An Error Residual Generator for Fault Detection and Isolation in a Data Acquisition System Used For Carbon Mono-Oxide & Nitrogen Oxide Monitoring

E.O. Ofoegbu - E. O. Ofoegbu is with Adeleke University ede, Osun State , Nigeria.
Email: **edoxnt@yahoo.com**

H. C. Inyiama - Nnamdi Azikwe University, Awka, Anambra State. Nigeria.
Email: **edoxnt@gmail.com**

Abstract: clean air is a basic necessity for all human beings living on earth, yet about 80% of world's population breathes air that has pollutants which exceed the World Health Organization's recommended level. Environmental air pollution has significant influence on the concentration of constituents in the atmosphere leading to effects like global warming and acid rains. To avoid such adverse imbalances in nature, an air pollution measuring system is of utmost importance. This paper presents fault detection and isolative model implemented in a novel fault tolerant microcontroller based data acquisition system design for air pollutant concentration measurement in industrial facilities in Nigeria. A supervisory control unit was incorporated in the data acquisition system design in an attempt at robust control. The model utilizes weighted standard deviation /data variance method to detect anomalies and correlation in measured data, with a view to data intelligence elicitation, an error residual generator was designed to handle fault isolation and accommodation. The overall system implements corrective procedures in the event of a fault or failure with appropriate indicators showing in-process operation. Microcontrollers, gas sensors, capacitors, resistors, connecting wires, transistors, voltage regulator, transformer, Light Emitting Diodes (LED's), Fan, Liquid Crystal Display (LCD), Buzzer, , Oscillator, associated signal conditioning circuits were used in the implementation of the system design. The system developed was able to measure CO and NO pollutant concentrations, trigger alarms, classify pollutant level, and display pollutant level on an LCD, implement basic fault detective algorithms and save measured data in an external memory for future access. Performance tests and reliability tests were performed to ensure conformity to the designed objectives.
Key Words: Air Pollution, Error–Residual, Fault Tolerance and Generator.

I. INTRODUCTION:

Pollution is the introduction of contaminants into the natural environment that causes adverse changes to it. Pollution can take the form of a chemical substance or energy such as noise, heat or light. Pollution is often classified as a point source or non- point source [1].

Air pollution has always accompanied civilizations and dates back to prehistoric times when man first created the first fires. Environmental pollution was a direct result of the industrial revolution, where the industrial revolution era caused the emergence of great factories and increased consumption of immense quantities of coal and other fossil fuels [2]. The resulting air pollution coupled with large volumes of industrial chemical discharges which when added to the growing load of untreated human waste constituted environmental pollution [3, 11].
The impact of air pollution on health is one of the most significant concerns of the World Health Organization, with the rising cost in Health Care; the burden on the economy is another major impact

that air pollution has on society. Billions of dollars are spent globally to address the health concerns [1, 12].
Global Warming is an undeniable issue with the earth average temperature "increasing by about 0.8°C over the past 100 years, with about 0.6°C of this warming occurring over just the past three decades determining polluted areas using an air quality monitoring system is important as the initial process of common air-quality improvement techniques such as source control, improved ventilation, and air cleaning has gradually been phased out [1, 2].

Conventional air quality monitoring approaches such as Gas Chromatography (GC) are limited with respect to time, expense, and installation sites [3]. Therefore, limited data is available for the estimation of ambient air toxins. Further, air quality monitoring systems built into compact, handheld devices have spatial and temporal limitations, since the measurements are conducted manually [3, 13]. Recent advances in micro-electro-mechanical systems (MEMS) and wireless sensor network (WSN) technology have allowed the creation of air pollutant monitoring system and its deployment in real environments [18, 19]. The integration of an air pollutant monitoring system with technology will reduce installation costs and enable the quick and easy reconfiguration of the data acquisition and control systems [20]. In addition, networked air pollutant monitoring system allows continuous and low-cost observation of air pollutants. It also allows pollutant concentrations to be monitored accurately and ideally so that sources may be identified quickly and the atmospheric dynamics of the process is understood and more user-friendly [3].

II. RELATED WORKS:

A fault tolerant supervisory control scheme for discrete event systems using a plant possessing both faulty and non-faulty parts was developed by [4]. where the goal of the fault tolerant supervisory control was to enforce a certain specification for the non-faulty plant and another (perhaps more liberal) specification for the overall plant to further ensure that the plant recovers from any fault within a bounded delay so that the recovery of the system state is equivalent to a non-faulty state (as if no fault occurred). The notion of fault tolerant supervisory control to provide a necessary and sufficient condition for the existence of such a supervisor is therefore based on conditions involving the usual notions of controllability, observe ability and relative closure together with the notion of state stability. Since in real life most systems are not able to achieve complete fault tolerance which would mean complete recovery of full functionality of the original system a fault tolerant supervisor would thus allow the controlled system to achieve partial functionality without violating safety specification.

