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Internet of Things (IoT) based Air Pollution Monitoring in Kaduna, Nigeria

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Abstract-- **Conventional approach to air pollution monitoring using tempo-spatial measurements with instruments and air quality meters is cumbersome, stressful and unable to offer continuous monitoring. An Internet of Things (IoT) – based air pollution monitor using low cost micro-scale sensing technology was designed and developed. This system is convenient, cost effective and offers round the clock monitoring. The IoT-based air pollution monitoring system comprises of a sensor node, microcontroller (MC), internet gateway and a cloud server. Data is transmitted to ThingSpeak cloud server through HTTP command. The results are displayed on ThingSpeak webpage and remotely accessed. Three separate hardware devices were developed and deployed in three different locations within Kaduna city. These areas are Kakuri industrial layout, Ahmadu Bello way commercial center and Gonin Gora residential area. The results from these locations which are remotely assessed, indicated that the developed devices offer continuous monitoring of air pollution with minimal human intervention. Furthermore, using percentage difference, the results from the IoT – based air pollution monitor are compared with those of conventional air quality meters and found to be accurate with a tolerance value of** $\pm 5\%$.

Keywords: Air pollution, Internet of Things, Kaduna, Monitoring.

I. INTRODUCTION

Air pollution is a major problem in emerging and advanced nations of the world. Its effect on humans and the ecosystem ranges from several health hazards such as irritation of the eyes, nose and throat, lung and heart diseases, asthma and bronchitis, to environmental degradation. It is a contributing factor to climate change which is today, a major world challenge. Air pollution stem from various sources which could be anthropogenic (man-made) or natural. Anthropogenic source include burning activities (coals, wood, fossil fuel), construction, waste disposal, vehicular emissions and combustion as a result of industrial and agricultural activities. Natural sources include cosmic dust, dust as a result of wind activities, volcanic eruptions etc [1]. Mitigating air pollution starts with the knowledge of air quality humans breathe. The knowledge of the quality of air in the atmosphere is a factor of air pollution monitoring. The need to continuously monitor air pollution concentrations cannot be overemphasized as these enables individuals, organizations, government agencies and authorized bodies take adequate measures in quelling its effects.

In Kaduna, the non-existence of continuous air pollution monitoring system is a challenging factor in effecting policies to combat air pollution. Monitoring environmental air quality is necessary not only for precaution but also for awareness. Conventional approach to air pollution monitoring using tempo-spatial measurements with instruments and air quality meters is cumbersome, stressful and unable to offer continuous monitoring. It is against these drawbacks that a cost effective IoT – based air pollution monitoring system was developed. Nevertheless, recent advancement in the development of low-cost micro-scale sensing technology is radically changing the conventional approach to allow the remote access to real-time information.

A paradigm shift in technological evolution is IoT becoming an essential tool for developing smart cities. IoT makes real time monitoring of air pollution possible. IoT is a system of inter-related devices connected to the internet to transfer and receive data from one to the other. IBM simply defines Internet of Things (IoT) as the connection of devices to the internet [2]. The IoT-based air pollution monitoring system comprises of a sensor node, microcontroller (MC), an internet gateway (GSM module) and a cloud server. The sensors acquire data of temperature, humidity, Carbon Monoxide (CO), Nitrogen Dioxide (NO_2), Particulate Matter 1.0 (PM1.0), Particulate Matter 2.5 (PM2.5), and Particulate Matter 10 (PM10). These sensor data are transmitted through the MC and the internet gateway to the cloud with the aid of a developed program code written in C++. Data aggregation and visualization takes place on ThingSpeak cloud server. ThingSpeak is an IoT open cloud platform that enables things and physical devices to connect to the cloud. It uses HTTP or MQTT communications protocols to provide connection between the things and the cloud. It allows registered users to display, analyze and visualize sensor data on the platform [3].

