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A Design and Implementation of a Cloud-Integrated IoT Framework for Real-Time Urban Air Quality Monitoring

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Abstract

The rapid urbanization of cities worldwide has led to a significant increase in air pollution, posing severe health risks to urban residents. High costs, limited coverage, and a lack of real-time capabilities often limit traditional air quality monitoring methods. This paper proposes a novel IoT-based Air Pollution Monitoring (APMIoT) system designed to accurately track and evaluate urban air quality. The system utilizes a Raspberry Pi Pico W with wireless capabilities and multiple sensors to monitor Particulate Matter (PM), Carbon Dioxide (CO_2), Total Volatile Organic Compounds (TVOCs), humidity, temperature, and GPS location. The APMIoT modules transmit real-time data to a cloud-based platform, which manages data collection, visualization, and analysis from a distributed network of APMIoT sensors across urban spaces. The system leverages FreeRTOS for modular programming, facilitating efficient and independent processing and data transmission.

Keywords: IoT monitoring, Air quality monitoring, Measuring algorithms, APMIoT.

1 | Introduction

Air quality is a critical aspect of urban living, directly impacting public health and well-being. Elevated pollutant levels can result in respiratory illnesses, cardiovascular diseases, and premature mortality. Traditional air quality monitoring stations often face limitations in terms of cost, limited coverage, and a lack of real-time data capabilities. Internet of Things (IoT) technology presents a promising solution for comprehensive and

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cost-effective air quality monitoring in urban areas. By leveraging IoT devices and sensors, it is possible to establish a dense network of monitoring stations, enabling real-time data collection and analysis [1].

1.1 | The Silent Threat: A Deep Dive into Air Pollution

Air, an invisible yet vital component of our existence, has been silently deteriorating due to the relentless march of industrialization and urbanization. The once pristine air we breathe is now laden with a cocktail of harmful pollutants, posing a significant threat to human health and environmental sustainability. From the bustling metropolises to the serene countryside, the pervasive issue of air pollution has become a global concern. The insidious nature of these pollutants, often imperceptible to the naked eye, makes their impact even more alarming. As we delve into the complexities of air pollution, it becomes evident that understanding its sources, consequences, and mitigation strategies is imperative for safeguarding our planet and its inhabitants [2].

1.2 | Internet of Things

The IoT refers to the network of physical objects or "Things" embedded with sensors, software, and other technologies that connect and exchange data with other devices and systems over the internet. These devices, from household appliances to industrial machines, collect and share data, enabling automation and smarter decision-making across various applications. By gathering real-time data, IoT applications enhance everything from smart homes and healthcare to transportation, environmental monitoring, and industry, transforming how we interact with the world [3].

1.3 | Air Quality Monitoring

Monitoring air quality is essential for keeping track of pollution levels, which directly affect our health, the environment, and the climate. As cities expand and industries grow, harmful pollutants in the air, like small Particulate Matter (PM), Nitrogen Dioxide (NO_2), Sulfur Dioxide (SO_2), Carbon Monoxide (CO), and Ozone (O_3), become more common, leading to health risks. Tracking these pollutants helps governments, health groups, and communities understand pollution sources and develop ways to address them.

In the past, monitoring air quality required expensive, fixed equipment that could only cover limited areas and often couldn't provide live updates. With the help of the IoT, air quality tracking has become more advanced and affordable. IoT-based systems use small sensors that collect real-time data from multiple places simultaneously, giving a clearer picture of pollution levels. This data allows communities and policymakers to make informed decisions that help protect public health and create cleaner, healthier urban spaces [4].

1.4 | Impact of Air Pollution

Air pollution causes millions of premature deaths each year. Fine Particulate Matter (PM10) is a major threat due to its ability to penetrate the respiratory system. Regulations are in place to control air pollution levels [5].

1.5 | Types of Air Quality Analysis

There are indoor and outdoor air quality analyses. Indoor air quality analysis involves testing the air within buildings. Outdoor air quality analysis can range from basic screenings to complex modeling. The type of analysis needed depends on factors like project size and potential pollutants.

