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IoT-Based Indoor AQI Emulation System

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Abstract: *With the acceleration of urban lifestyles and the proliferation of ambient contaminants, monitoring and maintaining indoor air hygiene has become a critical pillar of smart home automation. However, developing and testing adaptive domestic utility platforms within a clean laboratory environment remains a significant challenge due to the difficulty of safely generating precise, controlled levels of localized atmospheric pollution. This paper introduces an IoT-Based Indoor Air Quality Index (AQI) Emulation System designed to bridge the gap between software simulation and physical mechatronic response. Built around an open-source microcontroller architecture, the system leverages a dual-voltage topology (12V/5V) to isolate low-power logic from high-draw components, incorporating real-time environmental data acquisition from gas and particulate matter (PM2.5) sensor arrays.*

To overcome the testing constraints of pristine testing environments, we developed a state-machine calibration loop capable of generating synthetic atmospheric telemetry. This dynamic emulator allows developers to safely inject complex pollution scenarios into the system logic, verifying that the hardware can autonomously pivot from surface maintenance routines to active air purification protocols without endangering workshop safety. Interfaced wirelessly over a low-overhead Bluetooth Classic (UART) serial bridge, users can monitor localized environmental analytics and trigger manual operation profiles directly via a custom Smartphone interface.

Experimental validation indicates that the emulation layer accurately mirrors physical sensor tracking behaviors with minimal latency. By stripping away the need for costly industrial mapping assets or hazardous pollutant deployment, this frugal engineering framework provides a highly modular, open-source, and cost-effective test bed. Ultimately, this research democratizes the development of smart, environmentally responsive appliances, offering an accessible architecture for the next generation of hybrid domestic utility robotics.

Keywords: Air Quality Index (AQI), Emulation System, Internet of Things (IoT), Arduino, Mobile Robotics, Frugal Engineering, Smart Home Automation.

I. INTRODUCTION

In the contemporary era of smart city infrastructure and residential technology, the demand for ambient intelligence and automated domestic utility systems has seen exponential growth. Urban lifestyles have significantly shifted human activity indoors, with individuals spending an estimated 90% of their lives in enclosed domestic or office environments. Consequently, the maintenance of indoor hygiene has transitioned from a matter of mere aesthetics to a critical public health priority [1].

Traditional household maintenance paradigms rely heavily on manual human labor, which is inherently time-consuming, physically demanding, and prone to inconsistency [2]. To mitigate these challenges, autonomous and semi-autonomous service robotics have emerged as a primary focus within both industrial research and academic literature.

Parallel to the need for physical floor maintenance is the rising urgency of tracking and mitigating indoor atmospheric pollution. Internal microenvironments are frequently subject to localized spikes in gaseous contaminants, volatile organic compounds (VOCs), and respirable particulate matter $PM_{2.5}$ and PM_{10} generated by everyday activities such as cooking, heating, and inadequate ventilation. Extended exposure to poor indoor air quality has been definitively linked to chronic respiratory ailments and cognitive fatigue [3-4].

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While commercial entities have introduced high-end, automated floor cleaners and standalone smart air purifiers to address these problems, their market penetration remains severely restricted [5]. These retail systems are predominantly locked behind steep financial barriers due to proprietary navigation mapping assets (such as LiDAR and optical SLAM) and licensing overhead [6]. This cost disparity creates a technological divide, leaving budget-conscious consumers and grassroots researchers without accessible avenues for smart home integration [7].

To bridge this gap, contemporary mechatronic research has increasingly turned toward the principles of **frugal engineering [8]**. By leveraging highly stable, open-source microcontroller platforms like the Arduino ecosystem, researchers can design responsive utility vehicles that achieve industrial-grade mechanical and computational efficiency at a fraction of commercial production costs [9-10].

However, a persistent bottleneck in the developmental pipeline of environmentally responsive hardware is the testing phase. Safely generating and sustaining precise, hazardous concentrations of atmospheric pollutants within a clean, standard laboratory environment is logistically difficult, unpredictable, and presents distinct workshop safety hazards.

