2) Digital to Analogue (D/A) converters with a voltage range of - 10 to +10. The necessary level measurement in the tanks, are being achieved with the aid of a piezoresistive differential pressure sensors. The three measurement transducers deliver a voltage signal between the ranges of -10 to +10 volts, depending on the level in the tanks.

The level in the tanks are denoted by l_1 , l_2 and l_3, in tank 1, tank 2 and tank 3 respectively.

The given system above, has two (2) flow rates Q_1 and Q_2 with three (3) measured outputs l_1, l_2 and l_3, indicating the fluid level in each of the tanks. The process is used in a closed loop. The volume flows of lateral tanks ($Q_1$and Q_2) are controlled such that the liquid level in the corresponding tanks (l_1 and l_2) can be independently assigned. The third output of the process, level l_3 in the middle tank, is uncontrollable. The purpose is to control the system around an operating point which is fixed.

The system is linearized around this operating point using a Taylor expansion, the linear system is described by a discrete linear state space representation with a sampling period T_s = 1s as:

$$X_{k+1} = AX_k + BU_k \quad - - - - - - - - - \quad 1$$

$$X_{k+1} = \begin{pmatrix} 0.9880 & 0.0001 & 0.0109 \\ 0.0001 & 0.9778 & 0.0114 \\ 0.0109 & 0.0114 & 0.9776 \end{pmatrix} X_k + \begin{pmatrix} 64.576 & 0.0014 \\ 0.0014 & 64.212 \\ 0.3571 & 0.3721 \end{pmatrix} U_k \quad - - - - - \quad 2$$

$$Y_k = X_k \rightarrow \quad Y_k = CX_k + DU_k \quad - - - - - - - - \quad 3$$

$$Y_k = \begin{pmatrix} 1.0000 & 0.0000 & 0.0000 \\ 0.0000 & 1.0000 & 0.0000 \\ 0.0000 & 0.0000 & 1.0000 \end{pmatrix} X_k + \begin{pmatrix} 0.0000 & 0.0000 \\ 0.0000 & 0.0000 \\ 0.0000 & 0.0000 \end{pmatrix} U_k \text{--} \quad - - - - - \quad 4$$

$$\bar{u} = \begin{pmatrix} \overline{Q1} \\ \overline{Q2} \end{pmatrix} = \begin{pmatrix} 0.350 \\ 0.375 \end{pmatrix} \times 10\text{^} - 4 \; [m^3/s] \text{-} \quad - - - - - - - \quad 5$$

$$\bar{x} = \begin{pmatrix} \overline{L1} \\ \overline{L2} \\ \overline{L3} \end{pmatrix} = \begin{pmatrix} 0.400 \\ 0.200 \\ 0.295 \end{pmatrix} [m] \text{-} \quad - - - - - - - - \quad 6$$

To regulate the tank levels, a proportional controller with a full state feedback was added to the system. This is expressed in the equations below.

$$\begin{pmatrix} Q_1 \\ Q_2 \end{pmatrix} = \begin{pmatrix} \overline{Q1} \\ \overline{Q2} \end{pmatrix} + \begin{pmatrix} 5.0 \times 10^{-6} \times (0.4 - L1) \\ 5.0 \times 10^{-6} \times (0.895 - L_1 - L_2 - L_3) \end{pmatrix} [m^3/s] \quad 7$$

IV. FAULT DETECTION

In every Fault Detection and Isolation (FDI) system design, there first concern is the detection performance of the fault detection design, which signifies the ability of the FDI to check the system and identify failure, fault and disturbance accurately with minimal delay.

The FDI task consists of two sub-tasks:

- Detection of a malfunction and
- Isolation of the faulty component (determination of its location)

These tasks were performed sequentially, using the Analytical Redundancy Method (ARM) of diagnosis. This method makes use of mathematical models of the concerned physical system to check the actual system behaviour for consistency with the model. The analytical redundancy consists of two main parts as shown in Fig 2 below, which are:

1. The residual generator and
2. The decision maker

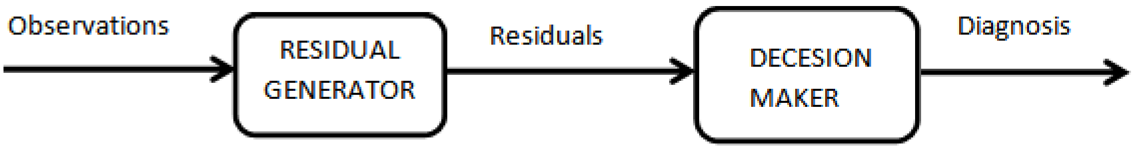

FIG 2: Block diagram of FDI Analytical Redundancy Method

Residuals are quantities that represent the inconsistency the actual plant variables and the mathematical model. They are computed from plant 'Observables' and are ideally zero. These plant observables include the measurement values for the measured plant variables (outputs and measured inputs) and the command values for the controlled input.

