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Design and Prototyping of a Low-Cost IoT-Based Air Pollution Monitoring Hardware System for Warri City

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ABSTRACT: *The deployment of real-time air quality monitoring infrastructure in developing cities is often constrained by high cost and limited scalability of conventional monitoring stations. This paper presents the design, prototyping, and field evaluation of a low-cost Internet of Things (IoT)–based air pollution monitoring hardware system developed for urban deployment in Warri Metropolis, Nigeria. The proposed hardware prototype integrates particulate matter and gas sensors with a microcontroller-based data acquisition unit and a GSM communication module for real-time data transmission to a cloud server. The system measures key air pollutants including $PM_{2.5}$, PM_{10}, ozone (O_3), and carbon monoxide (CO), while allowing integration of meteorological parameters such as temperature and relative humidity during data interpretation. Detailed hardware architecture, sensor specifications, electrical characteristics, calibration ranges, and field measurement outputs are presented. Field deployment results demonstrate stable sensor performance and reliable data transmission under real environmental conditions. The proposed hardware system offers a scalable, energy-efficient, and cost-effective solution for urban air quality monitoring in resource-constrained environments.*

KEYWORDS: Air Pollution Monitoring, IoT Hardware, Gas Sensors, Particulate Matter, Arduino, GSM Communication engine.

I. INTRODUCTION

Urban air pollution remains a significant environmental and public health concern, particularly in rapidly industrializing cities where continuous air quality monitoring infrastructure is limited. Long-term exposure to particulate matter ($PM_{2.5}$ and PM_{10}) and gaseous pollutants such as ozone (O_3) and carbon monoxide (CO) has been strongly associated with respiratory and cardiovascular diseases, reduced life expectancy, and premature mortality (Kampa & Castanas, 2008; Cohen et al., 2017; WHO, 2018).

Conventional reference-grade air quality monitoring stations provide high measurement accuracy but are expensive, bulky, and sparsely distributed, making them unsuitable for dense urban deployment in resource-constrained environments (Cheng et al., 2014). As a result, recent research has focused on low-cost sensing technologies integrated with Internet of Things (IoT) platforms to enable scalable, real-time air quality monitoring (Postolache et al., 2009; Kumar & Jasuja, 2017).

This paper presents the design and prototyping of a low-cost IoT-based air pollution monitoring hardware system developed for urban deployment in Warri Metropolis, Nigeria. The study focuses exclusively on the hardware architecture, detailing the sensors, microcontroller, communication module, electrical interfacing, calibration ranges, and field measurement outputs.

II. SYSTEM ARCHITECTURE

The proposed hardware system follows a layered IoT architecture comprising a sensing layer, processing layer, communication layer, and power layer. Similar multi-layer IoT architectures have been widely adopted in environmental monitoring systems due to their modularity and scalability (Botta et al., 2014; Fioccola et al., 2016).

Obodoeze et al. (2021) designed a cloud-enabled IoT framework for real-time monitoring of air and acoustic pollution using the Smart Citizen Kit sensing platform. The architecture supported multi-parameter environmental acquisition and automated dataset storage for downstream analytics. Field deployment within Awka Metropolis confirmed the operational reliability of the system, with particulate matter concentrations peaking at 76 µg/m³ (PM10) and carbon dioxide levels reaching 2506 ppm. Despite demonstrating strong capability for environmental data generation, the study stopped short of applying predictive machine learning techniques, thereby leaving an important gap in intelligent pollution forecasting research.

Low-cost particulate matter and gas sensors constitute the sensing layer, while an Arduino-based microcontroller performs data acquisition and preprocessing. Real-time data transmission to a cloud server is achieved using a GSM communication module, enabling remote access and monitoring, consistent with prior IoT air quality systems (Kumar & Jasuja, 2017; Zhao et al., 2020).

Although the present hardware prototype focuses primarily on air pollutant sensing, meteorological parameters such as ambient temperature and relative humidity were considered during data interpretation and system evaluation. These parameters are known to influence gas sensor sensitivity and particulate dispersion in urban environments. In this study, meteorological conditions were obtained from nearby weather stations and publicly available meteorological services and were used qualitatively to contextualize observed pollutant trends rather than being directly sensed by the hardware node. This approach is consistent with prior low-cost air quality monitoring studies where external meteorological data complement pollutant measurements (Botta et al., 2014; Zhao et al., 2020).

