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Performance Analysis of Temperature Monitoring and Control System for Industrial Gas Plant Using Wireless Sensor Network

C.O. Ohaneme
Department of Electronic and Computer Engineering
Nnamdi Azikiwe University
Awka, Nigeria
E-mail: co.ohaneme@unizik.edu.ng

B. Onwubalili
Department of Electrical/Electronic Engineering
Federal Polytechnic
Oko, Anambra State Nigeria
E-mail: tochalili2@gmail.com

S.U. Ufoaroh
Department of Electronic and Computer Engineering
Nnamdi Azikiwe University
Awka, Nigeria
E-mail: sufoaroh@yahoo.com

ABSTRACT

This paper describes the analysis of a remote temperature monitoring and control system for an industrial gas plant using wireless sensor network. Software has been developed with JAVA programming language which provides an operator with a graphical user interface to remotely monitor the temperature of the industrial gas plant and also to remotely control the temperature of the plant by regulating the speed of a DC Fan. An operator could also choose to allow the DC fan to be automatically regulated so that when temperature of the plant rises above a certain limit, the DC fan will be automatically switched on. ZigBee modules are used to establish the wireless sensor network because of its low cost and high data integrity even in harsh industrial environments and LM 35 has been used as the temperature sensor because of its direct read out in the Celsius scale. The result shows that the temperature of the gas plant was able to be controlled remotely using an incorporated dc fan as the cooling system.

Keywords: Temperature Monitoring and Control, Wireless Sensor, Gas plant

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1. INTRODUCTION

Gas plants have been developed over the years for the manufacture of various gases at a commercial scale. Some of these plants include oxygen gas plant, ammonia gas plant, liquefied natural gas (LNG) plants, etc. in recent past, a considerable world trade in LNG was developed. Presently, LNG represents a significant component of the energy consumption of many countries and has been utilized as household fuel for cooking and also industrial fuel for heating and generating power. Liquefied natural gas is the liquefied form of natural gas at cryogenic temperature of -160˚C. This is done mainly for the purpose of storage and transportation since the volume of LNG shrinks by a factor of approximately 600 when liquefied.

However raw natural gas is made up of predominantly methane and other contaminants such as ethane, propane, hydrogen sulphide, carbon dioxide, etc. and must be purified to meet the quality standards specified by the pipeline transmission and distribution companies [1]. The LNG plant therefore undergoes a number of processes to separate the contaminants from the gas so as to meet up with specified standards and also liquefy it for storage and transportation purposes. The contaminants such as hydrogen sulphide and carbon dioxide can be removed using chemical processes, however, hydrocarbon contaminants like ethane, propane and butane must be removed through distillation. The distillation stage of the plant involves first the liquefaction of the natural gas at a temperature of about -160˚C and then raising the temperature of the resulting liquid to the boiling point temperature of the various contaminants so that they are recovered as vapours which are then led through various distillation columns to their respective reservoirs. The distillation stage of this plant therefore requires critical temperature monitoring and control as when the temperature of the plant surpasses the specified boiling point temperature of the required contaminant, a mixture of natural gas with the contaminants will occur [1]. These various contaminants are recovered at very low temperatures of less than 0˚C since the gas must be liquefied before any separation can occur through distillation. These temperatures fall within the handling capacity of the temperature sensor (LM 35) used in this work and it is thus suitable at the distillation stage of this plant.

Temperature monitoring and control were previously achieved in this plant using wired systems, but included an added cost of installing, terminating, testing, maintaining and troubleshooting the wired network. However, recent advances in technology have made possible the production of wireless intelligent, autonomous and energy efficient wireless sensors which can be deployed in large numbers across the plant [2]. The wireless sensor network (WSN) therefore consists of a network of spatially distributed sensor nodes which acquire temperature readings from the plant and relay such information to a sink node which gathers the information, processes it and may therefore control the temperature of the plant by for example, activating a relay to switch on a cooling fan. The wireless sensor nodes used at the distillation stage of the LNG plant can thus be distributed at the various distillation columns of the contaminants to ensure recovery of only the contaminants without any mixture with the desired natural gas (methane). Temperature control shall be achieved in this plant by utilizing fans which will act as a cooling system.

Although, wired monitoring and control systems have been successfully employed to monitor and control the temperature in the LNG plant, the immovability of the wired system and the high cost of running cables makes WSNs more preferable as cables are only required in WSNs for connection of the sink node to a personal computer (PC). Compared with wired monitoring systems, WSNs have many inherent advantages such as lower cost, convenience of installation and ease of relocation [3].

2. REVIEW OF RELATED LITERATURES

In a work done by [4], remote monitoring and control system was developed for oil and gas industry using Zigbee based wireless communication approach. The parameters to be monitored in such industry include pump status, valve status, temperature, pressure and fluid levels. The equipment that need these monitoring are pumps (motors), valves and pipelines. The pipeline temperature for example, is a very critical parameter that needs monitoring and an overshoot of localized temperature in the pipeline can lead to accidents. The pipelines are spread across several kilometres and the only solution is to monitor them from a remote centralized location. The technique that was utilized in this work was to deploy temperature sensors on each of the pipelines equally distributed along the entire length of the pipeline.

The temperature measurements gotten from these pipelines are then sent to the centralized remote location for output control execution. The control in this work was implemented by decreasing the rate of the oil inflow into the pipelines as the temperature increased by controlling a set of inlet valves and oil pumps since an increase in the rate of the oil inflow leads to an increase in the pressure of the oil that eventually results in an increase in the temperature of the oil pipeline due to increase in the kinetic energy of the oil molecules. According to the author, Zigbee was seen as a new wireless technology operating in the Industrial, Scientific and Medical (ISM) bands that has been widely deployed in wireless sensor networks. It has major applications focused on sensor and automatic control such as military application, industrial control, smart buildings and environmental monitoring.