Also, the processed measurement are called the Residual and the enchanced failure effect on these residuals are called the signature of the failure. The residuals are examined for the presence of failure signature and are calculated using residuals.

The state model in equation 1 and 3 above, are modified in the presence of faults and the expression is given below.

$$X_{k+1} = AX_k + BU_k + EP \quad 8$$

$$Z_k = CX_k + DU_k + FP \quad 9$$

Equations 2 and 4 show the actual values for A, B and C, D respectively. The matrix of potential faults can be expressed as:

$$P = \begin{pmatrix} \Delta X1 \\ \Delta X2 \\ \Delta X3 \\ \Delta U1 \\ \Delta U2 \\ \Delta Y1 \\ \Delta Y2 \\ \Delta Y3 \end{pmatrix} \quad 10$$

$$E = [A, B, zeros(nx, ny)] \quad 11$$

The number of inputs and outputs are represented by nx and ny respectively.

$$E = \begin{pmatrix} 0.9880 & 0.0001 & 0.0109 & 64.5760 & 0.0014 & 0.0000 & 0.0000 & 0.0000 \\ 0.0001 & 0.9778 & 0.0114 & 0.0014 & 64.2120 & 0.0000 & 0.0000 & 0.0000 \\ 0.0109 & 0.0114 & 0.9776 & 0.3571 & 0.3721 & 0.0000 & 0.0000 & 0.0000 \end{pmatrix} \quad - \quad 12$$

$$F = [C, D, I(ny)] \quad - - - - - - - - - - \quad 13$$

$$F = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad - - - - - - - \quad 14$$

Fault can be detected by using the ARM process described above and carrying out the following:
- measurement system outputs
- observation
- analyzing the obtained signals and
- making a decision if the system is behaving normally

A change in the normal behaviour of the system indicates the probability of a presence of fault in that system.With the Analytical Redundancy Method (ARM), parity equations from state space models are used to generate residuals which represent the comparison between the real and the modeled systems.
Ideally, if there are no faults, then it will be zero.
The representation of the non-fault system is given the expression:

$$Pk = wT(Yk - MUk - LXk) = 0 \quad - - - - - - - - \quad 15$$

Where:
wT is a transforming vector
$Y_k$is measurement data
$U_k$is the input and
M is dependent on state model parameters.

$$Uk = \begin{pmatrix} u_{k-7} \\ \vdots \\ u_{k-2} \\ u_{k-1} \\ u_k \end{pmatrix} \quad - - - - - - - - - \quad 16$$

$$Xk = \begin{pmatrix} x_{k-7} \\ \vdots \\ x_{k-2} \\ x_{k-1} \\ x_k \end{pmatrix} \quad - - - - - - - - - - \quad 17$$

$$Yk = \begin{pmatrix} y_{k-7} \\ \vdots \\ y_{k-2} \\ y_{k-1} \\ y_k \end{pmatrix} \quad - - - - - - - - - - \quad 18$$

The left null space of matrix L can be found using Singular Value Decomposition [1]. The transforming vector wT is selected such that it lies in the Left Null Space of L.
Therefore wTL=0

$$L = \begin{pmatrix} C \\ CA \\ CA^2 \\ \vdots \\ CA^5 \end{pmatrix} \quad \text{- - - - - - - - - - -} \quad 19$$

$$M = \begin{pmatrix} D & ZD & ZD & ZD & ZD & ZD & ZD & ZD \\ CA^0B & D & ZD & ZD & ZD & ZD & ZD & ZD \\ CA^1B & CA^0B & D & ZD & ZD & ZD & ZD & ZD \\ CA^2B & CA^1B & CA^0B & D & ZD & ZD & ZD & ZD \\ CA^3B & CA^2B & CA^1B & CA^0B & D & ZD & ZD & ZD \\ CA^4B & CA^3B & CA^2B & CA^1B & CA^0B & D & ZD & ZD \\ CA^5B & CA^4B & CA^3B & CA^2B & CA^3B & CA^0B & D & ZD \\ CA^6B & CA^5B & CA^4B & CA^3B & CA^2B & CA^1B & CA^0B & D \end{pmatrix} \quad \text{- - - - - -} \quad 20$$