II. RELATED LITERATURE

Basic components of IoT include:

i. The Things: these gather data and perform commands received from the cloud. Sensors and actuators belong to this category [4].

ii. The Network and Protocols: refers to existing Network infrastructure, technologies and protocols. These include; Wi-Fi, Bluetooth, Cellular, LPWAN, TCP/IP, HTTP, MQTT [5]

iii. The Platform, Apps and Services: they collect, distribute, store and analyze data. Amazon Web Service (AWS), Microsoft Azure, Google Cloud, ThingsBoard and ThingSpeak are in this category [6].

Some related works reviewed are:

In [7], a low-cost, high-fidelity air quality monitoring system was developed. MQ2 is used to sense CO, Hydrogen and Methane gasses. The sensor data is transmitted to an IoT platform through WiFi. Notification is sent to an authorized personnel when the threshold level is exceeded. The authors in [3] developed an IoT based Air and Sound pollution monitoring system. The device is built using MQ7, a sound sensor, GPRS module and an Arduino MC. The device is connected to ThingSpeak cloud platform for real-time visualization of the results. Relevant authorities and interested individuals can remotely monitor the air quality around them through the use of their laptop and mobile devices with ease. In [8], the study assessed ambient air quality in major sawmill sites in Ilorin metropolis, Kwara state of Nigeria. Handheld mobile multi – gas meters were used to take readings of various air pollutants in the sample areas. The results indicated that the concentrations of some pollutants were above acceptable limits while others were within acceptable limits. Criteria Pollutants from ten sample locations in Port Harcourt, Nigeria were evaluated for periods representing peak dry and early wet seasons of the year in [9]. The air pollution data was collected using portable air quality measuring equipment. Testo 350XL Gas Analyzer was used for measuring NO2 and CO while a 5 in 1 digital hand held air detector, BRV8 was used for measuring PM2.5 and PM10. Measurements were taken within three hours per session, morning and evening from January to April, 2017. The air quality assessment showed that NO2 and PM10 were significant and above the recommended limit.

III. METHODOLOGY

The design of the IoT – based air pollution monitoring system is developed after the block diagram shown in Fig. 1. The system consist of a sensor node comprising of DHT11, MICS 6814, and PMS5003 sensors interfaced directly with the Arduino Uno microcontroller. DHT11 measures temperature and humidity, MICS 6814 measures Carbon Monoxide (CO), and Nitrogen Dioxide (NO_2), while PMS 5003 measures Particulate Matter 1.0 (PM1.0), Particulate Matter 2.5 (PM2.5), and Particulate Matter 10 (PM10). The Arduino Uno MC receives the signals from the sensors, processes them with the aid of the developed program code then transmits the results remotely through the internet gateway (SIM 800 GSM/GPRS module) to the ThingSpeak cloud server. The data is transmitted to ThingSpeak cloud through HTTP command. The results are displayed on ThingSpeak webpage and remotely assessed. Three separate hardware devices were developed and deployed in three different locations within the city. These areas are Kakuri industrial layout, Ahmadu Bello way commercial center and Gonin Gora residential area.

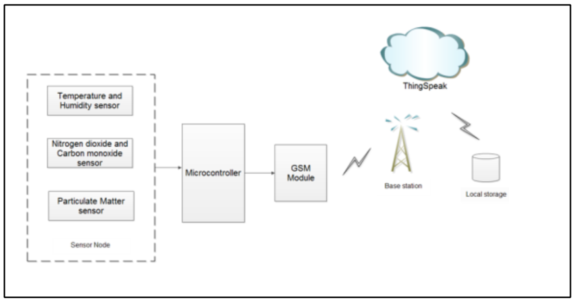

Figure 1: Functional block diagram of the IoT – based air pollution monitoring system

A. Calibrating MICS 6814 Sensor

MICS 6814, unlike its digital counterparts, DHT11 and PMS5003, is an analog sensor that was not factory calibrated. Therefore, calibration was done using the information provided in the manufacturer's datasheet. Calibration in this case means setting the output value to a standard unit which is parts per million (ppm). The characteristic curve of MICS 6814 is presented in [10]. This curve provides the relationship between the sensor resistance ratio (RS/R0) and the concentration of the target gas in part per million (ppm). The sensing layer of the sensor has a resistance (RS), which changes in accordance with the concentration of the target gas. RS is combined with R0, to produce the sensing ratio RS/R0. R0 is the sensing resistance of the sensor in clean air.