The Zigbee protocol was defined by Zigbee alliance as a suite of high level communication protocols using small, low power digital radios based on the IEEE 802.15.4 standard for wireless personal area networks (WPAN) which allows the technology to be widely deployed in wireless control and monitoring applications. The low power usage allows longer life with smaller batteries and the mesh networking provides higher reliability and longer range. According to the author, the frameworks of the Zigbee operating arrangement can be classified as a high-tech network where each node can sense, compute and communicate with each other. They can either receive or transmit (full duplex operation) to a gateway via self-configuration and multi-hop routing in the sense that these modules have limited communication areas and must use this technique to access the nodes out of their communication areas. In this network, a node is selected and used as the coordinator node, other nodes can then function either as coordinator nodes or end sensor nodes.

The coordinator node which is usually connected to a PC has the ability of coordinating the wireless transmission of data assigning addresses to the router nodes. The router nodes defined as a full function device (FFD) are responsible for selecting the routing paths using a routing algorithm and also assigning addresses to the end sensor nodes in its coverage zone. The end sensor nodes defined as a reduced function device (RFD) are capable of only sending data to the coordinator node or router node. In a work done by [5], remote monitoring and control system was developed for a water treatment plant using Supervisory Control and Data Acquisition (SCADA) and sometimes referred to as digital control systems. It is a computer based system that remotely controls processes previously controlled manually. SCADA allows an operator using a central computer to supervise (monitor and control) multiple networked computers at remote locations. Each remote computer can control mechanical processes (pumps, valves, etc.) and collect data from sensors at its location. The central computer is referred to as the master terminal unit (MTU).

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The operator interfaces with the MTU using software referred to as human interface machine (HMI). The remote computer is referred to as the remote terminal unit (RTU) and its function is to activate a relay (or switch) that turns mechanical equipment on and off. The RTU also collects data from sensors. In the water treatment plant, the parameters to be monitored are fluid level, temperature pressure, water density, water purity and pipeline flow rates and the common water treatment equipments includes valves, pumps and mixers for mixing chemicals in the water supply. The technique that was utilized in this work was to deploy a number of sensors such as fluid level sensors, pressure sensors, temperature sensors, etc. in the plant. In the water treatment plant, distillation is used to separate certain chemical elements such as magnesium, potassium and calcium from the water and this process requires critical monitoring since water vaporizes at 100˚C and above this, other chemical elements may vaporize along with the water. The readings from the various sensors in the plant are then relayed to the RTU which processes the data and may then activate control by for instance putting on a pump. The readings received at the RTU are also conveyed to the MTU which may also activate control from its remote location by sending control signals through an air interface (which maybe a microwave link, satellite link or more recently the internet) to the RTU.

In another work done by [6], a wireless automation system was proposed for a cryogenic air separation plant based on embedded web technology. This plant separates atmospheric air into its primary constituents typically nitrogen and oxygen. The plant utilizes cryogenic distillation whereby the air is first cooled until liquefaction, then the various composition of air (mainly nitrogen and oxygen) is selectively extracted by distilling the components at their boiling point temperatures. This process makes use of expanders and heat exchangers which are usually temperature monitored and controlled to ensure that only pure gases are retrieved from air without mixtures with other gases.

In this work, an operator can monitor and control the temperature of the heat exchangers through a web browser. This system makes use of an 8051 microcontroller, ADC 0808, MAX232 and temperature sensor all connected to an embedded board known as Samsung mini 24440 board which is a low cost ARM 9 development board utilizing Samsung S3C2440 processor clocked at a frequency of 400MHz. To indicate the temperature present in the heat exchangers, a temperature sensor was made to acquire the temperature readings in analogue format and ADC0808 converted the analogue readings into digital readings which could be further processed by the embedded board. The embedded board was connected to the internet through an Ethernet connection.

Thus, the temperature readings gotten in the heat exchangers are relayed by the embedded board to the internet through the Ethernet connection and thus the readings can be accessed from any location on earth through a web browser provided there is an internet connection. Also, temperature of the heat exchanger can be controlled from any remote location by activating or deactivating a cooling fan that is already interfaced to the embedded board.

Remote monitoring and controlling system has been developed for a hydrogen chloride gas synthesis plant using GSM technology as depicted by [7]. The synthesis of the hydrogen chloride gas is achieved by burning hydrogen and chlorine together in an enclosed graphite crucible and heating to a maximum temperature of 158˚F controlled by an electric heater. This temperature, the gases would not synthesize. In this system, GSM/SMS is used between the automation process and the plant operator thereby extending the mobility of the operator and GPRS based web technology for logging the monitored data to a remote server.

Hence, there is no need of a dedicated PC as the data is logged in remote server using GPRS. The system makes use of STM32V ARM Development board and GSM SIM 900A modem with GPRS activated. The above system was designed to inform the operator about the plant's temperature when it crosses the threshold value by sending SMS to the operator's mobile phone and through the mobile phone the plant's temperature can be controlled by activating or deactivating the power supply to the electric heater by having the operator send specific control messages to the ARM board through the cellular network. The temperature values can also be logged onto an SD card available on the ARM board or a remote server through the GPRS network for future reference. The advantages of this system are: (i) Establishing wireless link between the control unit and the operator using the existing infrastructure of the cellular network that reduces the initial set up time and cost (ii) Extending the mobility of the operator as the GSM Network is accessible even to remote locations. (iii) SMS cost has reduced drastically and thus system can be operated with less communication cost. The concern in this system is the unpredictable delay in message transfer between the operator and the control unit.