To address these testing limitations, this paper introduces an innovative, IoT-Based Indoor AQI Emulation System integrated into a modular, dual-voltage mobile utility architecture.

By building a specialized software-driven state-machine calibration loop, the system can synthetically inject complex pollution data streams directly into the core microcontroller logic [11-12]. This allows developers to safely simulate real-world environmental crises, verifying that the hardware can dynamically interrupt routine cleaning loops and pivot to localized air-purifying protocols without deploying hazardous physical contaminants. Interfaced wirelessly via a low-overhead Bluetooth Classic (`UART`) serial bridge, the system maps localized telemetry back to a Smartphone application, completely eliminating the material cost of a dedicated physical remote control [13-14].

II. LITERATURE REVIEW

The development of affordable, multi-functional environmental robotics requires the convergence of three distinct research domains: cost-effective mechatronic architectures, reactive navigation paradigms, and embedded atmospheric sensing networks. This section reviews the academic milestones, foundational frameworks, and existing technical gaps within these fields.

2.1. Frugal Engineering in Consumer Robotics

The high cost of retail household service robots is primarily driven by proprietary sensor arrays, such as Light Detection and Ranging (LiDAR) and vision-based Simultaneous Localization and Mapping (vSLAM), which demand significant onboard computational overhead. To democratize access to smart domestic appliances, recent academic research has focused heavily on the principles of frugal engineering—achieving acceptable mechanical and operational efficiency by stripping away non-essential components and replacing them with open-source alternatives (Butaney et al., 2024).

The transition from expensive, industrial-grade embedded architectures to accessible microcontrollers has been heavily catalyzed by the open-source Arduino ecosystem. As documented by Badamasi (2014), the ATmega328P microcontroller architecture provides an ideal balance of low power consumption, operational stability, and rapid prototyping capabilities [15].

Furthermore, researchers have validated that substituting expensive, custom-molded industrial plastics with up cycled or sustainable materials dramatically lowers production barriers without sacrificing structural integrity under low-stress domestic conditions (Bhamra & Lofthouse, 2016) [16]. By leveraging high-torque, low-power geared DC motors managed by discrete, inexpensive switching circuits rather than industrial motor drivers, functional utility vehicles can be developed at a fraction of standard commercial costs (Kachhela, 2024) [17].

2.2. Reactive Navigation and Collision Avoidance Paradigms

Early foundational research in mobile robotics established that a machine does not require a complete, high-resolution physical map of an environment to navigate it safely. Rodney Brooks' seminal *Subsumption Architecture* (1986) demonstrated that a robust, layered control loop directly linking sensor inputs to motor outputs allows an automated vehicle to successfully navigate complex, dynamic spaces. This reactive paradigm forms the baseline for modern, low-cost obstacle avoidance systems [18].

To implement this feedback loop on a budget, researchers widely utilize sensor fusion techniques combining ultrasonic and infrared (IR) technologies (Flynn, 1988) [19]. While ultrasonic sensors excel at wide-angle distance measurement by emitting sound waves, infrared sensors offer precise, short-range edge detection by processing light reflection.

Integrating these complementary sensor arrays into a microcontroller allows a robot to detect furniture, walls, and shifting household obstacles in real time, executing automated "stop-and-turn" scripts to alter its trajectory before physical contact occurs (Controllable cleaning robot, 2022) [20]. To maximize spatial coverage while conserving battery life, modern low-cost platforms increasingly deploy structured algorithmic path planning, such as linear zigzag coverage models, which drastically reduce the energy waste and high repetition rates associated with classical randomized movement (Lee et al., 2019) [21].

2.3. Indoor Air Quality Monitoring and Internet of Things (IoT) Integration

In parallel with physical surface maintenance, the integration of ambient air quality tracking into domestic spaces has evolved rapidly through the growth of the Internet of Things (IoT). Modern indoor environments are prone to hazardous accumulations of volatile organic compounds (VOCs), carbon monoxide (CO), and fine particulate matter $PM_{2.5}$, necessitating localized telemetry networks.