2.1 Hardware Block Diagram

The developed system, referred to as the Warri Air Quality IoT Metering System (WAIMS), consists of four major hardware subsystems:

1.Sensing Unit – gas and particulate matter sensors
2.Processing Unit – microcontroller-based data acquisition
3.Communication Unit – GSM cellular transmission
4.Power Supply Unit – regulated DC power system

The hardware setup/sensor node design was implemented in four stages as follows, and illustrated in Figure 2.1. Figure 2.2 depicts the block diagram of the system. Figure 2.3 shows the circuit diagram of the WAIMS system.

1)Integration of sensors with Micro Controller Unit (MCU)
2)Integration of MCU with communication devices
3)Field deployment using IP66 Casing
4)Power management

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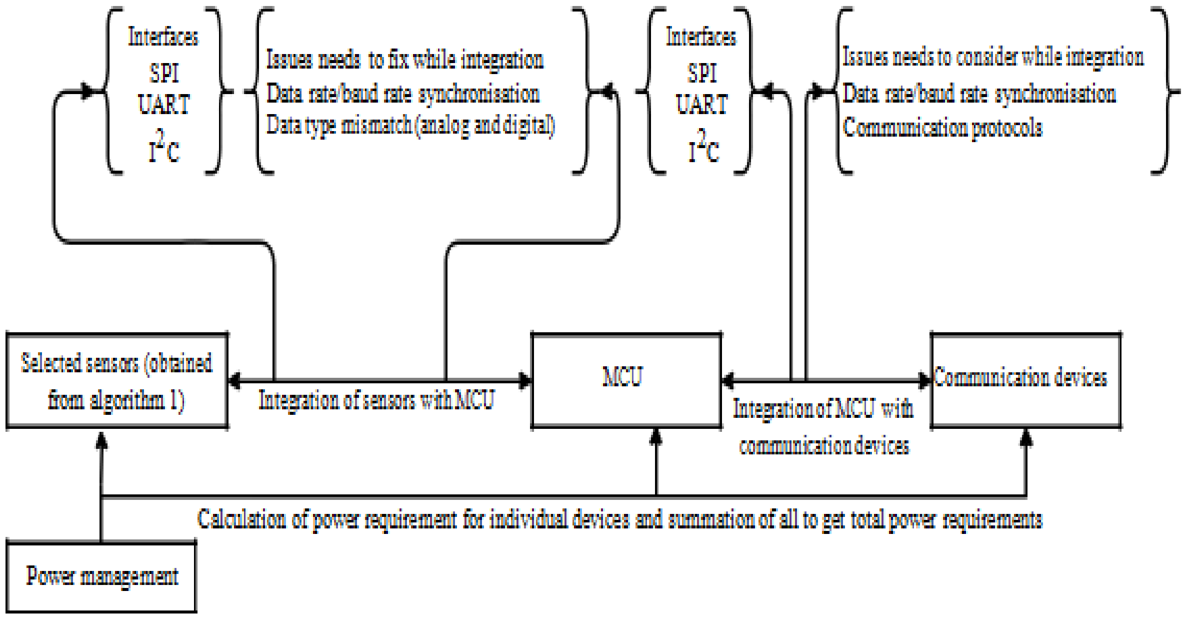