[5] Described an adaptive approach to active fault tolerant control where faults or process failures acting or occurring in dynamic systems are estimated and compensated within an adaptive control scheme with required stability and performance robustness.

[6] Designed Out of the Box Environmental Monitoring device called Sensor Scope. Sensor Scope is a large-scale wireless environmental monitoring system. Sensor Scope was developed to provide *in-situ* spatial and temporal observations across the landscape. Sensor Scope makes use of solar energy with extensive radio duty cycling to prevent power outages.

Integrated fault tolerant robotic control systems for high reliability and safety were discussed in [7]. The system was developed for applications that require high dependability (reliability, availability and safety), it consisted of a fault tolerant controller and an operation work station where the fault tolerant controller uses a strategy which allows for detection and recovery of hardware, operating system and application software. Protection against higher level unsafe events was provided by a software resident in a separate operator workstation which included features to predict collisions and reduce human workload thereby reducing errors and enhancing safety. The developed fault tolerant controller can be used by itself in a wide range of applications in industry, process control, and communication while the controller combined with the operator workstation can be applied to robotic applications such as space borne extravehicular activities, hazardous material handling etc. as well as every other task where a robot system failure poses a significant risk to life or property.

[8] Described the deployment of wireless sensors for air quality monitoring in India, where an environmental air pollution monitoring system that measures respirable suspended particulate matter, NO_x, SO_2 was designed with air quality index (AQI) reporting capabilities, several sensor nodes which measure pollutant information are uniformly deployed in the networks, thus creating a sensing phenomenon. Low power strategies and hierarchical routing protocol were used to cause the motes to sleep during idle time to conserve power utilization.
[9] Proposed a mobile air quality-monitoring network comprising of sensors that can detect O_3, NO_2 and CO/VOC. The scheme focused on data collection and presentation, but did not consider issues like the characteristics of the gas sensors and energy management

Some other work [10], Developed a solution for pollution monitoring using wireless sensor networks on real time basis called the real time wireless air pollution monitoring system. Commercially available CO_2, NO_2, CO and O_2 sensors were calibrated using appropriate calibration technologies. The pre-calibrated gas sensors were integrated with the sensor motes and deployed in the field at Hyderabad city campus using the multi hop data aggregation algorithm. A light weight middleware and web interface was developed to view the live pollution data in the form of numbers and charts from the test beds anywhere on the internet. Parameters such as temperature and humidity were also sensed along with the gas concentrations to enable data analysis through fusion techniques.

[11] Was a collaboration between Cambridge University, Imperial College London, Leeds University, Newcastle University and Southampton University. This system monitors vehicle occupancy, position, movement, temperature, humidity, noise, CO and NO_2. It has a low cost, low power ZIGBEE transceiver and a data logger on board. It collects data through a gateway to a central server.

III. METHOD:

The choice of research methodology used in carrying out this project design is the top- down design methodology. Prototypes are built early in the development lifecycle and are used to provide valuable insight into the look-and-feel, as well as the general workflow of an application.

Top-down research design methodology is essentially the breaking down of a system to gain insight into its compositional subsystem. In a top-down design, an overview of the system is formulated, specifying but not detailing any first – level subsystems.

The proposed system can be classified into its hardware and software components. The hardware consisted of components such an ATMEL 89C52, MICS 4514 sensors, capacitors, resistors, connecting wires, transistors, voltage regulator, transformer, Light Emitting Diodes (LED's), Fan, Liquid Crystal Display (LCD), Buzzer, , Oscillator, GSM Modems , GPRS Modems etc while the software involved utilizing C language written using the MIDE development environment for the microcontroller. The developed system thus comprised of the Data Acquisition unit, the Remote Terminal unit and the Data Analytics Phase.

The sensors would measure readings on hourly basis and transmit via its modem to the central remote terminal unit, this allow a node to sink approach if multiple DAS are employed in a given application. A standard deviation/variance model is used to determine data correlation as shown in the tables below, where a comparison with the condition

$$S_n <= 1.02\, S_{n-1}$$

Results in three possible fault scenarios labeled F-1, F-2 and F-3.