1.6 | How IoT Can Help

IoT technology revolutionizes air quality monitoring by enabling continuous, automated, and accessible tracking of pollutants in urban and industrial environments. Here's how it benefits real-time air quality monitoring:

I. Continuous data collection: small, energy-efficient IoT sensors can monitor air pollutants like CO, NO_2, PM, and Volatile Organic Compounds (VOCs) in real time. These sensors operate 24/7, collecting continuous data without human intervention, and can be deployed across large areas, from city centers to industrial sites.

II. Affordable and scalable networks: unlike traditional, costly monitoring stations that cover limited areas, IoT devices are much more affordable and easy to deploy. This makes it possible to create an extensive network of sensors that provide wide coverage and granular insights into pollution levels across a broad geographic area.

III. Instant alerts: IoT systems can be set up to issue real-time alerts if pollutant levels exceed safe thresholds. This enables local authorities, businesses, and residents to take immediate action. For example, schools, hospitals, and workplaces can be alerted to issue health advisories or limit outdoor activities when air quality worsens.

IV. Accessible data and analysis: IoT platforms typically use cloud technology to store, process, and visualize air quality data. This allows easy access to data from any location through apps or dashboards. Furthermore, AI and Machine Learning (ML) models can be applied to analyze trends and even predict pollution spikes, helping develop informed strategies for pollution control.

V. Community awareness and policy development: IoT-enabled air quality data makes pollution information easily available to the public, fostering greater health awareness. This data also aids policymakers in creating strategies that address pollution, like managing traffic congestion, regulating emissions, and planning urban greenery [6].

Table 1. Abbreviations and key concepts.

Abbreviation	Meaning
IoT	Internet of Things
PM	Particulate Matter
CO_2	Carbon Dioxide
APMIoT	IoT-based Air Pollution Monitoring
TVOCs	Total Volatile Organic Compounds
GPS	Global Positioning System
WHO	World Health Organization
AQI	Air Quality Index
AWS	Amazon Web Services
ESP-WROOM-32	Microcontroller Unit
PPM	Parts Per Million
ML	Machine Learning

2|Literature Review

Research on IoT's role in air quality monitoring has gained considerable attention. A study published in "Real-time air quality monitoring in smart cities using IoT-enabled advanced optical sensors" (the international journal of artificial intelligence, Vol. 15, No. 4, 2020) proposes an IoT framework utilizing inexpensive sensors to monitor key pollutants in alignment with World Health Organization (WHO) guidelines. This framework emphasizes the importance of data accuracy and highlights the potential of cloud-based analytics for enhanced pollution surveillance and prediction. Another relevant study, "IoT-based air quality monitoring system with ML for accurate and real-time data analysis" [7], investigates the use of ML algorithms for data analysis alongside IoT sensors. This approach can significantly improve air quality monitoring systems' accuracy and real-time capabilities [7], [8].

2.1|IoT Approach with Real-Time Alerts and AWS Integration for Air Quality Monitoring

This environmental monitoring system uses an affordable ESP-WROOM-32 device to collect live data about air quality and other environmental factors. The device takes in raw data and then cleans and labels it using a simple method, making it more accurate. This processed information is sent to Amazon Web Services (AWS) so users can easily access it anytime. Its low-power design makes the system reliable for continuous, real-time monitoring in various weather conditions. It provides a simple, cost-effective way to track environmental changes and helps people make informed decisions about air quality and pollution [8].

2.1.1 | Data collection

This dataset contains hourly readings from 5 chemical sensors deployed in a heavily polluted Italian city for one year. The data provides insights into seasonal and temporal air quality variations. However, the dataset has limitations like sensor cross-sensitivities, concept shifts, and sensor changes, which can affect the accuracy of concentration estimates. Careful analysis is needed to mitigate these biases [9], [10].