R0 was determined from the Analog voltage measured by the microcontroller. The analog voltage level on a microcontroller pin is converted to its equivalent digital value through its ADC. An Arduino Uno has a 10-bit Analog to Digital Converter (ADC). The ADC reports a ratio metric value which is depicted by equation 1 [11]

$$\frac{\text{ADC Resolution}}{\text{System Voltage}} = \frac{\text{ADC Reading}}{\text{Analog Voltage Measured}} \quad (1)$$

$$\frac{1023}{5} = \frac{\text{ADC Reading}}{\text{Analog Voltage Measured}} \quad (2)$$

From equation 2:

$$\text{Analog Voltage Measured} = \frac{\text{ADC Reading}}{204.6} \quad (3)$$

The Analog Voltage Measured (AVM) is the measured Analog voltage across the sensing resistor, $V_{RS.}$ Therefore, equation 3 can be re-written as:

$$V_{RS} = \frac{\text{ADC Reading}}{204.6} \quad (4)$$

ADC Reading is the digital output from the ADC of the microcontroller. This reading is determined by evoking the analogRead() command in Arduino programming.

As stated in the technical datasheet, the load resistance (R1), which is 56kΩ [21], forms a voltage divider circuit with the sensor resistance, RS. V_{RS} is the output of the sensor that changes with respect to the concentration of the target gas. An expression relating this to the sensing resistance (RS) and the supply voltage (Vcc) is given by equation 5.

$$V_{RS} = Vcc[\frac{RS}{RS+56k}] \quad (5)$$

From equation 5:

$$RS = \frac{56kV_{RS}}{V_{CC}-V_{RS}} \quad (6)$$

If R0 is the sensing resistance in clean air, by implication RS can be taken as R0 when the sensor is subjected to clean air. Therefore, equation 6 can be re-written as:

$$R0 = \frac{56kV_{RS}}{V_{CC}-V_{RS}} \quad (7)$$

Substituting V_{RS} in equation 5 into equation 7 gives:

$$R0 = \frac{56k\ (\text{ADC Reading})}{V_{CC} - (\text{ADC Reading})} \quad (8)$$

The digital equivalent of V_{CC} operating at 5V is 1023 considering a 10-bit microcontroller. Therefore, equation 8 can be re-written as:

$$R0 = \frac{56k\ (\text{ADC Reading})}{1023-\ (\text{ADC Reading})} \qquad (9)$$

To get the value for R0, equation 9 in was implemented in a program code using Arduino IDE. The executed program code returned 784 as ADC reading and 183.7kΩ as R0 for CO while 106 as ADC reading and 6.5kΩ for NO_2. These values are within the range stated in the technical datasheet.

B. Deriving Mathematical Relationship between Sensor Resistance Ratio (RS/R0) and the Gas Concentration in ppm

R0 combines with RS to form the sensing ratio RS/R0. The characteristic curve gives the concentration of the target gas in part per million (ppm) according to the sensing ratio (RS/R0). RS is the resistance of the sensor that changes depending on the concentration of the target gas and R0 is the resistance in clean air. The characteristic curves are shown in Fig 2 and 3 for CO and NO_2 respectively. Although, the relationship between the resistance ratio and gas concentration may seem linear, however, in reality, it is not. The scale of the graph is log-log. This implies that in a linear scale, the behavior of the gas concentration with respect to the ratio is exponential. Nevertheless, Microsoft Excel makes the otherwise complex transformations between logarithm, exponential and power functions easy.