3. SYSTEM DEVELOPMENT AND ANALYSIS

(A) Overview of the Hardware Development Process

(i) Hardware Requirements

Two types of sensor nodes will be utilized in this paper namely:

1. Coordinator node: This node will act to receive temperature readings from the various end sensor nodes and may occasionally convey control/actuator signals to the end sensor nodes.

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End Sensor node: This node will act to acquire temperature readings the industrial environment and occasionally activate a DC Fan based on the actuator signal received from the microcontroller

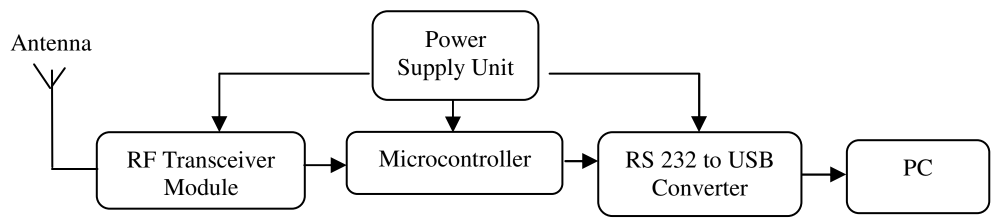

Figure 1: Block diagram of the Coordinator node

The various hardware Components/Units required for the implementation of the Coordinator node are:

- Power Supply Unit
- Microcontroller/Processing Unit
- RS232-to-TTL converter
- RF Transceiver modules
- Antenna

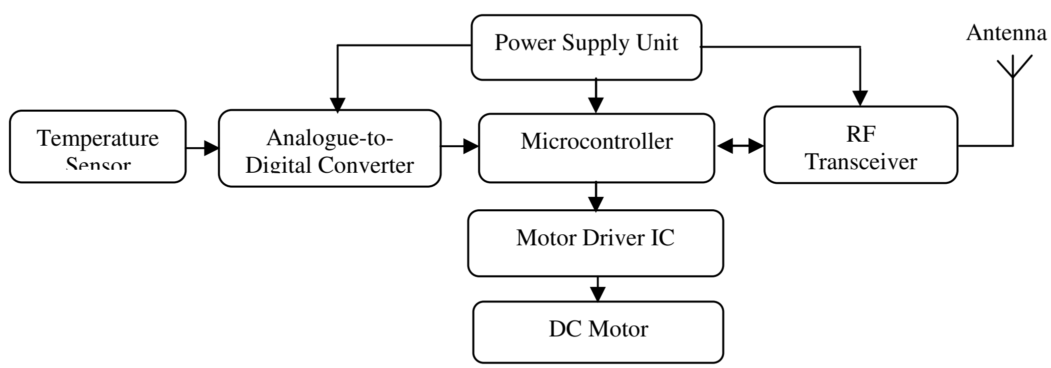

Figure 2: Block Diagram of the End Sensor Node

The various hardware Components/Units required for the implementation of the End Sensor node are:

- Power Supply Unit
- Microcontroller/Processing Unit
- Temperature Sensor
- Analogue-to-Digital Converter
- Radio Frequency (RF) Unit
- Actuator Unit
- Fan (DC Motor)

The arrangement of the end sensor node is shown in Fig. 2.

In the hardware processes, the temperature readings are acquired and relayed to the software on the PC by using the air interface. The hardware thus consists of five (5) functional units which are: Power supply unit which provides the regulated dc supply voltage of 12V d.c. from the 240Vac mains supply required for various components in the circuit to operate effectively; Sensing Unit which acquires the temperature readings from the industrial environment and forward same to microcontroller for processing; Microcontroller Unit (MCU)/Processing Unit where all processing is done; Radio Frequency (RF) the interface unit and Actuator Unit as shown in Fig. 3.

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The LM 35 requires only about 65microamperes from the supply and has a very low self-heating of 0.1˚C in still air and operates over a full -55˚C to +150˚C temperature range [8]. The analogue voltage is directly proportional (linear) to the temperature and also independent of the power supply.

(ii) Temperature Monitoring and Control Software

The software is created using Java Programming Language which is a high level language characterized by its simplicity, being object-oriented, dynamic, secured and high performance [9].

The flow chart diagram of Fig. 3 gives the operation of the software program.

