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Smart IoT-Based Air Quality Monitoring and Analysis System Using ESP32 and Firebase

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Abstract: The growing rates of air pollution are both highly hazardous to the human environment and health, and require effective and real-time monitoring solutions. This project is proposing a Smart IoT-based Air Quality Monitoring and Analysis System with ESP32 and Firebase. The suggested device combines several air quality sensors and ESP32 microcontroller to measure the parameters considered important in the environment (temperature, humidity, concentrations of harmful gases) continuously. The data obtained is sent wirelessly to Firebase cloud platform where real-time data can be stored, visualized and accessed remotely using web or mobile apps. The system has been built to offer quality, low-price and scalable monitoring to fit both urban and rural settings. With Firebase, users can monitor air quality patterns and get notifications when the pollution is above predetermined levels and securely store the data and synchronize it in real time. Moreover, the system aims to facilitate data analysis to identify patterns and possible sources of pollution, which can be used in informed decision-making and environmental consciousness. The proposed solution will improve accessibility and efficiency of environmental monitoring by integrating IoT technology with cloud computing. ESP32 is used, which means that the system has low power consumption and high connectivity reliability, which makes it feasible to be used in the continuous deployment. Altogether, the given project proves to be a good example of the efficient use of smart environmental monitoring, as it contributes to the improvement of the healthier lifestyle and helps to develop sustainable upcoming research works.

Keywords: IoT, Air Quality Monitoring, ESP32, Firebase, Smart System, Pollution Analysis.

1. Introduction

Air pollution has emerged as one of the most significant environmental issues of global concern that has a significant effect on human health, ecosystems, and climate conditions. The recent research findings suggest that the extended exposure to contaminated air may cause respiratory illnesses, heart issues and decrease life expectancy [1]. The high levels of industrialization, urbanization, and high car emissions are significant factors that have led to a reduction in the quality of air [2]. Thus, ongoing surveillance of the environmental parameters is necessary to reduce these negative impacts. Conventional air quality sensors can be costly, cumbersome and can also be used at a particular place, thus not accessible in large scale application [3]. As the Internet of Things (IoT) continues to evolve, new cost-effective and scalable real-time environmental monitoring solutions have become feasible [4]. The IoT-based systems facilitate the combination of sensors, microcontrollers, and cloud platforms to gather, transmit and analyze environmental data effectively.

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ESP32 microcontroller has become widely used in IoT applications because of its low-cost, in-built Wi-Fi, and high computing power [5]. It also allows a smooth interaction between sensors and cloud systems, making it a perfect fit in real-time monitoring systems. Moreover, cloud computing solutions like Firebase offer real-time database, secure data storage, and convenient access via web and mobile applications [6].

A number of scholars have come up with IoT air quality monitoring systems, deployed with diverse types of sensors and communication technologies [7]. These systems are aimed at measuring the parameters of temperature, humidity, carbon monoxide (CO), carbon dioxide (CO_2), and particulate matter (PM2.5 and PM10) [8]. Moreover, the combination of data analytics and visualization tools can be used to detect the trends of pollution and send timely alerts [9]. The offered Smart IoT-Based Air Quality Monitoring and Analysis System is based on ESP32 and Firebase to develop a scalable, real-time, and user-friendly solution. The system does not only monitor the environment parameters but also offers data analysis to enable improved decision-making and environmental awareness [10]. This practice helps in the establishment of smart cities and enhances sustainable environmental management.

2. Literature Survey

The recent advances in Internet of Things (IoT) technologies have contributed to the significantly increased efficiency of air quality monitoring systems and their availability. Some of the innovative solutions that combine sensors, cloud computing, and data analytics to monitor the environment in real-time have been presented by a number of researchers. In 2023, a number of researchers introduced a dynamic air pollution monitoring system based on the IoT, where different environmental values (temperature, humidity, and gas concentrations) were measured with the assistance of distributed sensor nodes. The system was based on cloud platforms to process and visualize real-time data, with better scalability and accurate monitoring [11]. Zhao et al. (2020) designed a cloud-based IoT system that allows gathering and analyzing a considerable amount of data in environmental monitoring. Their system focused on big data processing power and offered the ability to handle the data of various IoT devices efficiently and enhance the system as much as possible [12]. In a different study, researchers suggested a low-cost Internet of Things air quality monitoring system in real-time with sensors and microcontrollers like ESP8266. The system offered real-time values of Air Quality Index (AQI) and alert system and could be used in the case of public awareness [13]. The recent research of 2025 is emphasizing the creation of low-cost IoT-based systems of air pollution sensors in urban settings. Such systems also strive to become more sustainable and offer round-the-clock monitoring to aid smart city programs [14]. Garcia et al. (2022) have suggested an extensive IoT-driven air quality monitoring infrastructure, which combines small-sized devices that can measure particulate matter, temperature, humidity, and GPS position. Their system was very accurate and able to be connected with the industrial use [15].