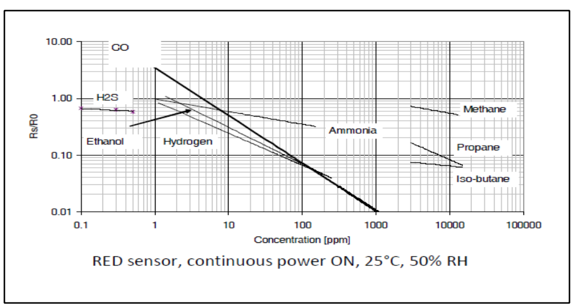

Figure 2: Characteristic Curve of CO sensor [10]

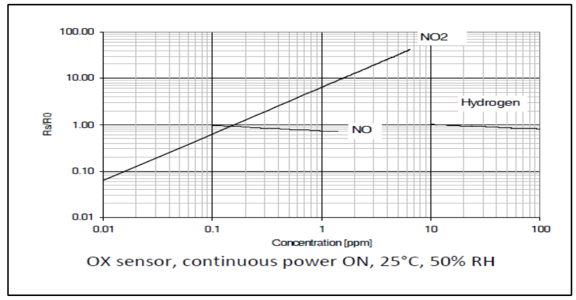

Figure 3: Characteristic Curve of NO_2 sensor [10]

Fig. 2 and 3 presents the relationship between the sensor resistance ratio (R_s/R_o) and the concentration of CO and NO_2 in ppm respectively. Several data points were manually taken from the characteristic curve, inputted into a two-column Excel sheet to generate a scatter plot. An equation derived from the trendline represents the mathematical relationship between the sensing ration (RS/R0) and the concentration of the target gas in ppm. The generated equations are displayed in equations 12 and 13. Fig. 4 and 5 are the graphs of the resulting trendline equations generated from MS Excel for CO and NO_2 respectively.

From the graph, the trendline is generated as:

$$y = 4.385x^{-1.1821} \qquad (10)$$

Where: x = concentration of the gas in ppm
y = sensor resistance ratio RS/R0
From equation 10:

$$x = 3.4917y^{-0.846} \qquad (11)$$

Therefore, equation 11 becomes:

$$COppm = 3.492(RS / R0)^{-0.846} \qquad (12)$$

Similarly:

$$NO_2\,ppm = 0.367(RS / R0)^{0.99} \qquad (13)$$

Equations 12 and 13 were implemented in the program code to calibrate the sensors.

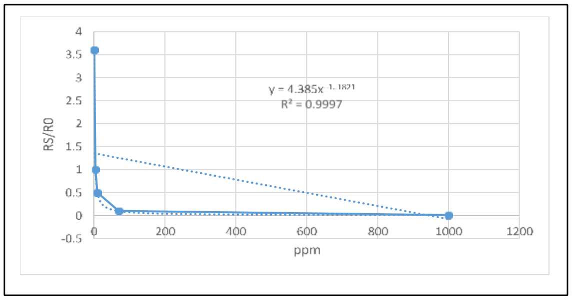

Figure 4: Excel plot showing the trendline equation for CO gas

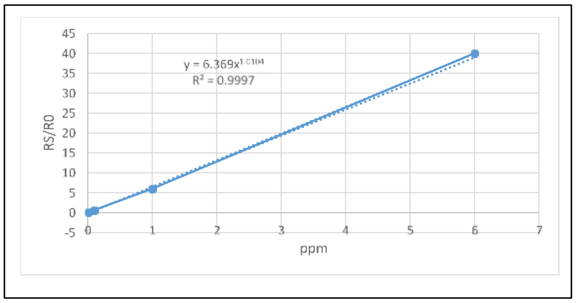

Figure 5: Excel plot showing the trendline equation for NO_2 gas

Considering the flowchart shown in Fig. 7, the program starts by loading the libraries and declaring variables. Next, the analog sensor MICS 6814 is calibrated. Furthermore, necessary computations are performed by the MC through the written program code. Serial communication is established between the sensors and the MC for data to be read from the individual sensors and results displayed on the serial monitor. Network connection is launched through the use of AT commands establishing TCP connection and Internet communication between the MC, Internet gateway and cloud. Sensor data are transmitted to ThingSpeak cloud server using HTTP GET command. The TCP connection is closed before more sensor data are read if needed, else, the program is terminated. The program is developed in C++ through the Arduino IDE. The developed hardware is displayed in Fig. 6.