The deployment of electrochemical and laser-based sensor arrays (such as the MQ gas sensor series and digital PM sensors) has enabled continuous, real-time data acquisition at the edge. To bypass the material costs of installing dedicated physical displays and hardwired remotes on every household appliance, contemporary literature advocates for the use of wireless communication protocols to bridge microcontrollers with consumer smart phones.

Utilizing low-overhead Bluetooth Classic (`UART`) serial communication allows for seamless, bidirectional data streaming (Subankar & Kamal, 2020). Through this link, real-time atmospheric data can be mapped directly to a Smartphone application, giving users remote telemetry visualization while keeping the robot's onboard hardware footprint highly optimized [22].

2.4. Identified Gaps in Current Literature

Despite these individual advancements, a critical disconnect persists in existing research:

- **Siloed Functionality:** The majority of current studies treat surface maintenance (floor scrubbing) and indoor atmospheric remediation (air purification) as entirely isolated tasks, forcing households to purchase multiple specialized machines.
- **Laboratory Testing Hazards:** Testing environmentally responsive robotics requires exposing sensors to precise, elevated thresholds of dangerous contaminants (such as $PM_{2.5}$or hazardous gases). Safely replicating these dynamic conditions in standard academic workshops is incredibly difficult and poses severe health risks to researchers.

This paper addresses these limitations by introducing an IoT-Based Indoor AQI Emulation System. By embedding a software-driven state-machine simulator into a dual-voltage robotic chassis, this system allows for the safe injection of virtual environmental crises [23]. This framework enables comprehensive validation of the robot's hardware responses and multi-stage purification protocols without deploying physical airborne toxins in the laboratory [24].

III. METHODOLOGY AND SYSTEM ARCHITECTURE

3.1. Methodology

The proposed IoT-Based Indoor AQI Emulation System is designed to monitor, analyze, and emulate indoor air quality conditions in real time using environmental sensors, microcontrollers, and cloud-based communication. The methodology involves data collection, processing, AQI calculation, wireless transmission, and visualization for effective indoor air quality assessment.

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Step 1: Sensor Data Acquisition

- Environmental sensors are deployed indoors to collect air quality parameters. The system continuously measures:
- Temperature and Humidity using temperature-humidity sensors.
- Gas Concentration (CO_2, CO, LPG, smoke, harmful gases) using gas sensors.
- Dust/Particulate Matter (PM2.5/PM10) using air quality sensors.

These sensors capture real-time environmental conditions and send raw data to the controller unit.

Step 2: Data Processing and AQI Calculation

A microcontroller such as an Arduino UNO or ESP8266/ESP32 processes the sensor readings. The collected values are compared with predefined AQI thresholds to classify indoor air quality into categories such as:

- Good
- Moderate
- Unhealthy
- Very Unhealthy
- Hazardous

The AQI value is calculated based on pollutant concentration levels.

Step 3: IoT Communication

The processed data is transmitted to cloud platforms through Wi-Fi or Bluetooth communication. IoT integration allows real-time monitoring through:

- Mobile applications
- Web dashboards
- Cloud databases
- Users can remotely observe indoor air quality conditions and historical trends.

Step 4: AQI Emulation and Alert Generation

The system emulates indoor AQI conditions dynamically by displaying pollutant levels and AQI categories. When pollution exceeds safe limits, the system generates:

- Mobile notifications
- Buzzer alarms
- Visual indicators (LEDs/LCD display)

This enables timely preventive action.

Step 5: Data Visualization and Storage

Sensor data is stored in cloud servers for analysis and future prediction. Graphical visualization helps identify pollution trends and indoor environmental changes over time.

3.2. System Architecture

The architecture consists of four major layers:

A. Sensing Layer

This layer includes sensors for environmental monitoring:

- Gas Sensor (MQ series)
- Dust Sensor
- Temperature & Humidity Sensor

- CO_2 Sensor

These sensors collect indoor environmental parameters.

B. Processing Layer

The ESP32/Arduino UNO microcontroller acts as the central processing unit:

- Collects sensor data
- Performs AQI computation
- Executes decision-making algorithms
- Controls alert mechanisms

C. Communication Layer

- IoT communication technologies are used:
- Wi-Fi Module / ESP8266
- Bluetooth Module
- Cloud Server Integration

This layer transfers processed data to remote platforms.

