IoT Enabled Hyperlocal Air Quality Monitoring and Prediction System Using ESP32 & Machine Learning

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Abstract: - Increasing pollution and its serious health implications demand more accessible and hyperlocal air quality monitoring solutions. This paper presents an IoT-enabled, low-cost air quality monitoring and prediction system using the ESP32 microcontroller, MQ135 gas sensor, and DHT22 temperature–humidity sensor. The system records environmental parameters at regular intervals and uploads them to a cloud database for real-time visualization through a custom online dashboard. A Long Short-Term Memory (LSTM) based recurrent neural network is incorporated to generate short-term air quality predictions, providing early insights into short-term AQI variations. The proposed system is cost-efficient, scalable, and suitable for residential and academic deployment.

Keywords: ESP32, Hyperlocal AQI, IoT, MQ135, DHT22, Machine Learning, Cloud Dashboard.

I. Introduction

Air pollution continues to rise globally, making localized monitoring systems essential for effective environmental awareness. Traditional air quality monitoring stations, although accurate, are limited in number and unable to capture micro-level variations caused by traffic congestion, indoor emissions, or localized industrial activity [1], [2]. As a result, large-scale monitoring infrastructures often fail to represent actual exposure levels experienced by individuals at a community scale.

Recent advancements in Internet of Things (IoT) technologies have enabled the development of low-cost, distributed sensing nodes capable of real-time environmental monitoring and cloud-based data access [3][5]. In this work, an ESP32-based hyperlocal air quality monitoring system is proposed, integrating MQ135 and DHT22 sensors to measure gas concentration, temperature, and humidity. The collected data is transmitted to a cloud platform and visualized through a live dashboard. Additionally, a time-series based LSTM prediction model is employed to forecast short-term air quality trends using historical sensor data, enabling proactive environmental awareness and decision-making [7], [9]. The system aims to offer an affordable and scalable solution suitable for community-level and academic applications.

II. Literature Review

Several studies have demonstrated the effectiveness of IoT-based environmental monitoring systems for achieving low-cost and scalable air quality assessment [1][3]. MQ135 sensors, despite their moderate absolute accuracy, have been widely adopted for trend analysis and relative air quality monitoring when combined with appropriate calibration techniques [4][8]. Similarly, ESP32 microcontrollers are frequently used in IoT applications due to their integrated Wi-Fi capabilities, low power consumption, and sufficient processing performance for real-time data acquisition and transmission [5][10].

Machine learning techniques such as Linear Regression, AR models, and Long Short-Term Memory (LSTM) networks have been extensively applied for short-term AQI forecasting [7][9][11]. Among these, LSTM networks are particularly suitable for air quality prediction due to their ability to capture short-term dependencies in time-series environmental data. However, many existing systems focus either on monitoring or prediction independently and lack a unified framework integrating sensing, cloud visualization, and machine learning-based forecasting. This work addresses these limitations by presenting an end-to-end hyperlocal monitoring pipeline.

III. System Architecture & Methodology

The proposed system is designed as a multi-layer IoT architecture consisting of sensing, communication, storage, analytics, and visualization layers.

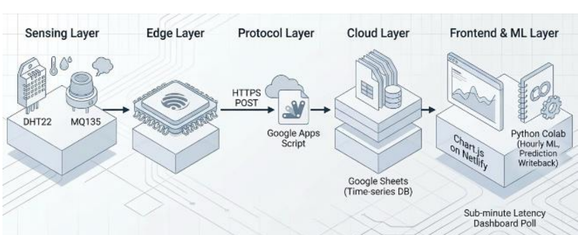

Fig.1 Overall Architecture of the IoT-Enabled Hyperlocal Air Quality Monitoring System

A. Hardware Setup

The ESP32 microcontroller serves as the central controller of the system, interfacing with the MQ135 gas sensor for air quality measurement and the DHT22 sensor for temperature and humidity sensing. These sensors provide continuous environmental data, which is periodically sampled and processed by the ESP32 before transmission to the cloud.