V. FAULT DETECTION ON DATASETS

From MATLAB coding, the figures below were developed,

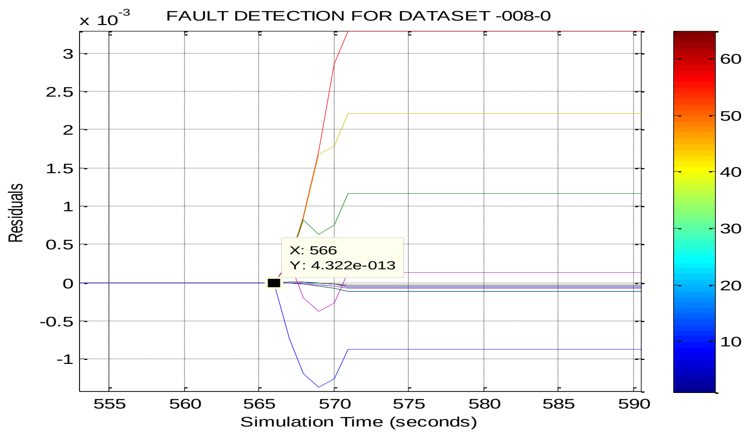

FIGURE 3: Residual Plot for dataset showing fault occurrence at time: approximately 566 seconds

Figure 3 is a plot of residuals for the dataset, with indication of fault occurrence. There is a fault in datasetand the fault occurred at about 566 seconds. The figures below were the results from the simulations.

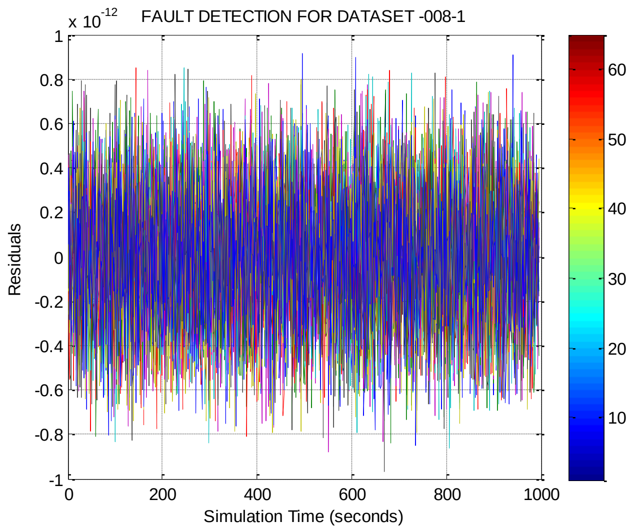

FIGURE 4: Residual Plot for datasetwith no fault occurrence but spikes

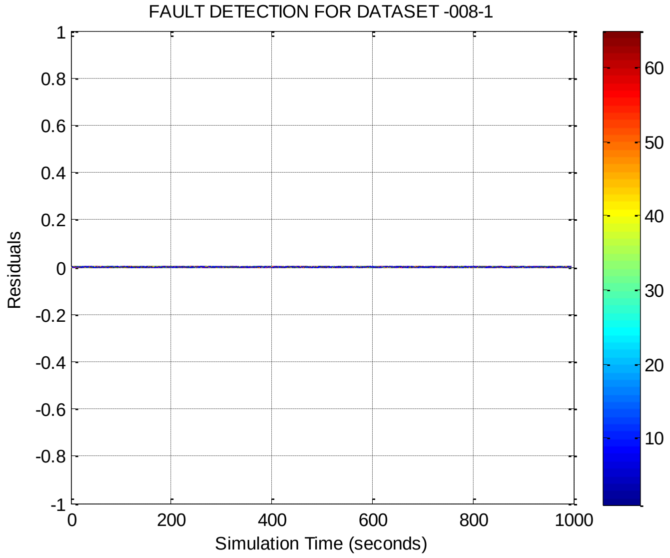

FIGURE 5: zoomed Residual Plot for dataset_008_1.csv showing no fault occurrence

Figures 4 and 5are plots of residuals for the datasetwith no indication of fault occurrence. This implies that there is nofault occurrence in the dataset.
Figure 5 is a zoomed (scaled y-axis of -1 to +1) version of figure 4.