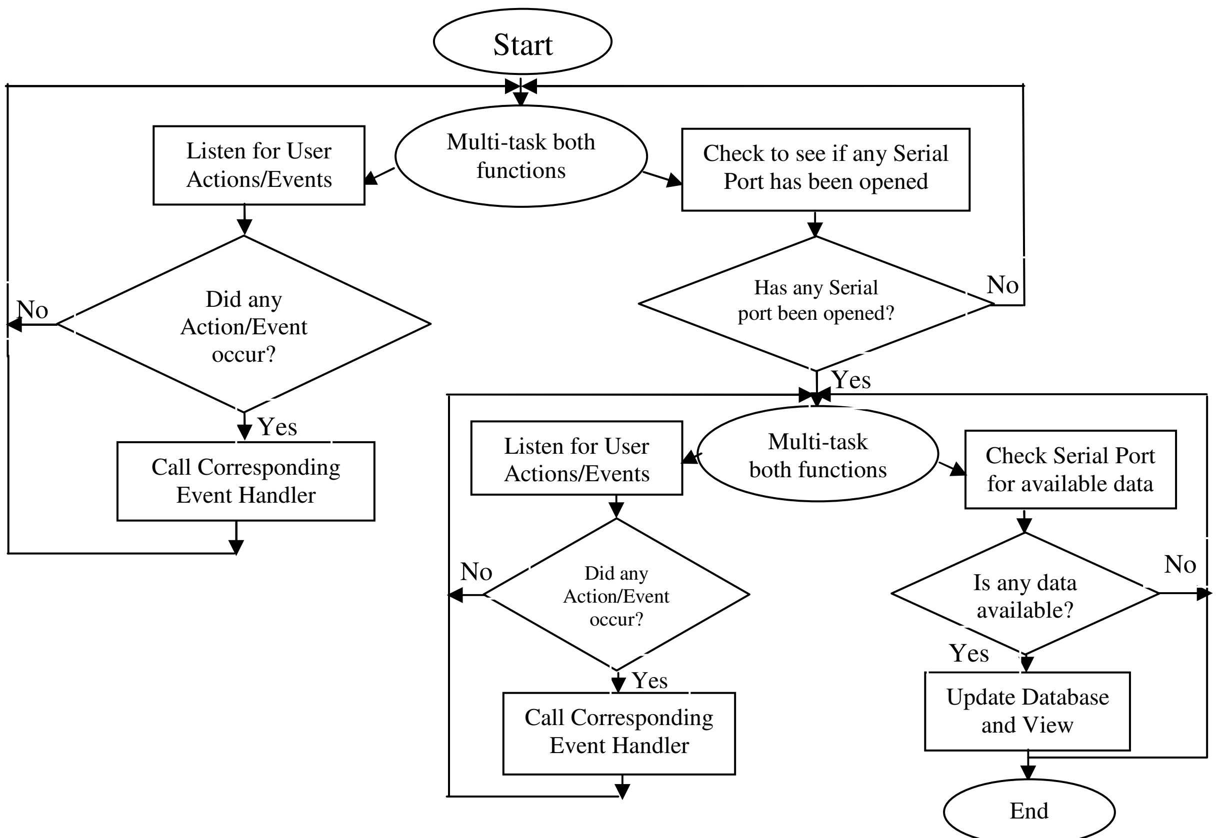

Figure 3: Flow Chart Diagram showing the model of the Temperature monitoring and control software

(B) Outline of the Software Design Process

The software is designed based on Model View Controller (MVC) pattern using an object oriented programming language known as JAVA. This pattern is used as an easy way to separate the application's logic from the GUI interface. It consists of three basic elements which are the model, view and controller as depicted in Fig. 4. From Fig. 3, the software can be developed to represent the entire process.

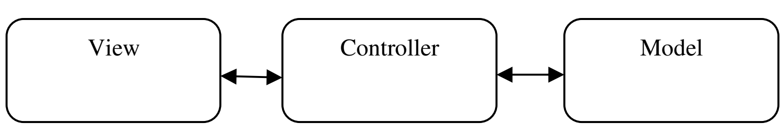

Figure 4: Block diagram of the Software Development Process

- *Model* - The model represents data and the rules that govern access to and updates of this data. This is done by Java Programming language.
- *View* - The view renders the contents of a model. It specifies exactly how the model data should be presented. If the model data changes, the view must update its presentation as needed. The view is done by FXML (FX mark-up language).
- *Controller* - The controller translates the user's interactions with the view into actions that the model will perform. This is also done using Java Programming language.

(i) Interaction between the various components of the software

The various components of the software interact in the following way [9]:

1. The controller is bound to the view. This typically means that any user actions that are performed on the view will invoke a registered listener method in the controller class.
2. The controller is given a reference to the underlying model.
3. The view registers acts as a listener on the model. Any changes to the underlying data of the model immediately result in a broadcast change notification, which the view receives. Note that the model is not aware of the view or the controller but simply broadcasts change notifications to all interested listeners.

Once a user interacts with the view, the following actions occur:

1. The view recognizes that a GUI action has occurred, for example, pushing a button or dragging a scroll bar triggers an event using a listener method that is registered to be called when such an action occurs.
2. The view calls the appropriate method on the controller.
3. The controller accesses the model, possibly updating it in a way appropriate to the user's action.
4. If the model has been altered, it notifies interested listeners, such as the view, of the change.

(a) Radio Frequency (RF) Unit

This paper makes use of a ZigBee R.F module for the realization of the air interface. ZigBee is a wireless data transceiver which is a low power spin-off of Wi-fi (Wireless Fidelity). It is a specification for small, low power radios based on IEEE 802.15.4-2003 Wireless Personal Area Network standard designed for small, low power devices like sensors for data transfer [10].

The ZigBee radios use a modulation technique known as Direct Sequence Spread Spectrum (DSSS). Direct sequence spread spectrum, also known as Direct Sequence Code Division Multiple Access (DS-CDMA) and is one of two approaches to spread spectrum modulation for digital signal transmission over the airwaves. In direct sequence spread spectrum, the stream of information to be transmitted is divided into small pieces, each of which is allocated across to a frequency channel across the spectrum. A data signal at the point of transmission is combined with a higher data-rate bit sequence (also known as a chipping code) that divides the data according to a spreading ratio. The redundant chipping code helps the signal resist interference and also enables the original data to be recovered if data bits are damaged during transmission.

(b) Microcontroller/Processing Unit

The processing unit utilized in this work is the "Arduino-Uno" which is a microcontroller board based on the ATmega328. It has 14 digital input/output pins (of which 6 can be used as PWM outputs), 6 analogue inputs, a 16 MHz ceramic resonator, a USB connection, a power jack, an In-Circuit Serial Programming (ICSP) header, and a reset button. It contains everything needed to support the microcontroller [11].

4. DESIGN MODEL OF THE MICROCONTROLLER UNIT IN THE SYSTEM

The microcontroller unit is the core of the monitoring and control system and it operates in the following ways:

- Acquires temperature readings from the temperature sensor and converts the readings into digital format using its internal ADC.
- Transmits these temperature readings serially from its serial port.
- Checks to see if the temperature of the system has exceeded a specific limit and performs necessary operations if it has.
- Also checks to see if data is present in its receive buffer (i.e. data received from PC wirelessly) and if present, identifies the specific commands in the received data and performs corresponding operations of the commands.