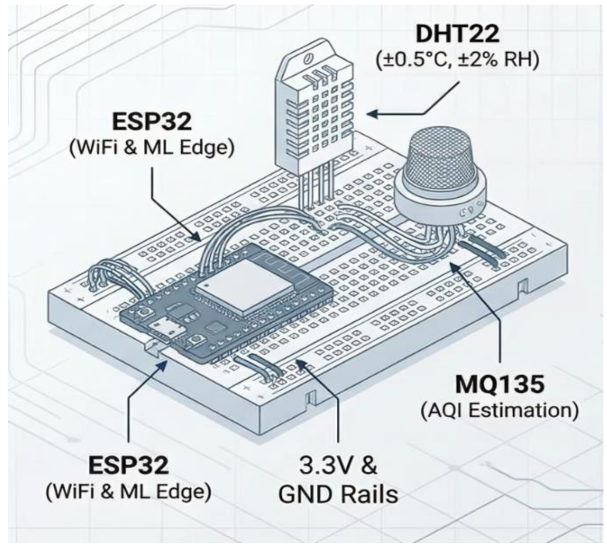

Fig.2 Hardware Implementation of the Proposed System Using ESP32, DHT22, and MQ135 Sensors

B. Data Communication

The ESP32 uploads sensor data to a cloud backend using Wi-Fi-based HTTP communication at fixed intervals. Cloud platforms such as Google Sheets or Firebase are used to store timestamped sensor readings, enabling remote access, long-term storage, and subsequent data analysis[5][10].

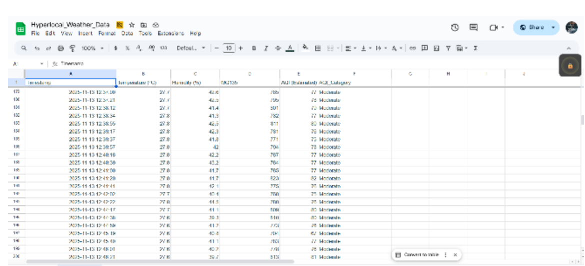

Fig.3 Cloud-Stored Time-Series Sensor Dataset Collected from the ESP32 Node

C. Machine Learning Prediction Model

To enable short-term forecasting of air quality trends, a Long Short-Term Memory (LSTM) based recurrent neural network is employed. LSTM networks are well suited for time-series data as they can effectively model short-term dependencies present in environmental parameters such as temperature, humidity, and AQI [7][9][11].

The model is trained offline using historical sensor data stored in the cloud database. Input features include recent sequences of temperature, humidity, and estimated AQI values, while the output corresponds to short-term AQI predictions. The LSTM model is utilized for trend forecasting and early indication of air quality variations rather than regulatory-grade AQI estimation.

D. Dashboard

A custom web-based dashboard developed using HTML, JavaScript, and Chart.js visualizes real-time and historical sensor data retrieved from the cloud database. The dashboard provides numerical indicators and graphical representations of environmental parameters, enhancing system usability and interpretability.

IV. Result

The proposed system successfully recorded and transmitted environmental data to the cloud backend, with real-time updates reflected on the dashboard. The collected dataset enabled continuous monitoring of temperature, humidity, and AQI variations at a hyperlocal level.

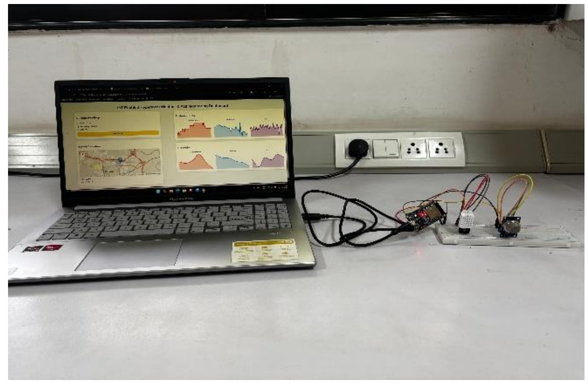

Fig.4 Real-Time Monitoring and LSTM-Based Prediction Dashboard

The LSTM-based prediction model generated short-term forecasts that closely followed recent data trends, demonstrating the practical feasibility of integrating machine learning for early air quality trend analysis [7], [11]. The dashboard interface effectively displayed live readings and predictions, validating the reliability and practical applicability of the system.

V. Security & Challenges

To ensure secure data transmission, encrypted Wi-Fi communication and controlled cloud API access mechanisms were employed [5]. Regular firmware updates further enhance system security. Key challenges encountered include sensor drift associated with the MQ135 sensor, Wi-Fi connectivity interruptions, environmental noise affecting prediction accuracy, and the requirement for a stable power supply for continuous operation [4][8].

VI. Future Scope

Future enhancements include the integration of precise particulate matter sensors (PM2.5/PM10), solar-powered outdoor deployment, on-device prediction using TinyML techniques, GPS-based pollution mapping, mobile application development with alert mechanisms, and deployment of a multi-node distributed monitoring network [7][9].

VII. Conclusion

This work presents a compact and cost-effective hyperlocal air quality monitoring system combining ESP32-based sensing, cloud storage, real-time dashboard visualization, and machine learning prediction. Despite minor limitations in sensor accuracy and connectivity dependency, the system is effective for residential and academic environments. The work forms a foundation for future large-scale smart-city environmental monitoring solutions.

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