VI. FAULT ISOLATION

This is the process of identifying and narrowing down a fault to a particular component (sensor or actuator) that is making the system to behave abnormally; this can be done using fault signatures or codes that are assigned specifically to certain behaviours that are exhibited in the system.

Faults are isolated using coding sets on residuals. Residual generated must be close to zero to achieve fault isolation. One way of enhancing the residual involves generating a residue vector so that, in response to a particular fault. Only a fault-specific sub-set is non-zero [3].
The fault in the system is assigned as a P matrix as expressed in equation 21.

$$\mathrm{Pk} = \mathrm{w} \times \mathrm{N} \times \mathrm{P} \neq 0 \qquad (21)$$

Since fault codes are specific for each fault, the fault signatures can be generated by multiplying P by alpha (α).

$$\mathrm{pattern} * \mathrm{Pk} = \mathrm{alpha} \times \mathrm{w} \times \mathrm{N} \times \mathrm{P} \qquad (22)$$

Where pattern refers to a vector set of fault codes whose components identify each fault in P. Then:

$$\mathrm{pattern(Joe)} = \mathrm{alpha} \times \mathrm{w} \times \mathrm{N} \qquad (23)$$

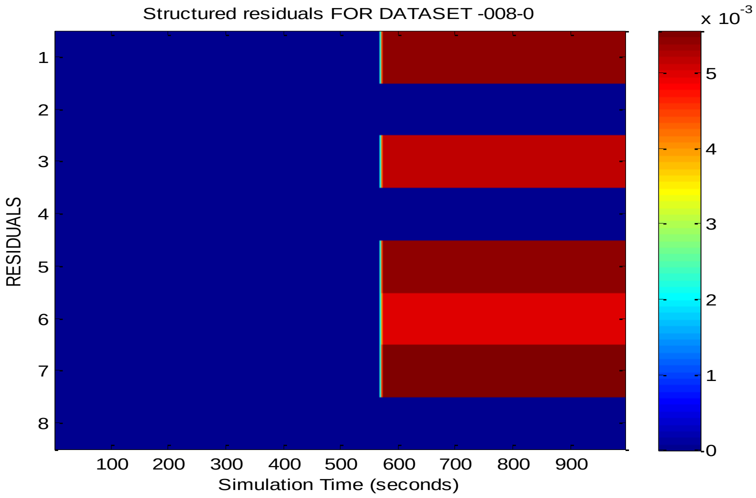

FIGURE 6: Structured Residual Image scan for dataset showing fault occurrence at time: approximately 566 seconds (Alpha*r)

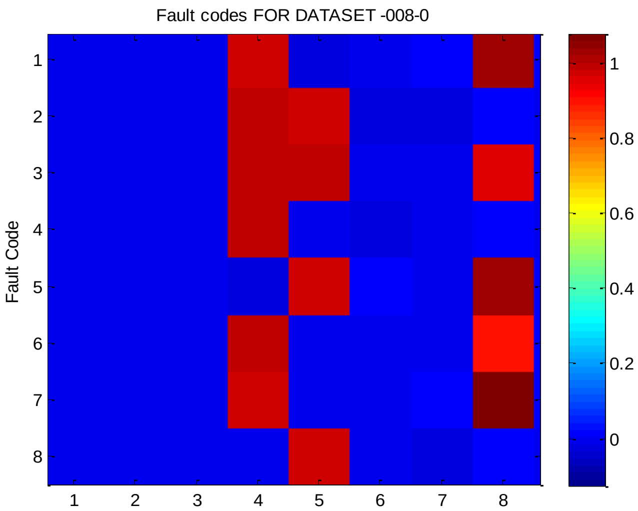

FIGURE 7: Zoomed **Fault Code scanned Image** for datasetshowing fault occurrence at the **third output Z_3(alpha (α)*W*N)**