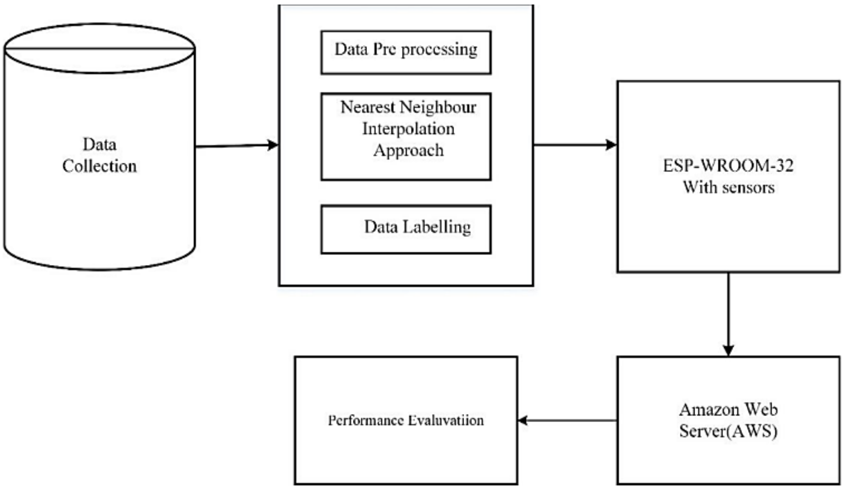

Fig. 1. Proposed diagram.

2.2 | IoT-Based Air Quality Monitoring

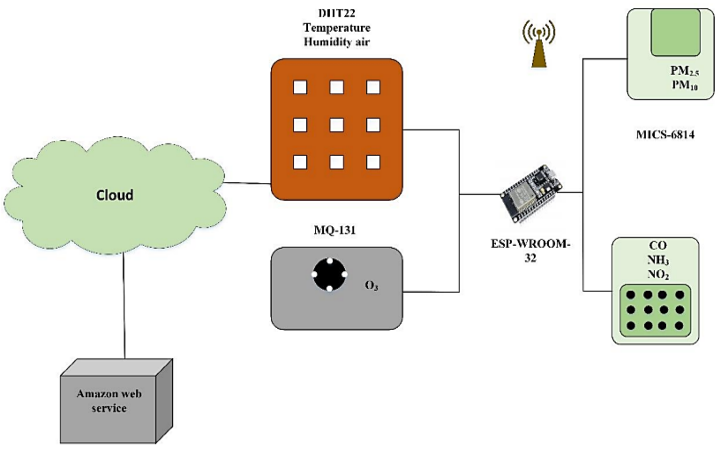

Fig. 2. IoT-based air quality monitoring.

This paper proposes an IoT-based air quality monitoring system using an ESP-WROOM-32 microcontroller.

The system is designed to measure various environmental parameters, including:

Air pollutants: PM2.5, PM10, O3, CO, NO2, and NH3.

Climate factors: temperature and humidity.

The collected data is transmitted to an AWS IoT Core for storage and analysis. Key components of the system include:

Hardware: ESP-WROOM-32 microcontroller.

Sensors: PMSA003, MQ-131, MICS-6814, DHT22

Software: Firmware for data collection and transmission, AWS IoT Core for data storage and analysis [8], [11].

2.2.1 | Flow chart

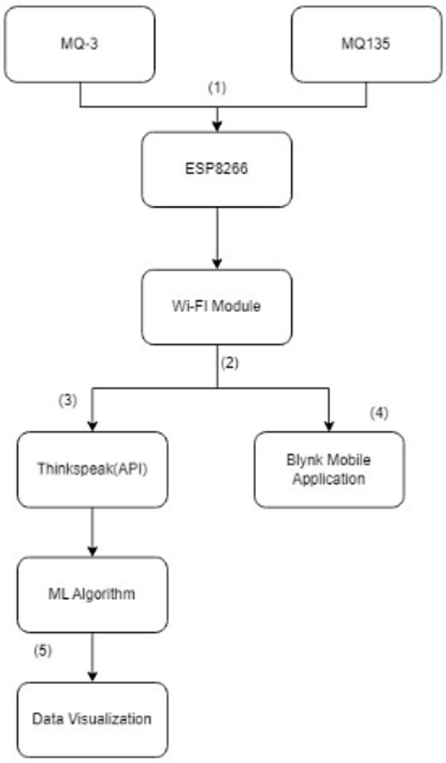

Fig. 3. Block diagram of data acquisition, transmission, and processing in the IoT-based air quality monitoring system.