Figure 2.1: Hardware setup preparation with Low Cost Sensors (LCS) for WAIMS

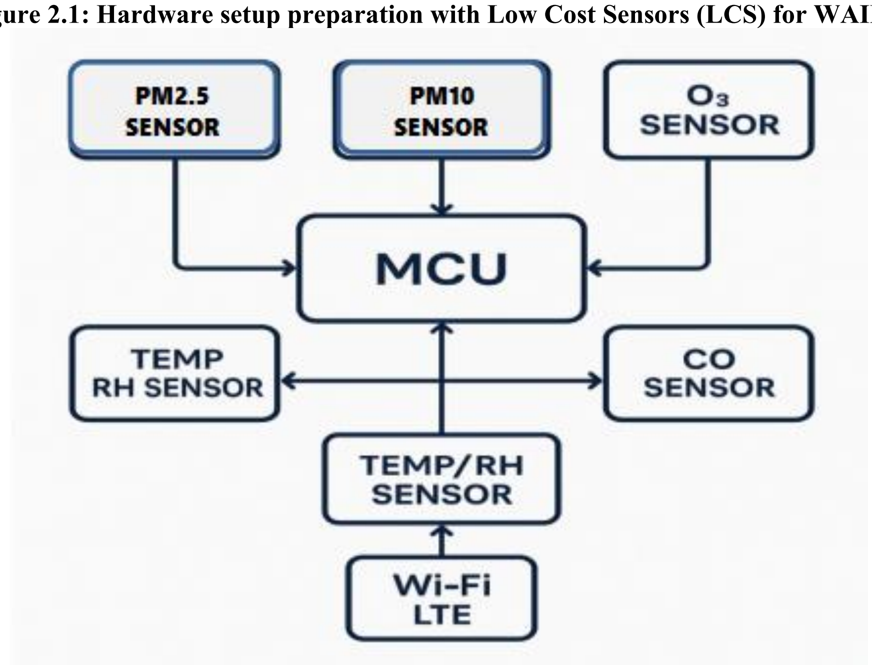

Figure 2.2: Block diagram of WAIMS Outdoor monitoring system

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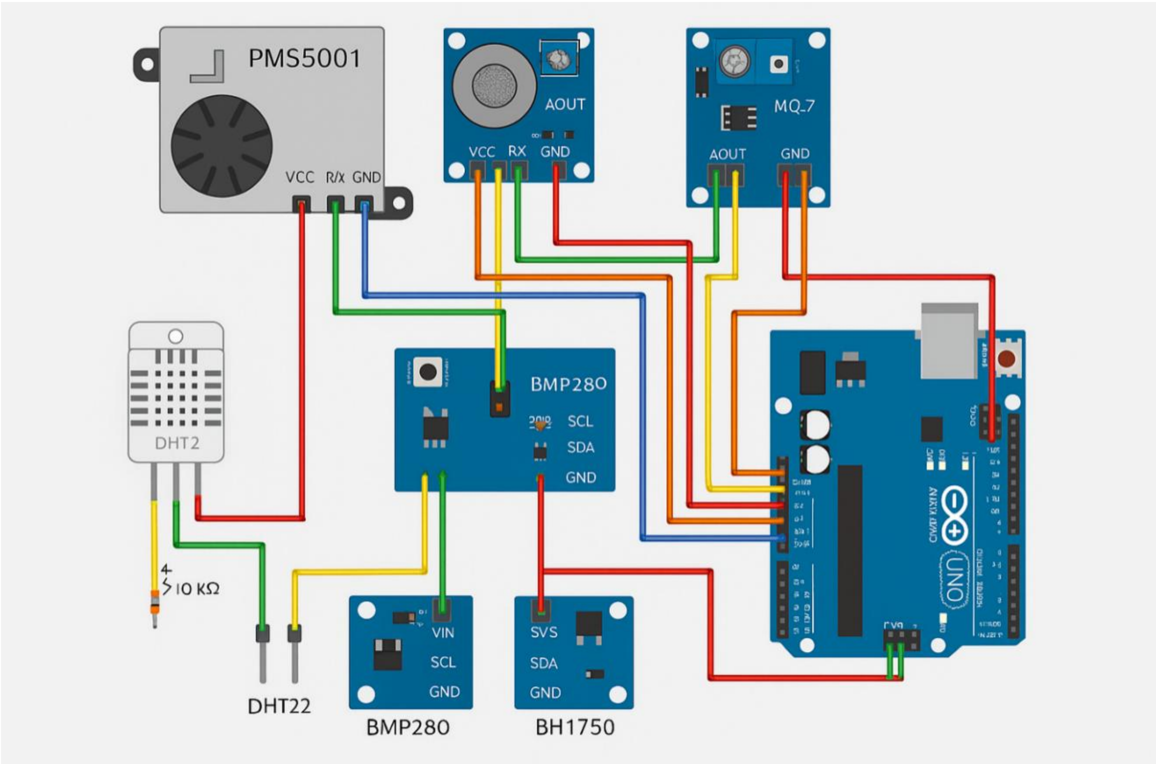

Figure 2.3: The circuit diagram of WAIMS Outdoor monitoring system

III. EXPERIMENTATION

3. Hardware Components and Specifications

3.1 Microcontroller Unit

An **Arduino Uno (ATmega328P)** microcontroller was employed as the central processing unit. Arduino-based platforms are widely used in environmental monitoring applications due to their low power consumption, ease of programming, and compatibility with a wide range of sensors (Bandyopadhyay & Sen, 2011; Postolache et al., 2009). Table 3.1 shows the Arduino Uno specifications.