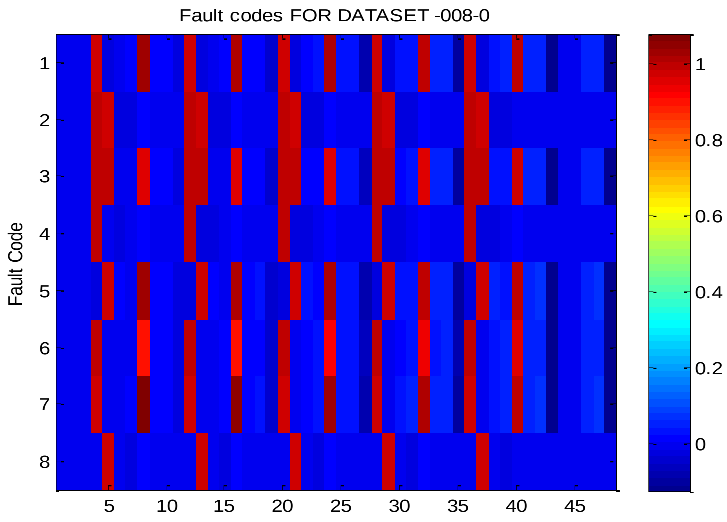

FIGURE 8: Fault Code scanned Image for dataset showing fault occurrence at the third output$\mathbf{Z_3}$ and it multiples **(alpha (α)*W*N)**

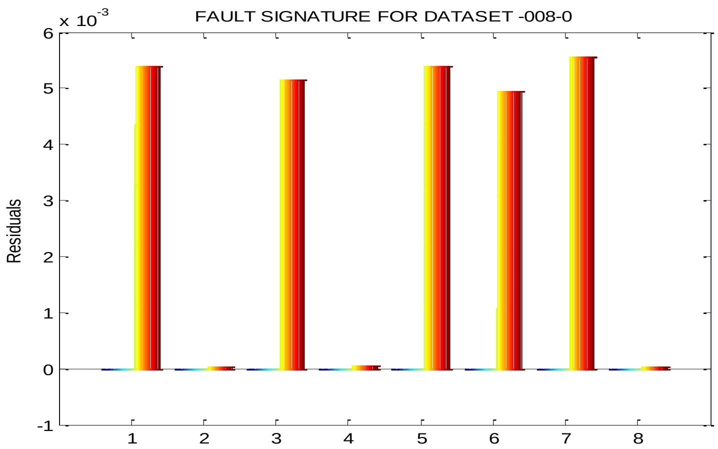

FIGURE 9: Bar (fault signature) for dataset showing fault residual structure

The figures 6, 7 and 8shows that the fault earlier detected in the datasetin Figure 3 was from the third output device $\mathbf{Z_3}$ of the system. The fault isolation was achieved by generating coding set (**Joe**). The coding set for the datasetis shown below and it is an 8x8 matrix with the Rows representing Residuals and the Column representing States (X_1, X_2 and X_3), inputs (U_1 and U_2) and Outputs (Z_1, Z_2 and Z_3).

Table 1: Coding Set for dataset_008_0 Fault Isolation

Joe =

1 0 1 1 0 1 1 1; r_1
1 0 1 1 1 0 1 0;r_2
0 0 0 1 1 0 0 1; r_3
0 1 1 1 0 0 1 0; r_4
1 0 1 0 1 1 1 1; r_5
1 0 1 1 0 0 0 1; r_6
0 1 0 1 0 1 0 1; r_7
1 0 1 0 1 0 1 0;r_8
$X_1X_2X_3U_1U_2Z_1Z_2Z_3$

The fault signature of the isolated the fault in dataset is as represented below:
(1 0 1 0 1 1 1 0)
This fault signature is similar to the one found on the eighth column (**Z_3**) of the coding set (Joe). Also this repeats in multiples of the eighth columns (16th, 24th, 32nd, and 40th) in Figure 8.

Since the first three columns of the coding set represents States X_1, X_2 and X_3 ,the 4th and 5th columns represents the Inputs (U_1 and U_2) and columns 6th, 7th and 8th represents the Outputs Z_1, Z_2 and Z_3 respectively.

Then it is observed clearly from Figure 7, that the fault in dataset that occurred at time of about 566 seconds (Figure 3) is at the third output device Z_3 and Z_3 has been isolated as the faulty device in the system, using structured parity equation.

The colourbar magnitude (range) of figures 6, 7 and 8 are the same. A close look at the fault code and the residuals generated,shows that they are represented by the same magnitudes and this further confirms the presence of the fault.

