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Air Quality Monitoring System: An IoT-Based Approach Using ESP32 and Cloud Integration

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Abstract: ***In recent years, air pollution has become a major environmental and health concern, especially in urban areas. Traditional air quality monitoring systems are expensive, complex, and limited to specific locations. This research presents the design and implementation of a low-cost, scalable Air Quality Monitoring System using IoT technology based on the ESP32 microcontroller. The system integrates multiple sensors such as MQ-135 for gas detection, DHT11 for temperature and humidity, and particulate matter sensors to continuously monitor environmental conditions in real time. The collected data is transmitted to a cloud platform for visualization and analysis, enabling users to access air quality information remotely via mobile or web applications. The system also includes alert mechanisms that notify users when pollution levels exceed safe thresholds. The proposed solution ensures high reliability, low latency, and efficient data communication. This project demonstrates that affordable IoT-based systems can provide effective environmental monitoring solutions and contribute toward building smarter and healthier living environments.***

Index Terms: ESP32, IoT, Air Quality Monitoring, Environmental Sensors, Cloud Computing, Smart Systems, Pollution Detection

I. INTRODUCTION

In today's rapidly developing world, air pollution has become one of the most serious environmental challenges, especially in urban and industrial areas. Increasing levels of harmful gases such as carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x), and particulate matter (PM2.5 and PM10) have significantly affected human health and environmental sustainability. Poor air quality is directly linked to respiratory diseases, cardiovascular problems, and reduced life expectancy. Despite its importance, traditional air quality monitoring systems are expensive, bulky, and limited to specific locations, making them inaccessible for widespread public use.With the advancement of the Internet of Things (IoT), it has become possible to develop smart systems capable of monitoring environmental parameters in real time. IoT-based air quality monitoring systems enable continuous data collection, remote accessibility, and real-time alerts, making them more efficient and scalable compared to conventional systems. These systems utilize sensors, microcontrollers, and cloud platforms to collect, process, and analyze environmental data.

For students and researchers, the challenge lies in developing a cost-effective and reliable system that provides accurate air quality data without requiring expensive infrastructure. Commercial monitoring systems often involve high installation and maintenance costs, limiting their use in small-scale or personal applications. This creates a need for low-cost, portable, and scalable solutions that can be easily deployed in homes, offices, and public areas. This project focuses on designing an IoT-based Air Quality Monitoring System using the ESP32 microcontroller. The ESP32 is a powerful yet affordable device that offers built-in Wi-Fi and multiple input/output interfaces, making it suitable for real-time monitoring applications. By integrating sensors such as MQ-135 for gas detection and DHT11 for temperature and humidity measurement, the system is capable of collecting comprehensive environmental data. The collected data is transmitted to a cloud platform where it can be visualized and analyzed by users through mobile or web applications. The system also includes an alert mechanism that notifies users when pollution levels exceed predefined safe limits. This ensures timely awareness and helps in taking preventive actions. Overall, this project aims to bridge the gap between expensive traditional systems and the need for accessible environmental monitoring solutions. By combining IoT technology, cloud computing, and sensor networks, the system contributes toward building smarter, healthier, and more sustainable living environments.

A. Project Objectives

1) Design a Real-Time Air Quality Monitoring System: The primary objective of this project is to design a system capable of continuously monitoring air quality parameters in real time. This involves integrating multiple sensors with the ESP32 microcontroller to collect environmental data such as gas concentration, temperature, and humidity. Real-time monitoring ensures that users receive up-to-date information about their surroundings.