Table 3.1: Arduino Uno (ATmega328P)

Parameter	**Specification**
Microcontroller	ATmega328P
Operating Voltage	5 V
Input Voltage	7–12 V
Clock Speed	16 MHz
Flash Memory	32 KB
SRAM	2 KB
EEPROM	1 KB
Analog Inputs	6 (10-bit ADC)
Digital I/O Pins	14

Justification:
Arduino Uno was selected due to its low power consumption, wide sensor compatibility, ease of programming, and robust performance in outdoor deployments.

3.2 Particulate Matter Sensor

The **Plantower PMS5001 laser scattering sensor** was used for $PM_{2.5}$ and PM_{10} measurements. Optical particle counters based on laser scattering principles have been shown to provide reliable particulate concentration estimates when properly calibrated, making them suitable for low-cost urban air quality monitoring (Cheng et al., 2014; Zimmerman et al., 2018). Table 3.2 shows the PMS50001 specifications.

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Table 3.2: Plantower PMS5001 (Laser Scattering Sensor)

Parameter	Specification
Measured Pollutants	$PM_{2.5}$, PM_{10}
Measurement Range	0–500 µg/m³
Resolution	1 µg/m³
Accuracy	±10 µg/m³ (0–100 µg/m³)
Operating Voltage	5 V
Communication	UART
Response Time	<1 s

Principle of Operation:
Laser scattering detects particle concentration based on light diffraction caused by airborne particulates.

3.3 Gas Sensors modules

Carbon monoxide and ozone concentrations were measured using **MQ-series metal oxide semiconductor (MOS) gas sensors**. MOS sensors are widely adopted in low-cost air pollution monitoring due to their high sensitivity, affordability, and ease of interfacing, despite known limitations such as cross-sensitivity and temperature dependence (Harrop, 2018; Anwar et al., 2020).Gas concentration values were estimated using manufacturer sensitivity curves, acknowledging that MQ-series sensors provide semi-quantitative measurements rather than reference-grade accuracy.

Table 3.3 shows the MQ-7 Gas Sensors'specifications.

3.3.1 Carbon Monoxide Sensor

Table 3.3: MQ-7 Gas Sensor

Parameter	Specification
Target Gas	Carbon Monoxide (CO)
Detection Range	20–2000 ppm
Heater Voltage	5 V (cycled)
Load Resistance	10 kΩ
Output Type	Analog
Preheat Time	≥24 hours

Principle of Operation:
Metal Oxide Semiconductor (MOS) technology; resistance changes in presence of CO gas.

Table 3.4 shows the MQ-131 Ozone sensor's specifications.

3.3.2 Ozone Sensor

Table 3.4: MQ-131 Gas Sensor

Parameter	Specification
Target Gas	Ozone (O_3)
Detection Range	10–1000 ppb
Operating Voltage	5 V
Output Type	Analog
Sensitivity	High to O_3
Cross-Sensitivity	NO_2 (low)

3.5 Communication Module

A **SIM7600 GSM module** was integrated to enable real-time data transmission over cellular networks. GSM-based communication has been extensively used in IoT environmental monitoring systems, particularly in regions with limited Wi-Fi infrastructure (Fioccola et al., 2016; Arroyo et al., 2019).
Table 3.5 shows the SIM7600 GSM Module's specifications.

Table 3.5: SIM7600 4G GSM Module

Parameter	Specification
Network Type	LTE / GSM
Data Transmission	HTTP / TCP
Operating Voltage	5–12 V
SIM Support	Nano SIM
Antenna	External

Function:
Transmits sensor readings in real time to a cloud server via cellular network.

3.6 Circuit Diagram Description

The hardware architecture consists of a sensing layer, processing layer, communication layer, and power layer. Particulate and gas sensors interface directly with the Arduino Uno microcontroller. Analog sensors are connected to ADC pins, while digital sensors communicate via UART. The GSM module handles real-time data transmission to the cloud. Table 6 shows the pin mapping table for all the sensors.

Table 3.6: Pin Mapping Table

Component	Arduino Pin	Signal Type
PMS5001 (PM Sensor)	TX/RX (D2, D3)	UART
MQ-7 (CO)	A0	Analog
MQ-131 (O3)	A1	Analog
SIM7600 GSM	TX/RX (D8, D9)	UART

3.7 Sensor Calibration and Measurement Ranges

Sensor calibration was performed following manufacturer-recommended burn-in procedures and baseline environmental measurements. While low-cost sensors cannot fully replace reference-grade instruments, prior studies have demonstrated that proper calibration significantly improves measurement reliability for urban monitoring applications (Zimmerman et al., 2018; Zhao et al., 2020). Table 3.7 shows the sensors' calibration ranges and their units.