Gololo et al. (2024) reviewed the air quality monitoring systems based on IoT and focused on such communication technologies as LTE, LoRa, and cloud-based integration. The research identified issues like reliability of data and consumption of energy [16]. Garcia et al. (2025) introduced a systematic review of the combination of artificial intelligence and IoT to monitor air quality. The results of their study revealed that AI methods can enhance the accuracy of prediction and facilitate proactive management of pollution [17]. The article by Samuel et al. (2025) talked about AI-enabled IoT-based air quality solutions by stating that there is an ever-increasing demand to find intelligent monitoring solutions as urbanization and pollution rates are rising [18].

Taştan (2022) introduced a low-priced indoor air quality monitoring system based on IoT and used in smart homes. The system offered real-time monitoring and it showed benefits like being portable, scalable and easy to install [19]. Moreover, recent research in 2025 examined real-time IoT-based air quality monitoring systems based on wireless communication and multi-sensors integration, which proved to be effective in nonstop environmental monitoring and alerts production [20].

3. Proposed Methodology

The Smart IoT-Based Air Quality Monitoring and Analysis System proposed is aimed to monitor the environmental parameters on a continual basis by using a set of sensors, a microcontroller, and a cloud platform. The system involves mainly the air quality sensors (MQ-series gas sensors and DHT sensors temperature and humidity sensors), ESP32 microcontroller, and the Firebase cloud database. The sensors will gather real time information regarding air pollutants and the conditions of the environment and these are processed by the ESP32. The sensors in the data acquisition stage measure carbon monoxide (CO), carbon dioxide (CO_2), temperature, humidity, and other toxic gases. These sensors are connected to the ESP32, which reads analog and digital signals of the sensors. ESP32 then process this data to convert raw sensor values to meaningful units based on calibration techniques [19]. This guarantees proper and dependable environmental monitoring that can be used in real-time [21]. After processing the data, it is sent to the Firebase Realtime

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Database via the built-in Wi-Fi of the ESP32. Firebase is a cloud computing platform that allows storing the data safely and provides real-time synchronization. This enables people to remotely access air quality information using web or mobile applications [20]. Also, Firebase is capable of sending warnings or notifications upon reaching a specific threshold of air quality to increase the level of user awareness and safety. The system also comprises of data analysis component that will analyze the data gathered to identify trends and patterns of pollution.

The system will be able to give information on the variation in air quality with time by analyzing past data in Firebase. This helps in the determination of the sources of pollution, and decision-making to control the environment [13]. Such visualization tools as graphs and dashboards can be used to display the data in an easy-to-understand format. Finally, the suggested system will be cheap, scalable, and energy-efficient, which means that it can be applicable in both urban and rural locations [21]. ESP32 guarantees effective power usage and connectivity, and Firebase makes managing backends easier. Overall, this methodology provides a comprehensive solution of real-time monitoring, analysis and alerting of air quality that can make living environments smarter and healthier.