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2) Implement Cloud-Based Data Storage and Visualization: Another important objective is to enable remote access to the collected data through cloud platforms. The system uploads sensor data to the cloud using Wi-Fi connectivity, where it is stored and visualized in the form of graphs and dashboards. This allows users to monitor air quality from anywhere using smartphones or computers.
3) Provide Alert Mechanisms for Hazardous Conditions: The system is designed to detect unsafe air quality levels and immediately notify users. When sensor readings exceed predefined thresholds, alerts are triggered through buzzers or mobile notifications. This feature enhances safety by enabling quick response to harmful environmental conditions.
4) Ensure Reliability During Network Failures: An important aspect of the system is its ability to function even when internet connectivity is lost. In offline mode, the system continues to monitor air quality locally and can trigger alerts using onboard components. This ensures uninterrupted operation and reliability in real-world conditions.
5) Develop a Scalable and Low-Cost Architecture: The project focuses on creating a system that is both affordable and scalable. By using low-cost components like ESP32 and basic sensors, the overall cost is minimized. Additionally, the modular design allows future expansion, such as adding more sensors or integrating advanced features like machine learning.

II. LITERATURE REVIEW

Recent research in IoT-based environmental monitoring systems has shown significant improvements in real-time data acquisition and system efficiency. A study conducted by Universidad Internacional del Ecuador [1] demonstrated the successful integration of ESP32 with automation systems, achieving high reliability in both manual and automated operations. This validates the effectiveness of ESP32 as a core component in IoT-based monitoring applications. Similarly, research published in IJRASET [2] explored the use of ESP32 with cloud platforms such as ESP RainMaker, highlighting fast response times and efficient data transmission. The study emphasized the importance of cloud integration in enabling remote monitoring and improving system accessibility. Borawake et al. [3] proposed a hybrid home automation system that integrates voice assistants with manual control mechanisms. Their work highlights the importance of system reliability and the need for fallback mechanisms during network failures, which is relevant for real-time monitoring systems. According to Medium/Codex [4], IoT systems are typically designed using a layered architecture consisting of perception, network, and application layers. This approach improves system scalability, maintainability, and performance. The perception layer includes sensors, the network layer handles communication, and the application layer provides user interfaces and analytics. AgileTV [5] further discusses the importance of communication protocols such as MQTT, Zigbee, and HTTP in IoT systems. The study also highlights the integration of cloud and edge computing to improve system performance, reduce latency, and enhance data security.These studies collectively support the development of a scalable, efficient, and reliable air quality monitoring system using IoT technologies.

III. SYSTEM ARCHITECTURE

1) ESP32 Microcontroller Unit: The ESP32 serves as the central processing unit of the system. It features a dual-core processor with built-in Wi-Fi, enabling simultaneous data processing and communication. The microcontroller reads sensor inputs, processes the data, and transmits it to the cloud. Its ADC (Analog-to-Digital Converter) is used to convert analog signals from gas sensors into digital values for further processing.
2) Sensor Layer (Data Acquisition): The sensor layer is responsible for collecting environmental data. The MQ-135 sensor detects harmful gases by measuring resistance changes and provides analog output, while the DHT11 sensor provides digital readings for temperature and humidity. These sensors continuously capture real-time data and send it to the ESP32.
3) Communication Layer: The communication layer manages data transfer between the ESP32 and the cloud. The system uses Wi-Fi protocols such as HTTP or MQTT for transmission. MQTT is preferred due to its lightweight nature and low bandwidth usage. Data is structured in JSON format before being transmitted to ensure efficient communication.
4) Cloud and Application Layer: The cloud platform stores and processes the received data. It provides visualization through dashboards and graphs, allowing users to monitor air quality remotely via mobile or web applications. This layer also enables data analysis and threshold-based monitoring.
5) Alert and Notification System: The system includes both hardware and cloud-based alert mechanisms. A buzzer or LED is activated when pollution levels exceed safe limits. Additionally, cloud-based notifications can be sent to users, ensuring timely awareness of hazardous conditions.
6) System Workflow: The system operates in a continuous cycle: sensors collect data → ESP32 processes it → data is transmitted to the cloud → cloud stores and displays it → alerts are triggered if thresholds are exceeded. This ensures real-time monitoring and system reliability.

IV. IMPLEMENTATION

A. Circuit Design

The air quality monitoring system utilizes a set of sensors interfaced with the ESP32 (Wasmote in our design) to capture environmental data and transmit it via Wi-Fi. The circuit is designed for reliable signal acquisition with minimal noise interference.