These fault conditions will be represented in the input and output matrices to show how they affect the measured data by creating a non-zero residual, and also how the system can modify them to get a zero residual.

$$r(s) = E(s)u(s) + F(s)y(s)$$

If $E_{(s)} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$ and $F_{(s)} = \begin{pmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix}$

The first row in the matrix represents fault condition (F-3), the second row in the matrix represents the fault condition (F-2), and while the last row in the matrix represents the fault condition (F-1) and these fault could result due to off-set bias fault or drop out sensor fault.

For any value of U(s) and Y(s) which is also a 3*3 matrix as shown below, the residual generator will always give a zero reading.

$$U_{(s)} = \begin{pmatrix} 75 & 0 & 0 \\ 0 & 75 & 0 \\ 0 & 0 & 75 \end{pmatrix}$$

Where in fault free condition the actual reading U(s) = the measured reading Y(s).
Therefore

$$y_{(s)} = \begin{pmatrix} 75 & 0 & 0 \\ 0 & 75 & 0 \\ 0 & 0 & 75 \end{pmatrix}$$

Then, $R_s = \left(\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 75 & 0 & 0 \\ 0 & 75 & 0 \\ 0 & 0 & 75 \end{pmatrix} + \begin{pmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix} \begin{pmatrix} 75 & 0 & 0 \\ 0 & 75 & 0 \\ 0 & 0 & 75 \end{pmatrix} \right)$

, $R_s = \left(\begin{pmatrix} 75 & 0 & 0 \\ 0 & 75 & 0 \\ 0 & 0 & 75 \end{pmatrix} + \begin{pmatrix} -75 & 0 & 0 \\ 0 & -75 & 0 \\ 0 & 0 & -75 \end{pmatrix} \right)$

, $R_s = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$

Therefore, the residual from the generator is thus zero. If we consider the three fault cases that are already detected by the remote terminal unit. In the first case we have a fault condition (F-1) when D_{CO} = 40. When the L_{CP} for CO is 75

The residual is thus represented below where only the affected row is input with a faulty data.

$$R_s = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 75 & 0 & 0 \\ 0 & 75 & 0 \\ 0 & 0 & 75 \end{pmatrix} + \begin{pmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix} \begin{pmatrix} 75 & 0 & 0 \\ 0 & 75 & 0 \\ 0 & 0 & 40 \end{pmatrix} \Bigg)$$

$$R_s = \left(\begin{pmatrix} 75 & 0 & 0 \\ 0 & 75 & 0 \\ 0 & 0 & 75 \end{pmatrix} + \begin{pmatrix} -75 & 0 & 0 \\ 0 & -75 & 0 \\ 0 & 0 & -40 \end{pmatrix} \right)$$

$$R_s = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 35 \end{pmatrix}$$

Therefore to get a zero –residual, the input matrix of the sensor should be modified as follows

$$R_s = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & .53333 \end{pmatrix} \begin{pmatrix} 75 & 0 & 0 \\ 0 & 75 & 0 \\ 0 & 0 & 75 \end{pmatrix} + \begin{pmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix} \begin{pmatrix} 75 & 0 & 0 \\ 0 & 75 & 0 \\ 0 & 0 & 40 \end{pmatrix} \Bigg)$$

$$R_s = \left(\begin{pmatrix} 75 & 0 & 0 \\ 0 & 75 & 0 \\ 0 & 0 & 40 \end{pmatrix} + \begin{pmatrix} -75 & 0 & 0 \\ 0 & -75 & 0 \\ 0 & 0 & -40 \end{pmatrix} \right)$$

$$R_s = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

In the second case when we have the fault condition (F-2) occurring, $D_{NO} = 120$, $U_{CP} = 107$
The residual is thus

$$R_s = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 107 & 0 & 0 \\ 0 & 107 & 0 \\ 0 & 0 & 107 \end{pmatrix} + \begin{pmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix} \begin{pmatrix} 107 & 0 & 0 \\ 0 & 120 & 0 \\ 0 & 0 & 107 \end{pmatrix} \Bigg)$$

$$R_s = \left(\begin{pmatrix} 107 & 0 & 0 \\ 0 & 107 & 0 \\ 0 & 0 & 107 \end{pmatrix} + \begin{pmatrix} -107 & 0 & 0 \\ 0 & -120 & 0 \\ 0 & 0 & -107 \end{pmatrix} \right)$$

$$R_s = \begin{pmatrix} 0 & 0 & 0 \\ 0 & -13 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