The flow chart diagram of Fig. 5 illustrates the microcontroller program design model and the C program code for the microcontroller system.

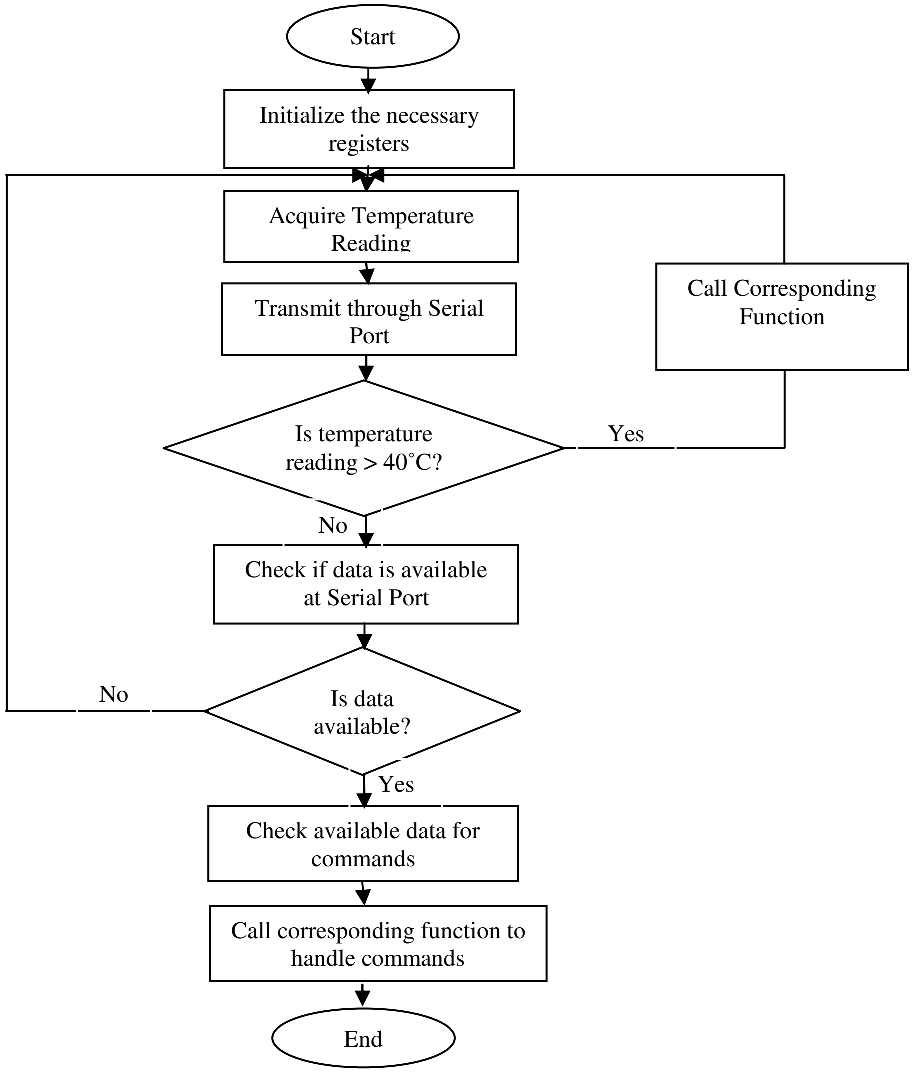

Figure 5: A Flow chart showing the design model of the microcontroller unit

(f) Actuator Unit

This unit is concerned with driving the DC fan through PWM pulses provided by the microcontroller. For this unit, the ULN2003A is used.

The ULN2003A is a high-voltage, high-current Darlington transistor array. It consists of seven NPN Darlington transistor pair that feature high voltage outputs with common-cathode clamp diodes for switching inductive loads. The collector current rating of a single Darlington pair is 500mA and can source voltages up to 50V.

The direct current (DC) motor requires a 12V, 120mA source in order to run at a maximum speed of about 3000 revolutions per minute (rpm) as specified from its data sheet.

The microcontroller however sources only 5V, 40mA which is not enough to start the motor. To resolve this issue, ULN2003A IC is used since the output of each Darlington transistor pair in the ULN2003A IC when using a 12V source is 12V, 500mA according to its datasheet.

Pulse width modulation (PWM) is utilized in controlling the speed of the DC motor by varying the duty cycle of the pulses delivered to the motor. Hence by controlling the duty cycle of the pulse supplied to the dc motor from the ULN 2003 IC, the voltage of the pulse is varied, however current remains the same. Hence through PWM, the voltage delivered to the motor can be varied effectively, thus controlling the speed of the motor.

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Average voltage delivered to the motor from a specific duty cycle is given as:

$$V_{AVERAGE} = Duty\ Cycle \times V_{INPUT} \quad (1)$$

where V_{INPUT} is the input voltage to the ULN 2003 IC which is 12V.

Therefore, a duty cycle of 50% will correspond to an average voltage of 12V × 50% = 6V.

The speed of the dc motor in rpm is given as:

$$\frac{V_{INPUT}}{V_{MAX}} \times Maximum\ speed\ of\ the\ motor\ in\ rpm \quad (2)$$

Therefore, an input voltage of 6V will correspond to $\frac{6V}{12V} \times 3000rpm$ = 1500rpm

Therefore, any motor speed can be gotten from a specific duty cycle by using the below formula:

$$DC\ motor\ speed\ (rpm) = Duty\ Cycle \times Max.speed\ of\ motor\ (rpm) \quad (3)$$

The PWM pulses of various duty cycles are generated in the internal PWM module of the ATmega 328 microcontroller through software code by specifying the duty cycle in the PWM library provided in the Arduino-Uno Integrated development environment (IDE) software.