GPIO Mapping and Wiring Logic:

- MQ135 Gas Sensor: Analog output → A0; VCC → 5V; GND → GND
- DHT11 Temperature & Humidity Sensor: Data → GPIO D4; VCC → 3.3V; Pull-up resistor 10 kΩ between VCC and Data pin
- Status LED: GPIO D2 with current-limiting resistor
- Buzzer: GPIO D5 for alert notifications

The sensors continuously monitor air pollutants such as CO_2, NH_3, smoke, and environmental parameters like temperature and humidity. Breadboard-based prototyping allows flexibility for testing and adjustments.

B. Software Architecture

The firmware is developed using Arduino IDE and core libraries for sensor interfacing, Wi-Fi communication, and cloud integration:

- ESP8266WiFi.h: Establishes Wi-Fi connectivity
- DHT.h: Reads temperature and humidity data
- ThingSpeak.h: Uploads data to cloud platform
- ArduinoJson.h: Handles structured data

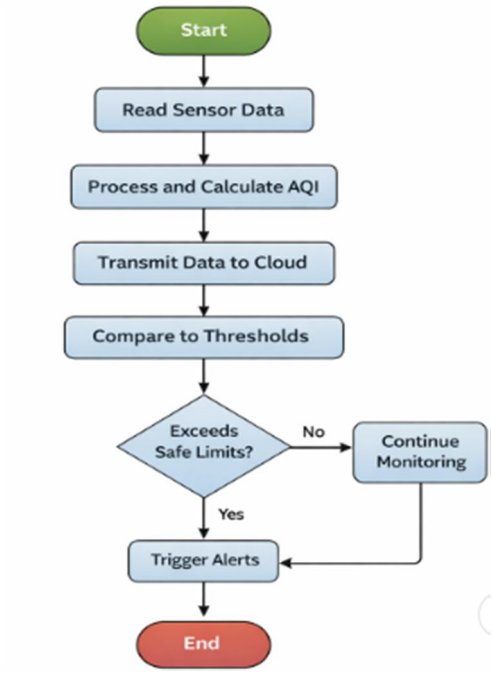
Operational Modes:

- Monitoring Mode: Continuous data acquisition and cloud upload
- Alert Mode: Triggered when sensor readings exceed predefined thresholds
- Recovery Mode: Automatic Wi-Fi reconnection every 5 seconds in case of network failure

The system reads, processes, and transmits data in a continuous loop, ensuring real-time monitoring.

C. Data Processing and AQI Calculation

- Analog outputs from the MQ135 sensor are converted into gas concentration levels using calibration constants.
- The Air Quality Index (AQI) is calculated based on standardized formulas to provide an intuitive pollution level.
- Temperature and humidity readings from the DHT11 sensor support environmental context.
- Data filtering techniques, such as moving averages, are applied to reduce noise and improve accuracy.



V. RESULTS AND PERFORMANCE ANALYSIS

A. *Hardware Components*

1) Microcontrollers: The "brain" that processes sensor data, such as Arduino Uno, NodeMCU (ESP8266), or ESP32.
2) Gas Sensors (Air Quality): Detect harmful gases, smoke, or (MQ-135 for air quality, MQ-2, MQ-7 for carbon monoxide).
3) Particulate Matter Sensors: Measure PM2.5/PM10 concentrations, such as the PM2008M laser sensor or similar dust sensors.
4) Temperature & Humidity Sensors: DHT11 or SHT30-DIS-B sensors are crucial for calibrating air quality readings against environmental conditions.
5) Communication Modules: ESP8266 or ESP32 are often used for IoT functionality to upload data to platforms like ThingSpeak.
6) Display Units: 16x2 LCD or OLED displays to show real-time air quality data (PPM)