The negative sign indicates explicitly that the measured variable is higher than the actual variable. This means that an external noise was added to the actual value to the tune of 13. Therefore to get a zero-residual, the system must modify the input matrix as follows

$$R_s = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1.121 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 107 & 0 & 0 \\ 0 & 107 & 0 \\ 0 & 0 & 107 \end{pmatrix} + \begin{pmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix} \begin{pmatrix} 107 & 0 & 0 \\ 0 & 120 & 0 \\ 0 & 0 & 107 \end{pmatrix} \Bigg)$$

$$R_s = \left(\begin{pmatrix} 107 & 0 & 0 \\ 0 & 120 & 0 \\ 0 & 0 & 107 \end{pmatrix} + \begin{pmatrix} -107 & 0 & 0 \\ 0 & -120 & 0 \\ 0 & 0 & -107 \end{pmatrix} \right)$$

$$R_s = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

The fault condition occurred when D_{CO} = 187 , L_{CP} = 75, U_{CP} = 450, the residual is thus

$$R_s = \left(\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 375 & 75 & 450 \\ 450 & 375 & 75 \\ 75 & 450 & 375 \end{pmatrix} + \begin{pmatrix} -1 & -1 & -1 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix} \begin{pmatrix} 187 & 112 & 263 \\ 263 & 187 & 112 \\ 112 & 263 & 187 \end{pmatrix} \right)$$

The matrices are generated by additions and subtraction between the measured data and the set points. 375 is chosen as the mid matrix value in the actual sensor value U(s) as it indicates the measurement span. The fault matrix Y(s) has values on the entire first row because this fault condition is likely dependent on the sensor, controller and environment.

$$R_s = \left(\begin{pmatrix} 375 & 0 & 0 \\ 0 & 375 & 0 \\ 0 & 0 & 375 \end{pmatrix} + \begin{pmatrix} -562 & -562 & -562 \\ -263 & -187 & -187 \\ -112 & -263 & -187 \end{pmatrix} \right)$$

$$R_s = \begin{pmatrix} -187 & -562 & -562 \\ -263 & 188 & -187 \\ -112 & -263 & 188 \end{pmatrix}$$

The residual is observed to be a non-zero term, thus to push the value to zero. The system must modify the input matrix E(s) as shown.

$$R_s = \left(\begin{pmatrix} 0.624 & 0.624 & 0.624 \\ 0 & 0.498 & 0 \\ 0 & 0 & 0.498 \end{pmatrix} \begin{pmatrix} 375 & 75 & 450 \\ 450 & 375 & 75 \\ 75 & 450 & 375 \end{pmatrix} + \begin{pmatrix} -1 & -1 & -1 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix} \begin{pmatrix} 187 & 112 & 263 \\ 263 & 187 & 112 \\ 112 & 263 & 187 \end{pmatrix} \right)$$

The system simply modifies the first row on the matrix to get zero values, while it changes all zeros in the matrices below to zero. Thus

$$R_s = \left(\begin{pmatrix} 562 & 562 & 562 \\ 0 & 187 & 0 \\ 0 & 0 & 187 \end{pmatrix} + \begin{pmatrix} -562 & -562 & -562 \\ -263 & -187 & -187 \\ -112 & -263 & -187 \end{pmatrix} \right)$$

$$R_s = \begin{pmatrix} 0 & 0 & 0 \\ -263 & 0 & -187 \\ -112 & -263 & 0 \end{pmatrix}$$

Since there are still non-zero values in the matrix, the system will attempt to force the residual to zero by

$$R_s = \begin{pmatrix} 0 & 0 & 0 \\ 263 & 0 & 187 \\ 112 & 263 & 0 \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 \\ -263 & 0 & -187 \\ -112 & 263 & 0 \end{pmatrix}$$

$$R_s = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

The added matrix $R_s = \begin{pmatrix} 0 & 0 & 0 \\ 263 & 0 & 187 \\ 112 & 263 & 0 \end{pmatrix}$ is a redundant version of the error residual, thus this implies the solution of this problem is for the system to switch to the redundant sensor in the data acquisition system