VII. FAULT VERIFICATION

The essence of fault verification is to simulate a system and inject the faults earlier detected and isolated in previous sections into a fault free system and observe if the faults will be detected in the same pattern and at the same time they occurred in the detection and isolation process.

VIII. FAULT VERIFICATION OF DATASET:

comparison of injected and earlier obtained

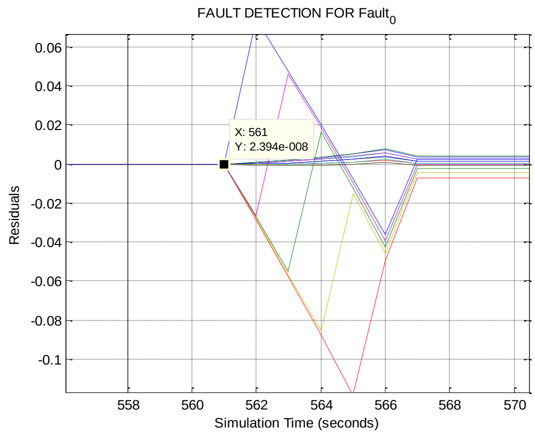

FIGURE 10:SIMULATED/ Injected Residual Plot for **fault** showing fault occurrence at tie: approximately 561 seconds

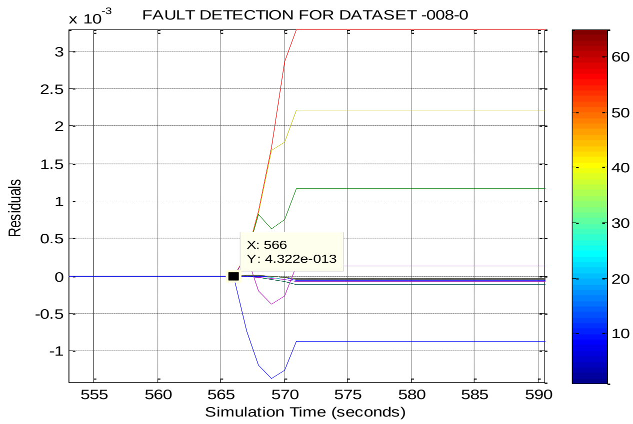

FIGURE 11: Residual Plot for dataset showing fault occurrence at time: approximately 566 seconds (**Earlier obtained**)

From figures 10 and 11, it can be observed that when the faults P(8) =0.9 was injected at the same time the fault occurred in dataset (566 seconds), into the fault free system simulated, it was observed that, the residuals plot showing time of fault occurrence, the fault residual structures, fault codes and the fault signatures of dataset: were similar in pattern to that of the **dataset**earlier obtained in section three above.

Comparing the figures as shown beside each other, they virtually matched, except that the time of occurrence of the injected fault happened at about 561 seconds and the initially detected fault of dataset _008_0 occurred at about 566 seconds. Also a slight difference was observed in the colourbar magnitude of the structure residuals image scan. Finally the fault signature Bars for the injected faults are on the negative region while that of the detected dataset _008_0 are on the positive and with greater magnitude.

It can also be observed that the simulated isolated fault and the earlier isolated fault occurred following the same pattern of fault signature P={1, 0, 1, 0, 1, 1, 1, 0} and both indicated faulty third output Z_3 of the system.

The faults earlier detected and isolated, have been verified after being injected into a fault free simulation the is similar to the one used in obtaining the dataset.

IX. CONCLUSION

From the above analysis and fault diagnosis, it can be observed that fault detection with specific time of occurrence can be achieved on either faulty state, input or output. Fault isolation is also achieved from the fore analysis and specific faulty device is isolated.

The objectives of this piece of work were achieved with the aid of a MATLAB program.A fault free simulation program was built for fault verification purposes. The isolated faults were further subjected to verification process; this was done to ascertain the faults obtained from the datasets were the same as the ones injected into the fault free simulation earlier.

The effects of complete failure of sensor L_3 was simulated and analysed. From the above analysis it was observed that detection of double fault occurring simultaneously can be detected with known dynamics behaviour of the system with no specific time of occurrence, but fault isolation was not possible. It will require a multi-fault isolation method.

The mitigation to such effect (complete failure of third output sensor) was also offered using the Fault Detection, Isolation and Adaptive Reconfigurable Controllers.Another method of mitigating the complete failure of L_3 is to decouple it from the system and re-define the output matrix.

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