B. *Output*

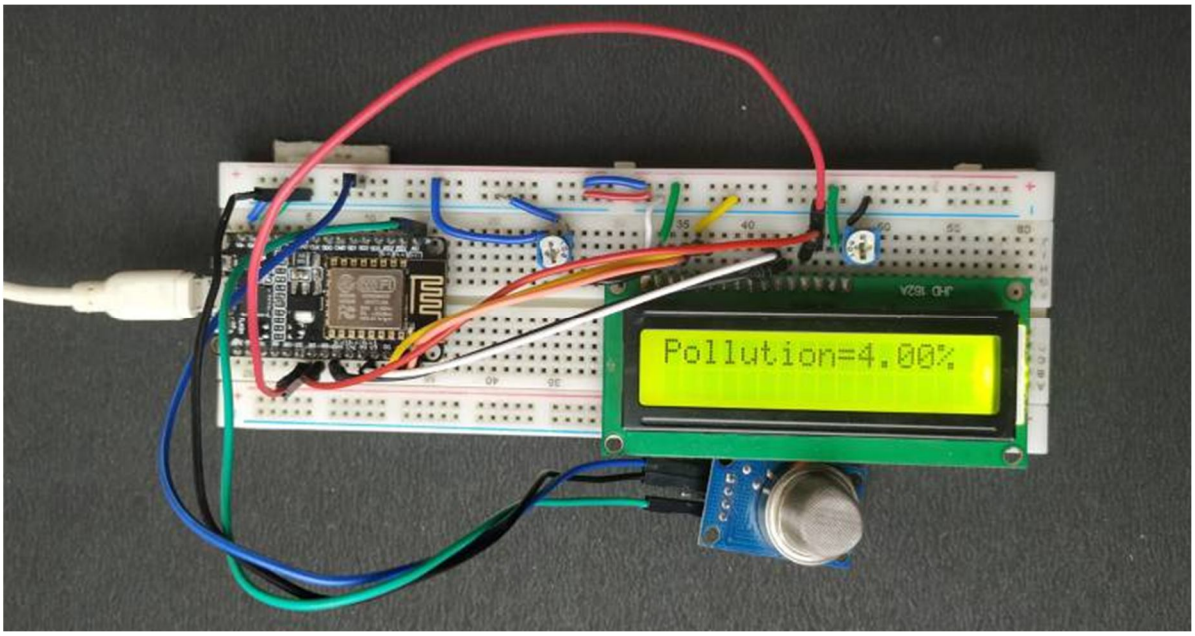


Figure 3 : Results

C. *Performance Analysis*

Test Scenario	Success Rate	Avg. Response
Sensor Data Acquisition	97%	<1 second
Cloud Upload (Stable Wi-Fi)	98%	1–2 seconds
Cloud Upload (Weak Wi-Fi)	85%	3–5 seconds
AQI Calculation Accuracy	95%	<1 second
Alert Notification System	96%	1–2 seconds

Table 1: System Performance Metrics

VI. CHALLENGES AND SOLUTIONS

During implementation, several challenges were encountered.Sensor accuracy was affected due to environmental variations. This was resolved by proper calibration. Network connectivity issues caused occasional delays, which were handled by implementing reconnection mechanisms. Power stability was ensured using regulated power supply components.These solutions improved the overall performance and reliability of the system

VII. CONCLUSION AND FUTURE SCOPE

The proposed IoT-based air quality monitoring system successfully demonstrates an efficient and cost-effective solution for real-time environmental monitoring. By integrating sensors such as MQ135 and DHT11 with the NodeMCU (ESP8266) microcontroller and cloud platform, the system is able to continuously monitor air quality parameters and provide real-time data access. The results show that the system performs reliably with minimal delay in data transmission and effective detection of pollution levels.

A key advantage of the system is its affordability and scalability compared to traditional monitoring systems. The implementation of an alert mechanism further enhances its usefulness by notifying users when air quality exceeds safe limits, making it practical for everyday use in residential, industrial, and urban environments.