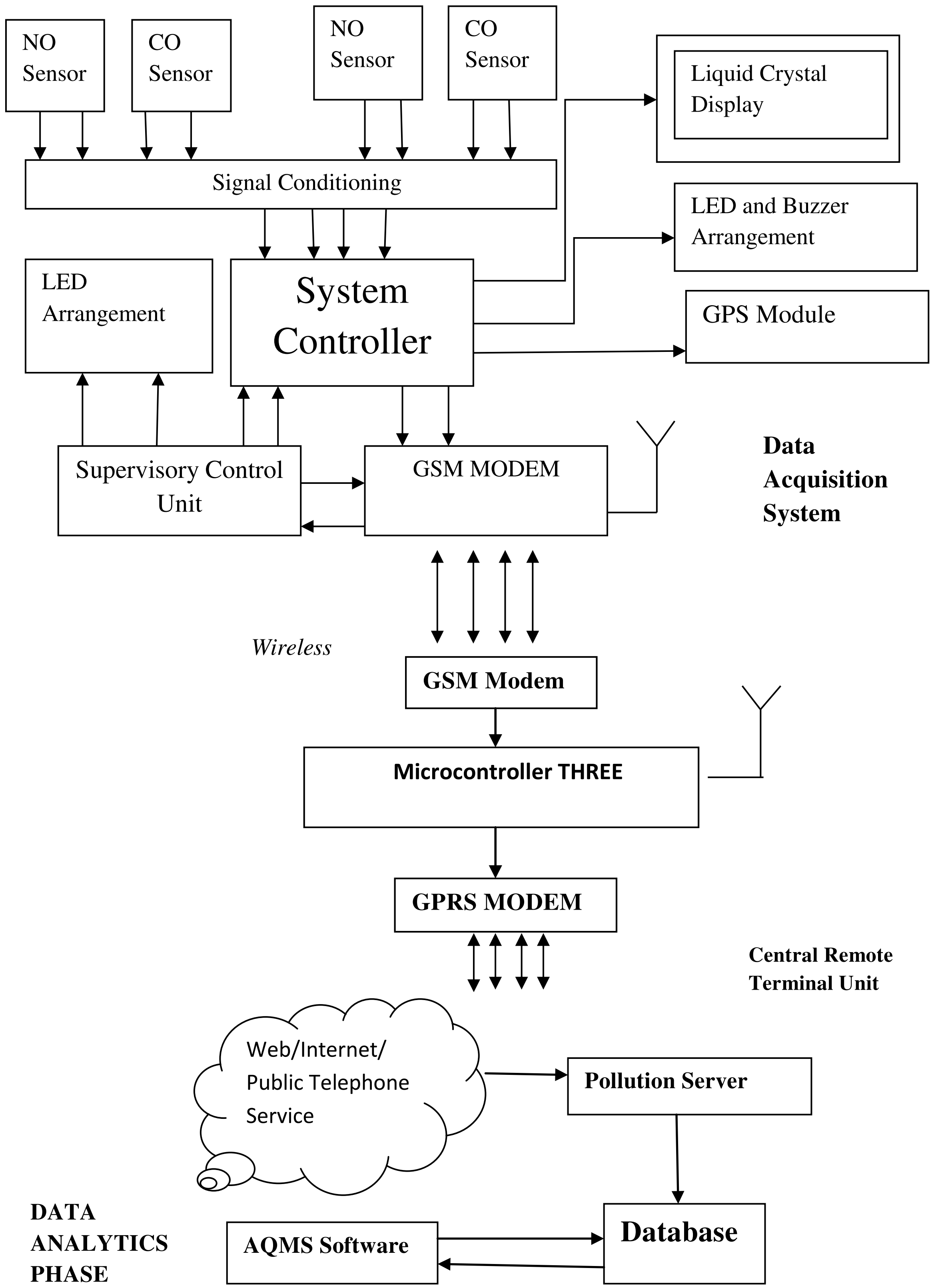

Figure 1: Overall System Diagram

IV. ESULTS AND DISCUSSION

Use The row in the input transfer matrices contains the following information

$$\left(SENSOR\left[\frac{output}{input}\right] \quad CONTROLLER\left[\frac{output}{input}\right] \quad ENVIRONMENT\left[\frac{output}{input}\right]\right)$$

Thus in the environment, if the output is less than the input, this implies it is endothermic with respect to heat and dust, this could imply why a reading could be less than L_{CP} (lower set point) or greater than U_{CP} (upper set point). The presence of dust on the sensitive layer of the sensor might have affected its sensitivity. The same applies to the heating temperature of the internal sensor heater being affected by the presence of dust as well as residual heat in the sensor itself.

In fault condition (F-1), the third row in the matrix is modified to a value less than unity for there to be no residual as observed above. Therefore the control action below should be taken to ensure that $\begin{pmatrix}1 & 0 & 0\\0 & 1 & 0\\0 & 0 & 1\end{pmatrix}$ could result in a zero residual.