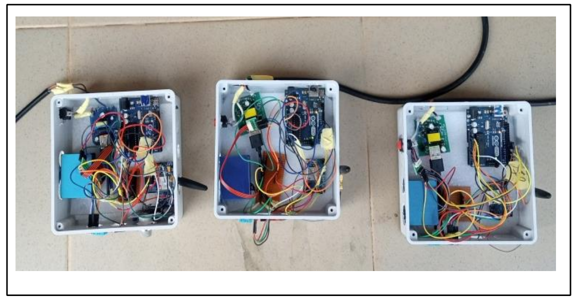

Figure 6: The three developed devices before deployment

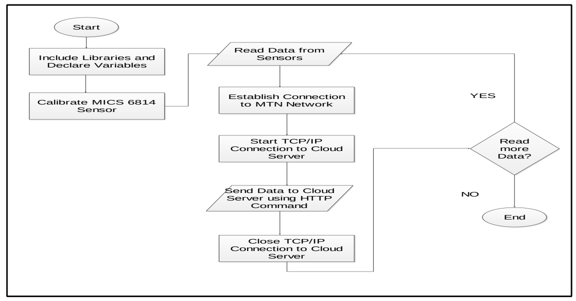

Figure 7: Program code flowchart

IV. RESULTS AND ANALYSIS OF RESULTS

The Arduino Uno MC receives the signals from the sensors, processes them with the aid of the developed program code and transmits the results through the internet gateway (SIM 800 GSM/GPRS module) to the ThingSpeak cloud server. The results are displayed in real-time on ThingSpeak webpage. Fig. 8 shows the air pollution result in real time as captured from ThingSpeak webpage. The site can be accessed remotely by logging in using its username and password. These results of the IoT – based air pollution monitoring system can be downloaded and stored in CSV format on a local storage such as a laptop. The setup acquires data at a sampling rate of one minute. Three separate hardware devices were developed and deployed in three different locations within the city. These areas are Kakuri industrial layout, Ahmadu Bello way commercial center and Gonin Gora residential area. 24 hour data was extracted from the results remotely acquired on December 8, 2021 to illustrate the continuous monitoring ability of the deployed devices. Hourly mean of each pollutant from each location was computed using MS Excel and displayed in Fig. 9 to 11.

Figure 8: Real time display of air pollution values on ThingSpeak webpage

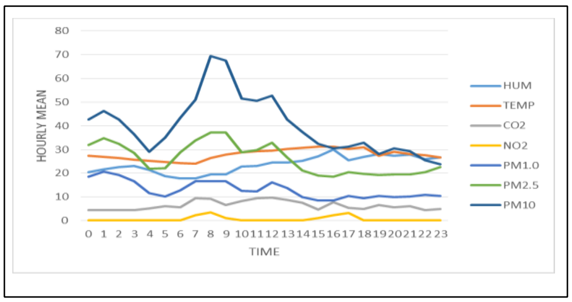

Figure 9: result of 24 hour continuous monitoring in Ahmadu Bello way (commercial)

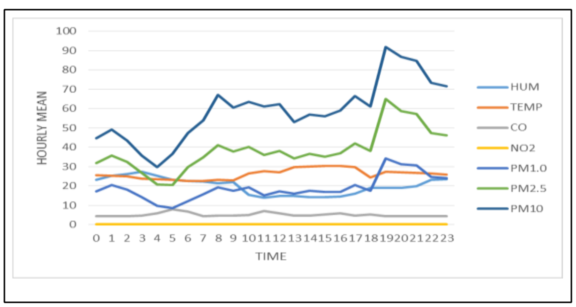

Figure 10: result of 24 hour continuous monitoring in Gonin Gora (residential)