Sensor calibration and interpretation were conducted with consideration of prevailing ambient temperature and humidity conditions, as these factors are known to affect the response characteristics of metal oxide semiconductor gas sensors.

Table 3.7: Sensor Calibration Ranges and Units

Sensor	Pollutant	Unit	Min	Max
PMS5001	$PM_{2.5}$	µg/m³	0	500
PMS5001	PM_{10}	µg/m³	0	500
MQ-7	CO	ppm	20	2000
MQ-131	O_3	ppb	10	1000

Calibration was performed using baseline environmental conditions and manufacturer-recommended burn-in procedures.

3.8 Electrical Interfacing and Data Acquisition

Analog gas sensors were interfaced with the Arduino's 10-bit ADC channels, while the particulate matter sensor and GSM module communicated via UART serial interfaces. Similar interfacing approaches have been reported in earlier IoT-based air quality monitoring systems (Postolache et al., 2009; Kumar & Jasuja, 2017).

- Analog gas sensors (MQ-7, MQ-131) connected to Arduino ADC pins
- PMS5001 connected via UART serial interface
- GSM module interfaced via serial communication
- Data sampled at fixed intervals and packetized for transmission

3.9. Field Deployment and Sample Sensor Readings

Field deployment was conducted across industrial, traffic-dense, and residential zones within Warri Metropolis. Observed pollutant concentrations reflected known emission patterns associated with vehicular traffic and industrial activities, consistent with previous studies conducted in oil-producing and urban regions (Balmes & Guarnieri, 2014; Minichilli et al., 2019).
Figure 3.4 shows the final WAIMS module deployed to different hotspots of Warri Metropolis.

Figure 3.4: WAIMS outdoor monitoring module

3.10 Deployment Locations

Ten sensor nodes were deployed across industrial, traffic-dense, and residential zones in Warri Metropolis. Table 3.8 depicts the sample field sensors' readings obtained from field deployments.

Table 3.8: Sample Field Sensor Readings

Location	$PM_{2.5}$ (µg/m³)	PM_{10} (µg/m³)	CO (ppm)	O_3 (ppb)
Industrial Area	58.4	121.6	3.21	46.8
Traffic Junction	44.7	96.3	2.87	38.2
Residential Area	29.5	62.1	1.44	24.6
Market Area	51.9	110.4	3.02	41.3

3.11 Power Consumption Analysis

Power consumption analysis revealed that the GSM communication module accounted for the largest energy demand during data transmission, a trend consistent with prior IoT monitoring studies (Botta et al., 2014; Fioccola et al., 2016). The total hardware cost of approximately USD 105 demonstrates the economic feasibility of deploying dense sensor networks for urban air quality monitoring in developing cities. Table 3.9 shows the power consumption analysis of the components.

Table 3.9: Power consumption analysis of the hardware components

Component	Current (mA)
Arduino Uno	~50
PMS5001	~100
MQ Sensors	~150
GSM Module	~300 (peak)

Total average consumption ≈ **600 mA** during transmission. Table 10 presents the Bill of Engineering and Measurement Evaluation (BEME).

Table 3.10: Bill of Materials (BEME)

Component	Qty	Unit Cost (USD)	Total (USD)
Arduino Uno	1	10	10
PMS5001 Sensor	1	30	30
MQ-7 Sensor	1	5	5
MQ-131 Sensor	1	7	7
SIM7600 GSM Module	1	45	45
Power Supply & Misc.	-	8	8

Estimated Total Cost: ≈ USD 105

3.12 Discussion

The hardware prototype demonstrated reliable pollutant sensing, stable operation under outdoor conditions, and successful real-time data transmission. Particulate matter sensors showed consistent response to traffic and industrial activities, while gas sensors effectively captured CO and ozone fluctuations.

The modular design allows easy sensor replacement, scalability, and integration with advanced analytics systems..

IV. CONCLUSION

This paper presented the design and prototyping of a low-cost IoT-based air pollution monitoring hardware system for urban environments. By integrating low-cost sensors, a microcontroller-based processing unit, and GSM communication, the system provides a scalable alternative to conventional air quality monitoring stations. The presented hardware design aligns with prior findings that IoT-enabled sensing platforms can significantly enhance spatial coverage of air quality data in resource-constrained settings (WHO, 2021; Zhao et al., 2020).

Future Hardware Improvements:

1. Integration of electrochemical sensors for NO_2 and SO_2
2. Solar-powered energy harvesting
3. On-board SD card redundancy
4. Ruggedized IP65 enclosure

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