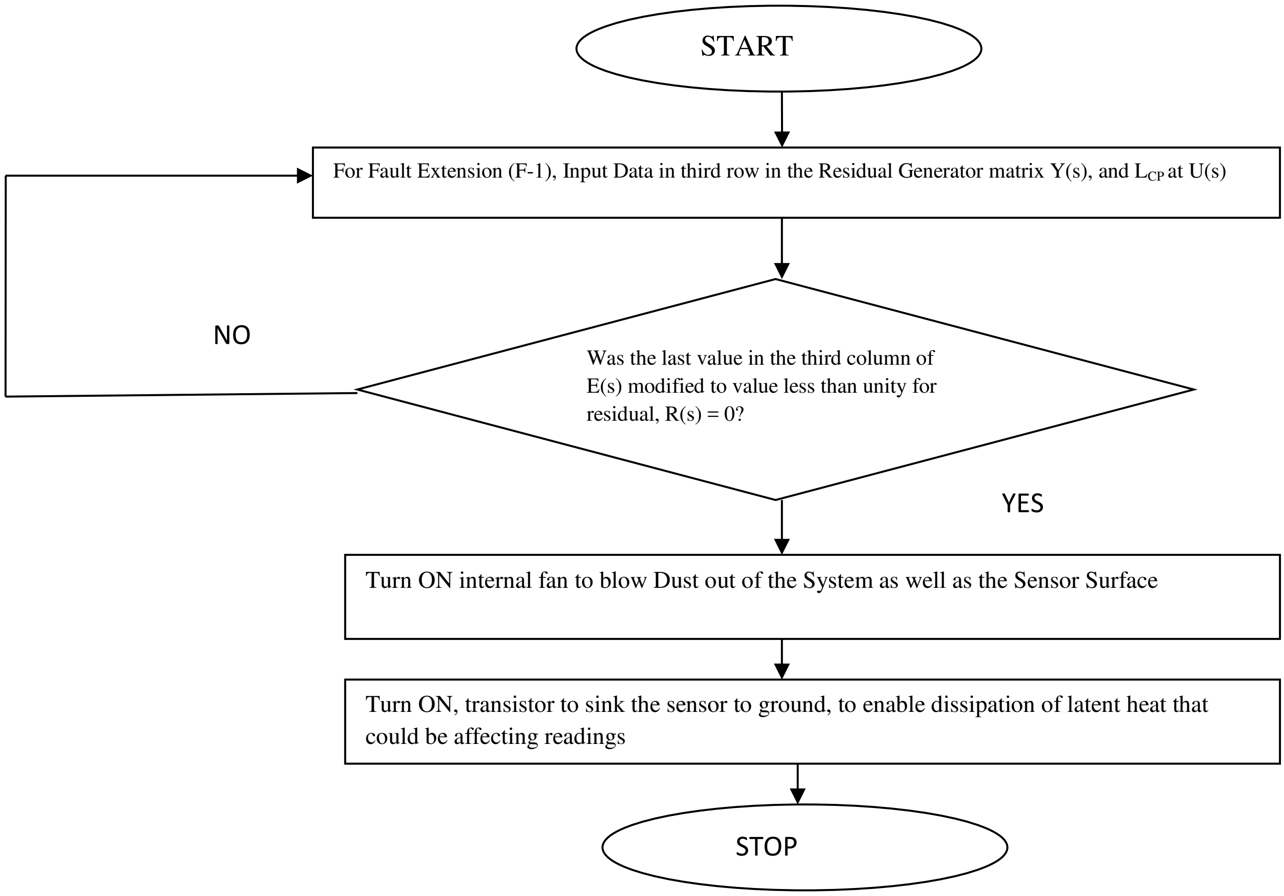

Figure 2: Flowchart Showing (F-1) Fault Handling

Thus in the controller, if the output is greater than the input, this could imply a bug in the software program impedes its ability to report correctly after a number of iterations or an additive noise in the measured reading. A reading higher than U_{CP} is a perfect example of a malfunctioning control program or an offset bias fault.

In fault condition (F-2), the second row in the matrix is usually modified to a value greater than unity for there to be no residual as observed above. Therefore the control action below should be taken to ensure that $\begin{pmatrix}1 & 0 & 0\\0 & 1 & 0\\0 & 0 & 1\end{pmatrix}$ could result in a zero residual.