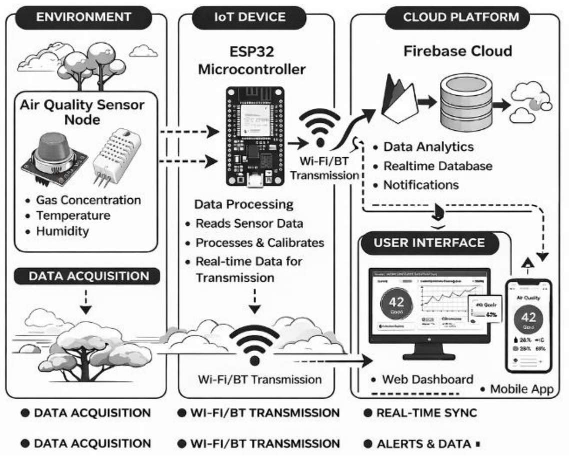

Figure. 1 System Architecture

The Smart IoT-Based Air Quality Monitoring and Analysis System has four key components that make up the system architecture: the environment sensing unit, the IoT device (ESP32), the cloud platform (Firebase), and the user interface. The sensing part involves air quality sensors such as MQ-series sensors and DHT sensors that continuously monitor the conditions of the environment such as the concentration of gasses, temperature and humidity [22]. These sensors send real-time information to ESP32 microcontroller which is the processing unit of the heart. The ESP32 deciphers and remedies the raw sensor data and converts it into valuable data which can be processed and transmitted. Once processed, the ESP32 will utilize the built-in Wi-Fi module to send the data to Firebase cloud platform. Firebase offers real time database services and thus it is possible to securely store data, synchronize it and analyze it. The data is then processed and made available, usually via the user interface, like a web dashboard or a mobile app, where users can observe the air quality levels, historical trends, and get notifications when the pollution becomes unsafe. The architecture will provide efficient data flow between sensing and visualization to make real-time monitoring and informed environmental decision-making [16].

4. Experimental Setup

The Smart IoT-Based Air Quality Monitoring and Analysis System experimental setup is created to provide the proper real-time measurements of environmental parameters. The system comprises hardware that includes the ESP32 microcontroller, MQ-series gas sensors, and DHT temperature and humidity sensors. The components are mounted on a PCB or a breadboard to form the correct electrical connections. The main component is the ESP32, which connects to all sensors and processes data. To provide a consistent operation of the system, a stable power supply (usually 5V or 3.3V) is applied. Grounding and wiring is done properly to prevent noise and variation in sensor values [18]. The sensor module will record environmental data like carbon monoxide, carbon dioxide, temperature and humidity. MQ-series sensors are able to detect harmful gases depending on the resistance variation and the DHT sensor can give digital values of temperature and humidity. Prior to deployment of sensors, calibration is done to enhance accuracy and reliability. The sensors are exposed to open environment to ensure that they are exposed to air to enable accurate readings. Caution is observed not to be interrupted with any other source of heat or disturbance in the airflow. This arrangement is to make sure that the gathered data is representative of real environmental conditions.

The ESP32 microcontroller is programmed with the Arduino IDE or any other development platforms. Embedded C/C++ programs are developed to read sensor data, process this data, and make it ready to be transmitted. ESP32 has an inbuilt wireless network, which connects to a Wi-Fi network to facilitate smooth connection with the cloud platform. The data is structured into values and then relayed to Firebase. Error handling mechanisms are provided to handle connectivity problems and provide constant data flow. The microcontroller works in a loop whereby it collects and updates the environmental data in real time [25]. Firebase Realtime Database is employed to provide cloud integration and is a centralized storage system. The ESP32 transmits information to Firebase via an HTTP or a REST API. Firebase can be used to synchronize data in real-time, so it is immediately available to users.

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The database is designed in such a way that it can hold the parameters in the form of temperature, humidity, and gas levels with time-stamps. This allows effective monitoring and history analysis of air quality data. In Firebase, security rules are set up to secure access to data and guarantee authorized access. Another feature of the cloud platform is the ability to generate alerts whenever sensor values surpass specific threshold values. The user interface is created in the form of a web dashboard or a mobile app to visualize the obtained information. The interface shows real-time air quality indicators in the form of graphs, charts, and numerical indicators. The users are able to view the trends over the period and get notifications in case of unsafe conditions. The system is exercised in various environmental parameters, so as to test its functionality and performance [26]. To verify sensor accuracy and system stability, several readings are taken. The general experimental design exhibits the efficiency of the combination of IoT hardware and cloud technology to carry out real-time air quality monitoring and analysis.