5. SYSTEM IMPLEMENTATION

(A) Simulation of the Microcontroller and Temperature sensing Unit:

Proteus VSM is also used in the simulation of these units as shown in Fig. 6

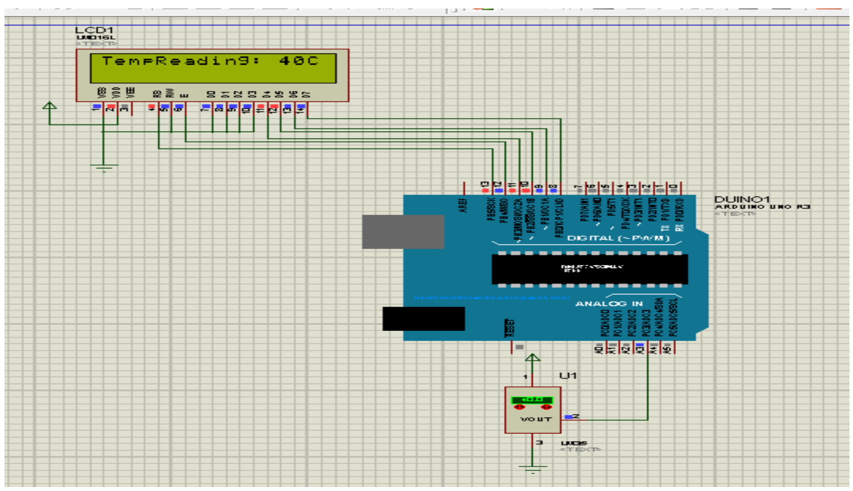

Figure 6: Simulation of the Microcontroller and Temperature Sensing Unit

For this test, LM35 on Proteus VSM is varied until it read 40˚C. The microcontroller code is then adjusted until the correct reading of 40˚C is displayed on the Liquid Crystal Display (LCD) screen.

(B) Testing of the Radio Frequency Unit

For the testing of this unit, the ZigBee Sensor Monitor software is utilized which is able to give a map of each of the nodes as they are connected to the coordinator node. For this test, the coordinator is first connected to the PC and the corresponding COM port that is created on the PC by the coordinator node is then opened on the Sensor monitor software. Then the end node is switched on which already has a temperature sensor connected to it.

The overall circuit diagram of the system is as shown in Fig. 7

(C) Units Integration

After testing and troubleshooting of the various units of the system is done, the entire units are then assembled together as shown in Fig. 7

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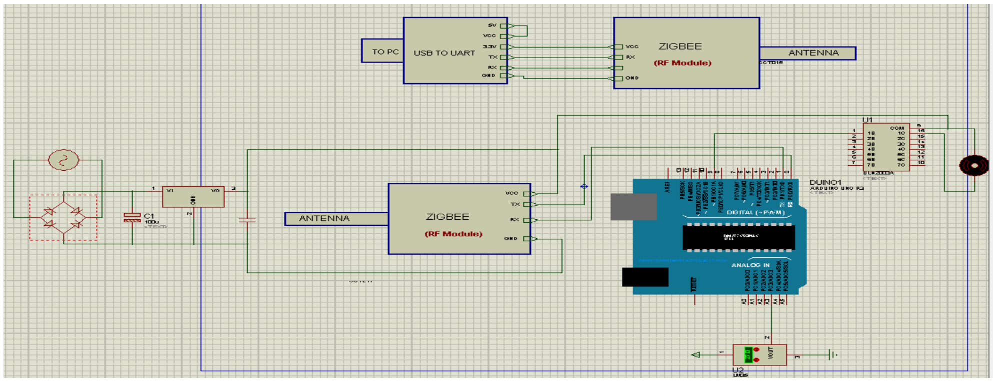

Figure 7: Circuit Diagram of the entire system

6. PERFORMANCE EVALUATION

The performance of the system is evaluated based on the test cases highlighted in Table 2. The observations and results of the system are then recorded at room temperature and on introduction of hot and cold water close to the temperature sensor (LM35).

Table 2: System's performance evaluation.

Test cases	Observation	Result
(1). At Room Temperature	Graph on the monitoring software displayed 25˚C	Fan is off
(2). On Introduction of Hot water	Graph on monitoring software displayed 80˚C	Fan came on
(3) On Introduction of Cold water	Graph on monitoring software displayed 10˚C	Fan is off