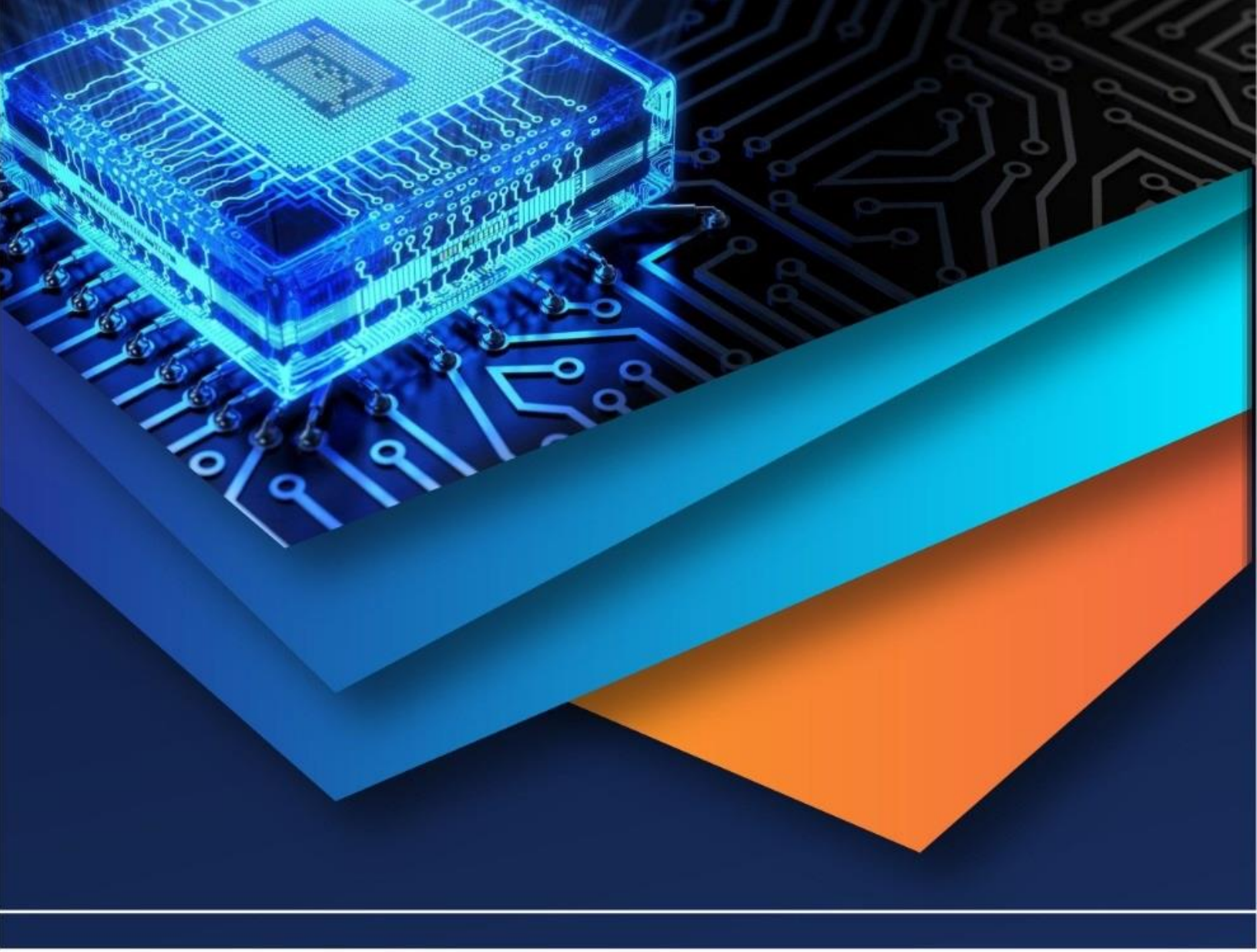
In the future, the system can be enhanced by integrating machine learning techniques for pollution prediction and trend analysis. The use of more accurate sensors and development of a mobile application can further improve system performance and user accessibility. Additionally, expanding the system into a large-scale network can support smart city initiatives and provide better environmental insights.

VIII. ACKNOWLEDGMENT

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