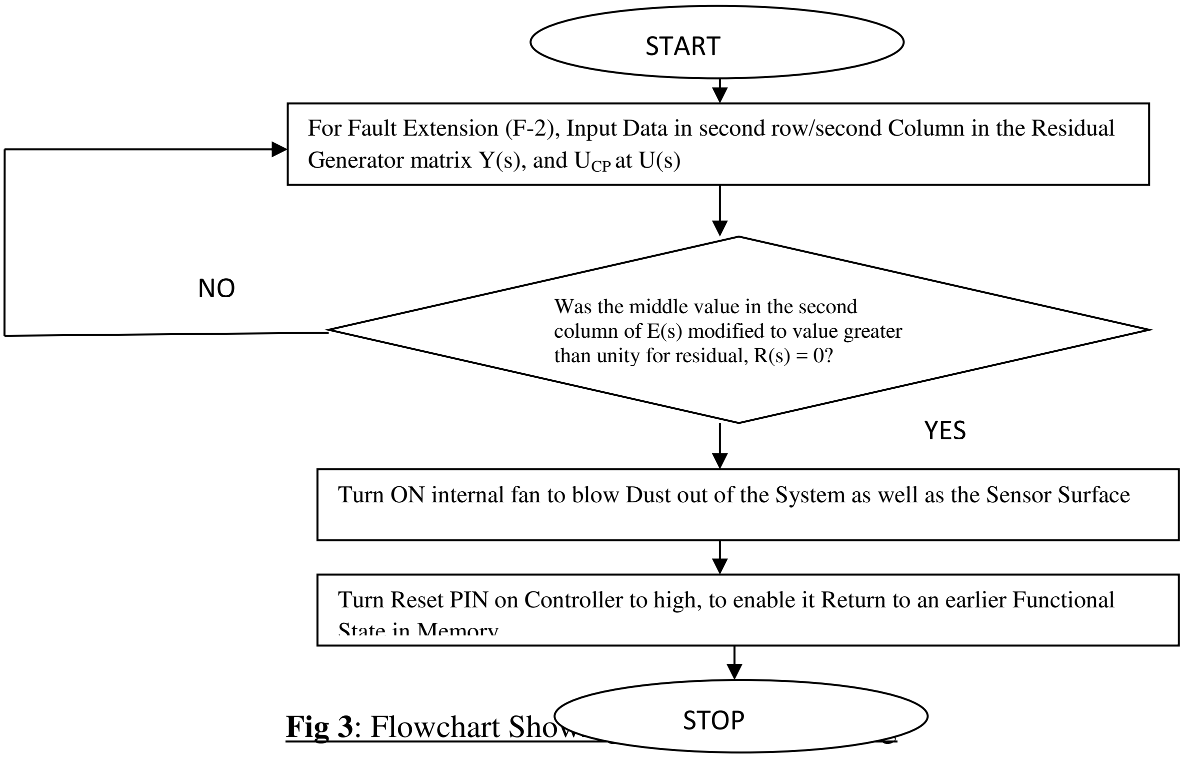

Fig 3: Flowchart Sho

Thus in the sensor, if the output is less or greater than the input, this implies the possibility of an off-set bias, if the transfer function is zero, it implies the possibility of a drop-sensor fault.

In fault condition (F-3), the matrix is modified for there to be no residual as observed, But if there is a residual, then the system uses a mirror image of the residual to push it to a zero value. This action is the case with respect to using redundancy to solve a problem.