I. Input from MQ3, MQ135 is taken in the format of analog and sent to the ESP8266.

II. The Wi-Fi module connected to the nearby Wi-Fi sends the data to ThingSpeak and the Blynk IoT platform.

III. The raw data from the sensors is sent to ThingSpeak.

IV. The calculated ppm values are sent to the Blynk IoT mobile application.

V. The data collected on ThingSpeak is exported as a CSV file and processed using a ML algorithm for air quality prediction.

2.2.2 | Algorithm

The following algorithm is followed to collect data.

Set up the device:

I. Configure the device with your Wi-Fi network details and Blynk account information.

II. Set up the sensors (MQ-3 and MQ-135) to measure air quality and alcohol levels.

Connect to the internet:

I. Connect the device to your Wi-Fi network.

Measure and send data:

I. Every second, the device measures the air quality and alcohol levels using the sensors.

II. It calculates the values and sends them to a cloud platform called ThingSpeak.

III. It also displays the real-time values on a mobile app called Blynk.

Analyze data:

I. The data stored on ThingSpeak can be analyzed to identify trends, patterns, and anomalies.

II. This analysis can help understand air quality conditions and potential risks.

2.2.3 | Limitations

Despite the promising potential of IoT-based air quality monitoring systems, this study presents several limitations that must be acknowledged.

I. The proposed design has not yet been validated through large-scale field deployment; hence, the real-time accuracy and calibration stability of the low-cost sensors remain uncertain. Environmental factors such as humidity, temperature fluctuations, and cross-sensitivity among gas sensors can lead to measurement drift over time [12].

II. The system's reliance on wireless connectivity (Wi-Fi or LPWAN) introduces potential data loss or latency issues, particularly in dense urban areas with network congestion.

III. The current framework does not include advanced data analytics or predictive algorithms that could provide early warnings or pattern detection.

IV. Privacy concerns associated with location-based data collection were not deeply analyzed, and energy consumption optimization at the sensor level requires further investigation [13].

2.2.4 | Future work

Future research will focus on transforming this conceptual framework into a fully functional prototype and validating its performance under real-world urban conditions.

In the next phase, multiple sensor nodes will be deployed across selected city zones to evaluate spatial accuracy, latency, and system scalability. Integration of ML techniques will enable predictive modeling of air quality trends and anomaly detection.

Furthermore, edge computing will be incorporated to minimize data transmission delays and reduce cloud dependency [2].

To strengthen security and transparency, blockchain-based data authentication can be explored for reliable sensor data exchange [14].

Lastly, long-term studies on sensor calibration, power efficiency, and citizen participation through crowdsourced sensing will be conducted to enhance the sustainability and reliability of IoT-enabled environmental monitoring systems.

3 | Conclusion

To sum up, IoT technology is revolutionizing the field of air quality monitoring, especially in densely populated areas where pollution levels have a profound impact on public health and ecosystems. Through deploying IoT sensors across large areas, it is now possible to continuously monitor harmful pollutants like CO, NO_2, PM, and VOCs in real-time, providing vital data on pollution. This system is more affordable and flexible than traditional monitoring stations, which are limited in coverage and real-time monitoring capabilities. Furthermore, IoT platforms store and analyze data in the cloud, making it accessible to many stakeholders—including policymakers, scientists, and the general public. This ease of access facilitates the rapid identification of pollution trends and enables prompt responses when pollutant levels reach unsafe limits. IoT technology supports long-term environmental management strategies through advanced data analysis and alerts. IoT-powered air quality monitoring enhances awareness, promotes healthier communities, and supports evidence-based policymaking.

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Data Availability

The raw data underpinning the findings of this IoT-based air quality monitoring system are available upon reasonable request from me. These data, which can be provided in various formats such as CSV or Excel, foster transparency, reproducibility, and further exploration of the research findings. To ensure appropriate access and utilization, interested parties should contact me directly to discuss specific data requirements and any necessary permissions.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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