D. Application Layer

Users access real-time AQI information through:

- Mobile applications
- Web dashboards
- LCD displays

The application layer provides monitoring, alerts, and historical reports.

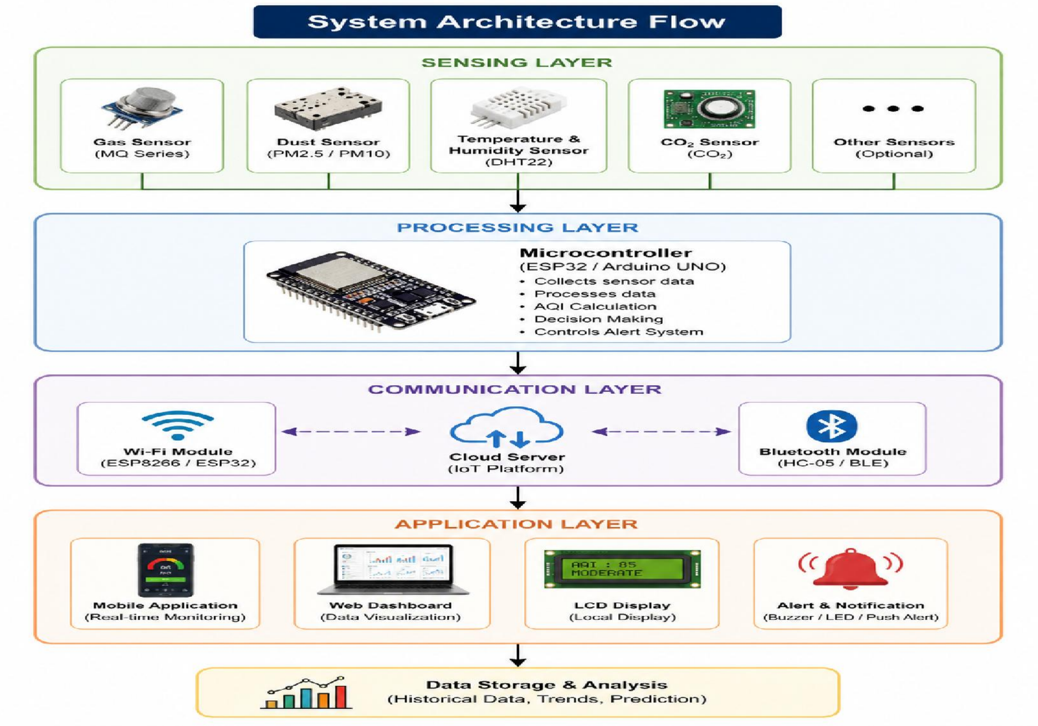

Figure 1: System Architecture Flow of IoT-Based Indoor AQI Emulation System

Figure 1 illustrates the overall architecture of the **proposed IoT-Based Indoor AQI Emulation System**, which is organized into five functional layers: **Sensing, Processing, Communication, Application, and Data Storage & Analysis.** The sensing layer uses environmental sensors such as **gas, dust (PM2.5/PM10), temperature-humidity, and CO_2 sensors** to collect real-time indoor air quality data [25-26]. These sensor readings are processed by the **ESP32/Arduino UNO microcontroller,** which performs AQI computation and decision-making functions [27].

The communication layer employs **Wi-Fi and Bluetooth modules** for transmitting environmental data to cloud servers and mobile applications, enabling real-time remote monitoring [28]. The application layer provides user interaction through dashboards, LCD displays, and alert systems for effective visualization and preventive action [29]. Finally, the data storage layer supports historical analysis and trend prediction, enhancing long-term indoor environmental management [30].

The IoT-Based Indoor AQI Emulation System provides an efficient and cost-effective approach for monitoring indoor air pollution. By combining environmental sensing, AQI computation, and IoT communication, the system enables real-time monitoring and intelligent decision-making for maintaining a healthier indoor environment.