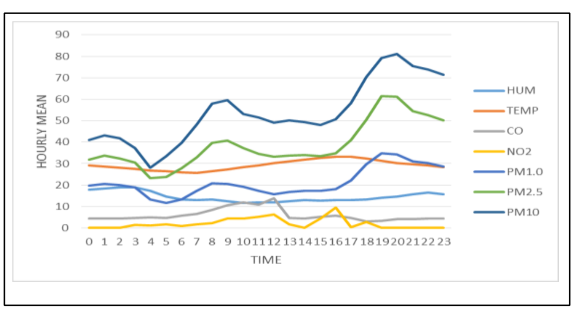

Figure 11: result of 24 hour continuous monitoring in Kakuri (industrial)

The developed IoT-based air pollution monitoring devices are capable of continuous monitoring of air pollution of any deployed area. This is indicated by the results of 24 hour continuous monitoring shown in Fig. 9-11. The result of the developed IoT – based air pollution monitoring device was compared with those from conventional air quality meters using percentage difference. The values were acquired simultaneously from the residential area (Gonin Gora). The test using the air quality meters were conducted for a period of two hours at a sampling rate of five minutes while that from the developed IoT device was remotely acquired from ThingSpeak cloud server. Three different air quality meters were used. AS8700A meter for measuring CO, BH-90A meter for measuring NO_2 and VSON air quality monitor for measuring temperature, humidity and particulate matter (PM1.0, PM2.5, PM10).

For any two numbers belonging to the same category, the percentage difference determines the difference between the two numbers expressed as a percentage. The percentage difference is used to determine the closeness of two values of the same category relative to each other. The results of this test is displayed in table 1 where the percentage difference is computed from the mean values acquired from the four devices. Percentage difference is given by [12]:

$$\%\ \text{difference} = \frac{|a-b|}{(a+b)/2}\, x100 \qquad (14)$$

Where a and b are real numbers

Using equation 14, the percentage difference for the measured parameters were computed and displayed in table I. In the table, A represents values from the IoT-based air pollution monitoring device while B represents values from the air quality meters.

TABLE I. COMPUTATION OF PERCENTAGE DIFFERENCE

Parameter	*A (mean)*	*B (mean)*	$\lvert A-B \rvert$	$A+B/2$	*% difference*
Humidity	54.06	55.41	1.35	54.735	2.47
Temperature	29.8	29.2	0.6	29.5	2.03
CO	6.21	5.94	0.27	6.075	4.44
NO_2	1.58	1.62	0.04	1.6	2.5
PM1.0	5.41	5.18	0.23	5.295	4.34
PM2.5	9.82	9.41	0.41	9.615	4.26
PM10	12.47	11.99	0.48	12.23	3.92

The percentage difference for humidity is 2.47%, 2.03% for temperature, 4.44% for CO, 2.5% for NO_2, 4.34% for PM1.0, 4.26% for PM2.5 and 3.92% for PM10. Generally, the resultant percentage differences are very low, basically, they are less than 5%. This implies that the measurements from the devices are very close having a tolerance value of $\pm 5\%$. Therefore, results of the IoT – based air pollution monitor are accurate with a tolerance value of $\pm 5\%$.

V CONCLUSION

A system that can continuously monitor the air pollution around a given location with minimal human intervention has been designed and developed. This system replaces the conventional approach to air pollution monitoring requiring tempo-spatial measurements with instruments and air quality meters which is cumbersome and stressful. The conventional approach is also limited in observation times. The IoT – based air pollution monitoring device is however, convenient, cost effective and offers round the clock monitoring. The results from the developed device, which is acquired remotely, is found to be accurate with a tolerance value of $\pm 5\%$. The IoT air pollution monitor can effectively replace conventional air quality meters and offers individuals, governmental agencies, and organizations firsthand information about the air quality around them.

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