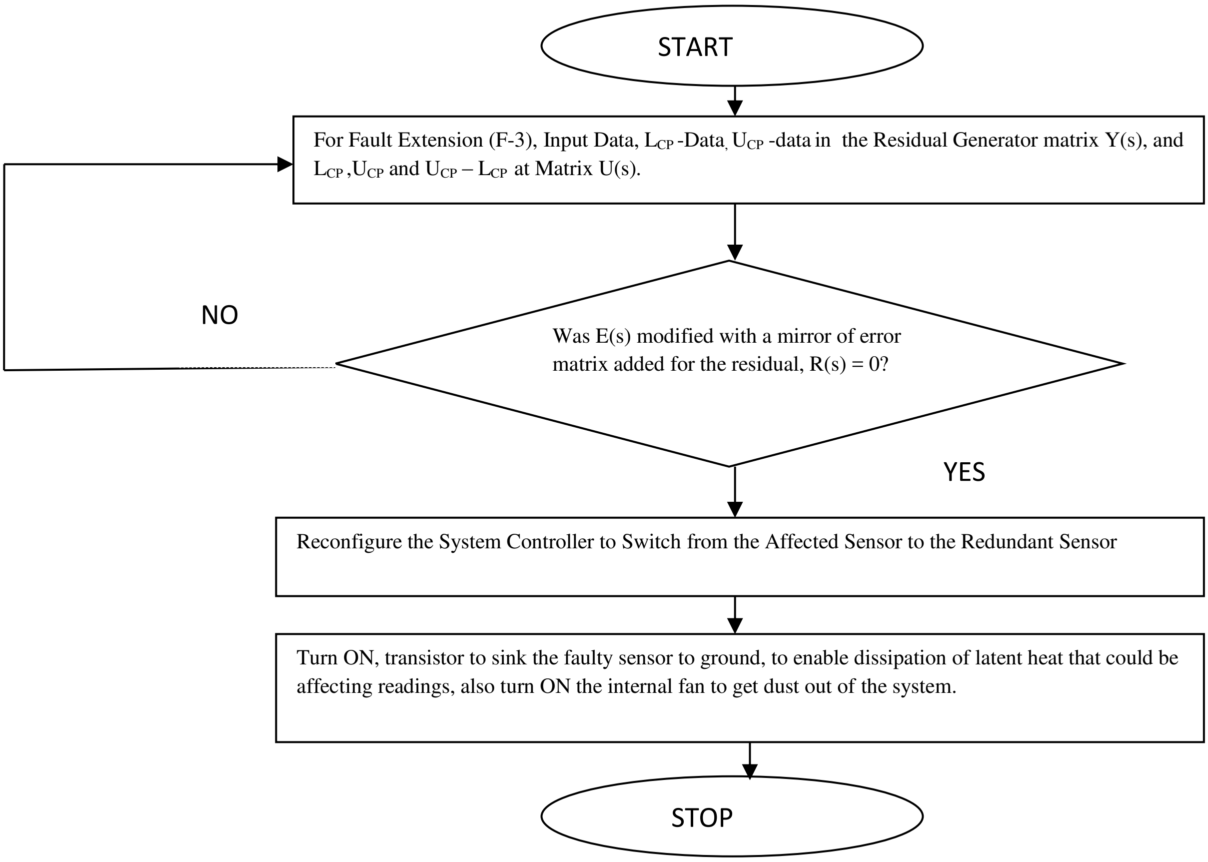

Fig4: Flowchart Showing (F-3) Fault Handling

V. CONCLUSION

The fault tolerant microcontroller based data acquisition system provides a tool for real time monitoring of pollutant level at any location deployed. The system was deployed at an industrial facility and it performed reliably. The use of control logic in the design is to provide flexibility as most industrial areas would require a measure of multiple pollutants not just CO and NO. the system provides onsite information relay to the organization of study to enable them deduce their pollution contribution to the overall air quality of their surrounding area and thus undertake whatever pollution control measure they may deem appropriate. The error residual generator based FDI is located at the supervisory control module. This ensures the system can switch between redundant sensors at will and also cut off a drop out sensor till future maintenance occurs.

VI. FUTURE WORKS:

This same technique can be used in more complex process control applications, where multiple sensors and actuators are employed. Faults and failures occur frequently and any deployed system must be robust enough to detect, isolate and control the variables to ensure degradable continuity even in the presence of undesirable conditions.

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Edward .O. Ofoegbu born on the 14th of December 1985, has a master's degree (distinction) in Electronics and Computer Engineering (Control) from Nnmadi Azikwe University, Awka , Anambra State, Nigeria in 2012 and a bachelors in electrical/electronic and computer engineering from Nnamdi Azikwe University, Awka, Anambra State, Nigeria in 2007.

He has worked as a production supervisor at Ricco Foods ltd, as a business development manager at joopee Nig Ltd, as a lecturer/researcher at Oduduwa University and currently as a Lecturer and researcher at Adeleke university ede, Osun, State, Nigeria

Engr Ofoegbu O Edward is a member of the Nigerian institute of management, Nigerian society of engineers and has numerous publications in the field of control and computing.

Hycainth .C. Inyiama born on the 14th of july 1948, has a Doctorate degree in microprocessor based electronic control from university of Manchester institute of science and technology (UMIST), Manchester, UK in 1981 and a bachelors in computer technology, university of Wales, university college of Swansea, SA2 8PP, UK in 1978

He has worked as an assistant radio and technical officer for Nitel Nigeria, a special research assistant at USMIT, Professor and head of department of computer science department at Enugu State University and is currently a professor at nnamdi azikwe university, awka ijn the department of electronics and computer engineering.

Prof H.C .Inyiama is a member of Nigerian society of engineers, council of registered engineers in Nigeria, member of IEEE, full member of institute of data processing management (MIDPM), UK. And also a member of the Nigerian Computer Society.