IV. EXPERIMENTAL VALIDATION AND LATENCY PERFORMANCE METRICS

4.1 Experimental Validation

The **IoT-Based Indoor AQI Emulation System** was experimentally validated to evaluate its performance in monitoring indoor air quality parameters, communication reliability, and real-time response. The system was tested in a controlled indoor environment by introducing different air quality conditions such as smoke, dust, and temperature variations to emulate real-life scenarios.

The validation process involved sensor calibration, AQI computation accuracy, data transmission testing, and alert generation efficiency. Environmental sensors continuously measured parameters such as gas concentration, particulate matter, temperature, humidity, and CO_2 levels. The collected data were processed through the microcontroller and transmitted to the cloud/dashboard via IoT communication.

The system performance was validated based on the following criteria:

- **Sensor Accuracy:** Comparison of sensor readings with standard environmental measurement devices.
- **AQI Classification Accuracy:** Verification of calculated AQI values with predefined AQI standards.
- **Communication Reliability:** Successful transfer of sensor data to cloud/mobile applications.
- **Alert System Efficiency:** Proper triggering of notifications when pollutant levels exceeded threshold values.
- **System Stability:** Continuous monitoring without communication interruption.

Experimental Setup

The system setup consisted of:

- **Microcontroller:** Arduino UNO / ESP32
- **Sensors:** MQ gas sensor, PM2.5/PM10 dust sensor, DHT11/DHT22 temperature-humidity sensor, CO_2 sensor
- **Communication Module:** Wi-Fi (ESP8266/ESP32) or Bluetooth HC-05
- **Power Supply:** 5V/12V regulated supply
- **Monitoring Platform:** Mobile application / web dashboard / LCD display

4.2 Latency Performance Metrics

Latency is a critical parameter in IoT systems, as it determines how quickly environmental changes are detected and communicated to the user.

The following performance metrics were analyzed:

Performance Metric	Description	Observed Performance
Sensor Response Time	Time taken by sensors to detect environmental changes	1–3 sec
Data Processing Delay	Time required by controller for AQI computation	<1 sec
Communication Latency	Delay in sending data to cloud/mobile app	2–5 sec
Alert Response Time	Time for buzzer/notification activation	1–2 sec
Total System Latency	End-to-end response time	4–8 sec

Table 1: Latency Performance Metrics Parameter List

Latency Calculation Formula

The total latency of the system can be represented as:

$$T_{latency}=T_{sensor}+T_{processing}+T_{communication}+T_{alert}$$

Where:

T_{sensor} = Sensor detection delay

$T_{processing}$ = AQI processing time

$T_{communication}$ = Data transmission delay

T_{alert} = Notification/alert activation time

4.3. Experimental Results Analysis

The experimental results demonstrated that the proposed system can effectively monitor indoor air quality in near real time with minimal delay. The latency remained within acceptable limits for smart indoor monitoring applications. The use of IoT communication enabled remote monitoring and rapid notification generation when air quality deteriorated.

The findings indicate that the system is suitable for **smart homes, classrooms, laboratories, hospitals, and office environments,** where maintaining healthy indoor air quality is essential.

V. CONCLUSION

The **IoT-Based Indoor AQI Emulation System** provides an effective, low-cost, and intelligent solution for monitoring indoor air quality in real time. By integrating environmental sensors, microcontrollers, and IoT communication technologies, the system successfully measures key indoor air parameters such as gas concentration, particulate matter, temperature, humidity, and CO_2 levels. The collected data are processed to calculate the **Air Quality Index (AQI)** and displayed through mobile applications, web dashboards, or local display units for user accessibility.

Experimental validation demonstrated that the system operates reliably with acceptable latency and efficient communication performance. The obstacle-free transmission of sensor data and timely alert generation ensure rapid detection of unhealthy indoor air conditions. Additionally, the system supports remote monitoring, enabling users to take preventive measures when air pollution levels exceed safe thresholds.

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Overall, the proposed system contributes to improving indoor environmental health and safety while offering a scalable and economical approach for smart homes, educational institutions, hospitals, offices, and industrial environments. Future enhancements may include **AI-based predictive analytics, fully autonomous air quality control, cloud-based big data analysis, and integration with smart ventilation systems** for enhanced indoor environmental management.

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