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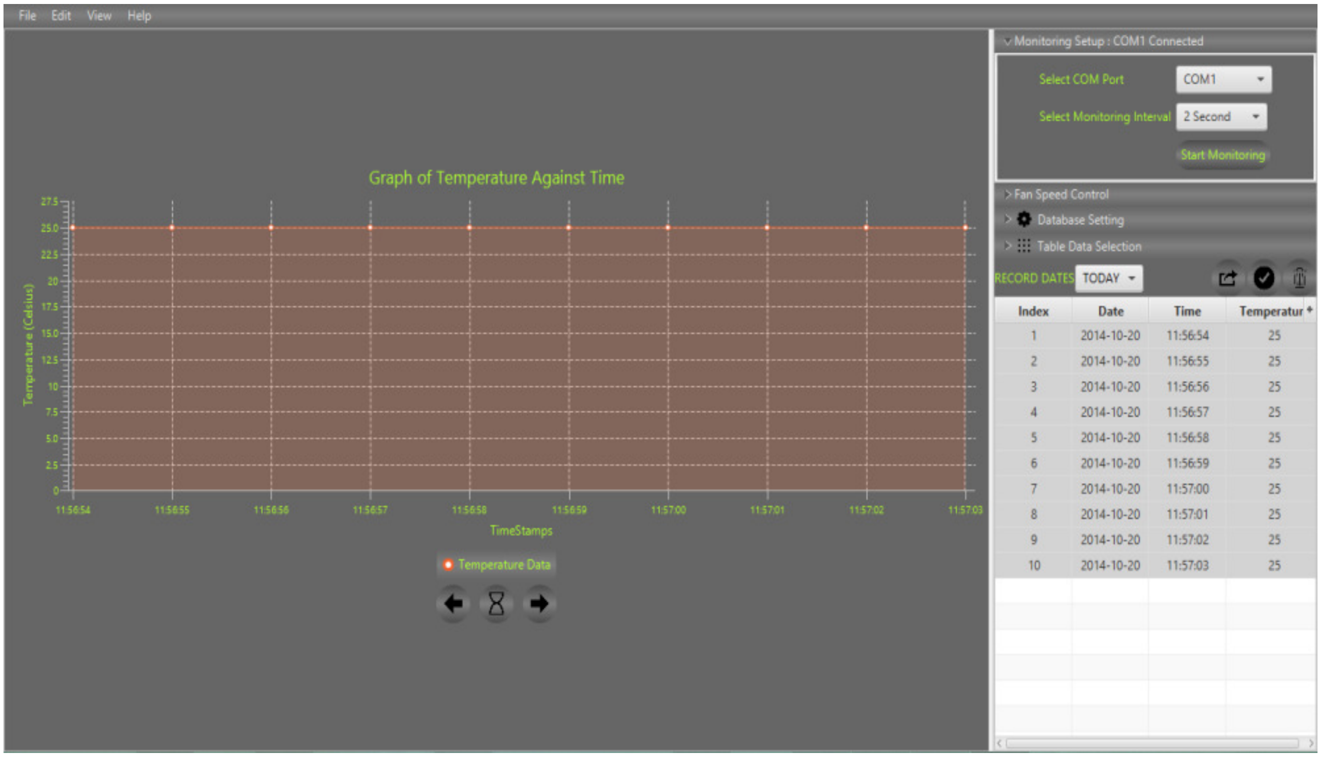

Figure 8a: Graph of temperature monitoring software at room temperature.

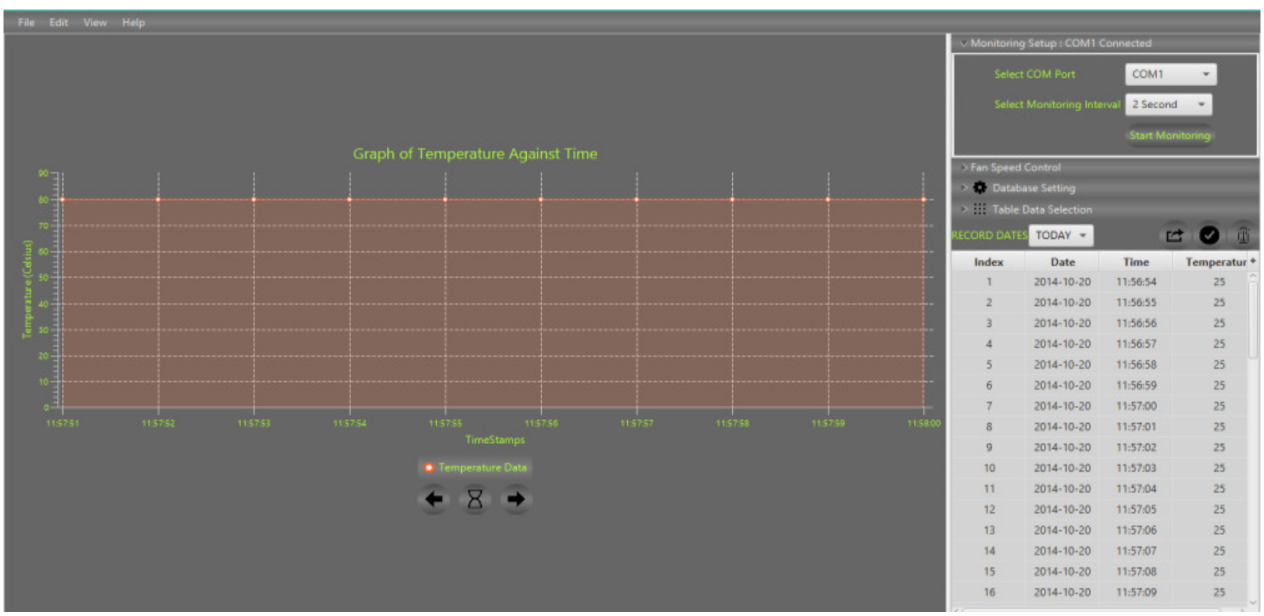

Figure 8b: Graph of temperature monitoring software on introduction of hot water

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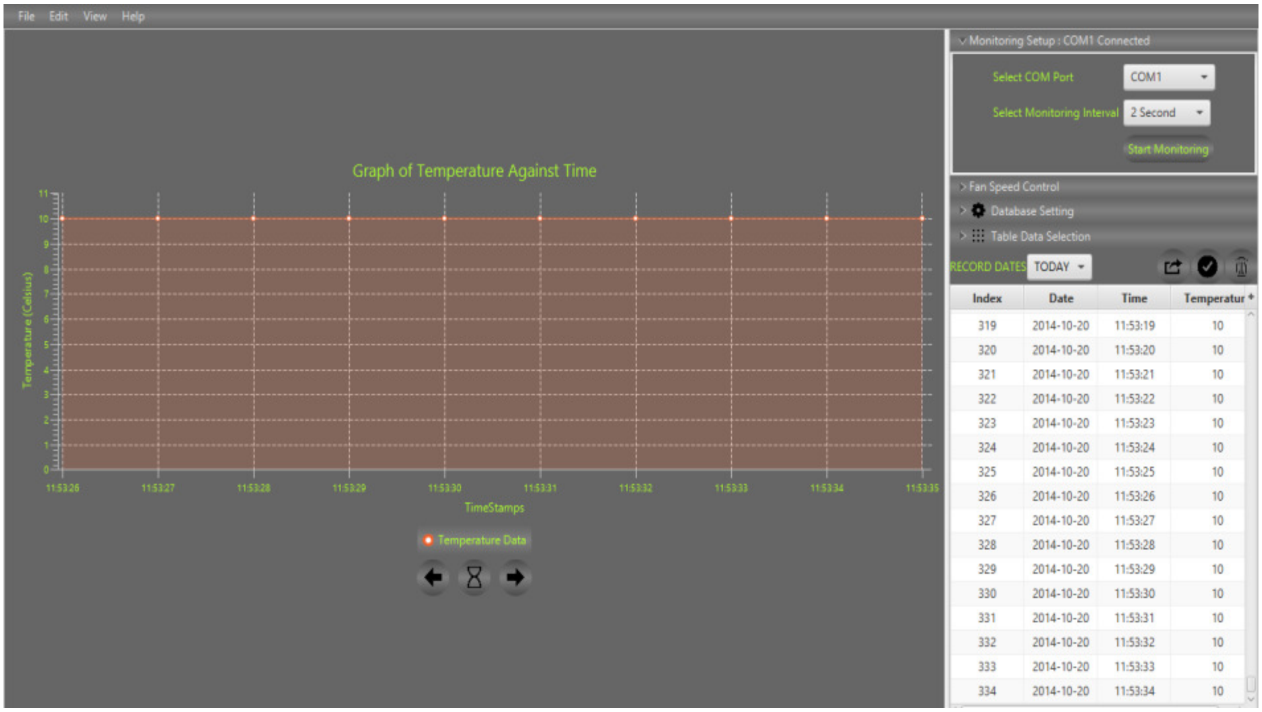

Figure 8c: Graph of temperature monitoring software on introduction of cold water

The temperature limit set for the system to switch on the fans is 40˚C. Hence at room temperature (25˚C) and on the introduction of cold water, the fan will be switched off and the graph of the monitoring software should adjust accordingly. However, on introduction of hot water, the fan should immediately turn on since the temperature (80˚C) reached has exceeded the temperature limit set at the microcontroller. These are all recorded in Table 2 and in the graphs of Fig. 8. Hence, the system functions as desired.

7. CONCLUSION

A remote temperature monitoring and control system has been fully designed and implemented for a gas plant using ZigBee based wireless sensor network. The system is capable of providing real time monitoring and control of temperatures in gas plants to facilitate effective products and/or prevent hazards having a range of more than 1km with a latency of about 40ms. The system is cheap and entails virtually no maintenance cost utilizing only two nodes. The coverage zone of this system can however be extended by utilizing more sensor nodes.

8. CONTRIBUTION TO KNOWLEDGE

The results obtained from the analysis shows that the temperature of an industrial gas plant can be monitored remotely. Since industrial gas plant posses some dangers to the personnel staff that manage the firm due to high temperatures, it therefore important that the deployment of temperature remote controller system be designed so as to

(i) Safeguard the lives of workers in the industry especially areas with very high temperature associated with gas plants
(ii) Safeguard the machineries that perform the operation in the industry
(iii) Give investors and designers the necessary technical skill to invest properly and in the most economic way to make the environment of the gas plant to be friendly to all and sundry.

Therefore, the content of this paper will enhance scholars on how temperature of the system can be monitored remotely thereby protecting lives and properties in industries and gas plant in particular.

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AUTHORS' PROFILE

1. **Cletus Ogbonna Ohaneme** is a Senior Lecturer in the Department of Electronic and Computer Engineering of Nnamdi Azikiwe University, Awka, Nigeria. He holds PhD degree in Communication Engineering in the Department of Electrical/Electronic Engineering of Enugu State University of Science & Technology Enugu, Nigeria. His research interest is on Wireless Communication and spectrum management. E-mail: engrohaneme@yahoo.com and co.ohaneme@unizik.edu.ng

2. **Christian N. Onwubalili:** is currently a Principal Lecturer in the Department of Electrical/Electronic Engineering Federal Polytechnic Oko, Nigeria. He holds B.Eng. and M.Eng. degrees in Electrical/Electronic and Computer Engineering and Electronic & Communication Engineering from the Department of Electrical/Electronic and Computer Engineering of Nnamdi Azikiwe University Awka Nigeria. He is presently a doctoral degree student in the Department of Electrical/Electronic Engineering, Emeka Odumegwu Ojukwu University Uli Anambra State Nigeria. His research interest is on Communication Engineering with special interest in Wireless & Mobile Communications.
E-mail: tochalili2@gmail.com

3. **Ufoaroh Stephen Uchenna** is currently a Lecturer in the Department of Electronic and Computer Engineering of Nnamdi Azikiwe University, Awka, Nigeria. He holds M.Eng. degree in Communication Engineering in the Department of Electronic and Computer Engineering of Nnamdi Azikiwe University Awka, Nigeria. He is also a doctoral candidate of Computer and Control Engineering in the Department of Electronic and Computer Engineering Nnamdi Azikiwe University, Awka, Nigeria. His research interest is on Software and Control Engineering. E-mail: sufoaroh@yahoo.com