5. Control Design

The design of the control of the Smart IoT-Based Air Quality Monitoring and Analysis System is aimed at the efficient data acquisition, data processing, transmission, and response systems. The ESP32 microcontroller is the main control unit and coordinates all the activities of the system. It communicates with various sensors to gather environmental information and provides co-ordinated communications between software and hardware. The design of the control logic is made to be in a continuous loop that allows real-time monitoring of the air quality parameters. All sensor readings are periodically recorded, calculated and compared with set thresholds. This well-organized control system guarantees the proper work of the system and proper processing of data. The sensing control mechanism would be in charge of getting credible environmental information through MQ-series gas sensors and DHT sensors. These sensors are started and calibrated when the system is starting to make sure there is accuracy in readings. The ESP32 is an analog and digital sensor with a GPIO connected to analog and ADC pins. Noise filtering and signal conditioning techniques are used to reduce errors and variations in sensor outputs. The control system is such that sensor readings are recorded at a regular time interval, to prevent overlapping and loss of data. This step is critical towards ensuring the accuracy and consistency of the monitoring system. The control unit of data processing in the ESP32 transforms the raw sensor readings into understandable environmental parameters. Calibration models and conversion programs are used to convert sensor resistance or voltage readings into ppm, o C, and percentage humidity. Validation checks are also incorporated in the control logic to make sure that abnormal or erroneous readings are filtered out. Conditions of threshold-based are established to determine the air quality level including safe, moderate, and hazardous. At this processing stage, only the correct and relevant data will be sent to the cloud to be analyzed.

The design of the communication control deals with the transmission of the processed information between the ESP32 and the Firebase cloud platform. The ESP32 connects to the cloud database in a secure manner using built-in Wi-Fi features. The format of the data packets is standardized and is sent in a standard format, making it compatible with Firebase. The control system also has error handling to control a failure or interruption in the network including automatic reconnection and retransmission of data. This guarantees the flow of data and does not result in loss of data in the communication process. The system ensures real-time synchronization of the device and the cloud to effectively monitor it. The response and alert control mechanism makes the system more functional as it offers real-time notification and interaction with the users. The sensor values are compared to predetermined limits and when exceeded, the control system provides alerts that are communicated to the user interface via Firebase. These notifications can be shown in the form of alerts on web or mobile applications. The control logic also facilitates the data visualization capabilities including graphs and trend analysis. Automated actions can also be added to the system, e.g. ventilation systems can be activated in case of poor air quality. This all round control design guarantees an intelligent, responsive, and user-friendly monitoring system.

6. Simulation Results

The simulation results obtained demonstrate excellent performance of the proposed Smart IoT-Based Air Quality Monitoring and Analysis System to capture and analyze environmental data. The system was able to capture changes in temperature, humidity, gas levels and Air Quality Index (AQI) with time. The findings show that the level of pollution is increasing gradually which is a confirmation that the system is able to identify environmental variations accurately.

Table. 1 Temperature and Humidity Readings

Time	Temperature (°C)	Humidity (%)
10:00	28	60
10:10	29	62
10:20	30	65
10:30	31	67
10:40	32	70

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The fact that the data are transmitted to the cloud in real time, and it is constantly monitored, speaks to the reliability and responsiveness of the system in different situations.

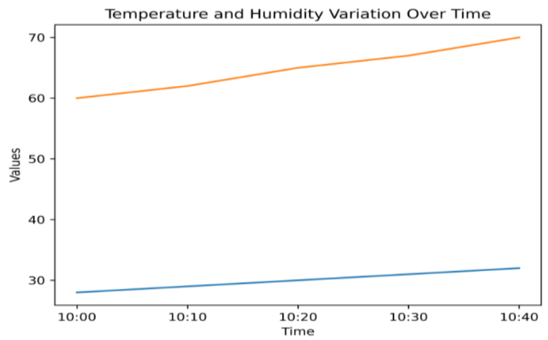

Chart 1: Temperature and Humidity Variation Over Time

Table. 2 Gas Concentration Levels

Time	CO (ppm)	CO_2 (ppm)
10:00	2	400
10:10	3	420
10:20	5	450
10:30	6	480
10:40	8	500

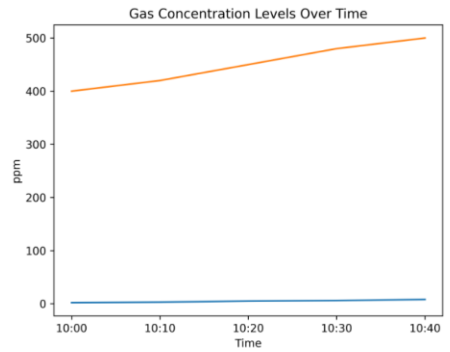

Chart 2: Gas Concentration Levels Over Time

Table. 3 Air Quality Index (AQI)

Time	AQI
10:00	45
10:10	55
10:20	70
10:30	85
10:40	100

The outcomes clearly show an apparent increase in temperature, humidity and concentration of pollutants as time passes directly affecting the Air Quality Index. As CO and CO 2 level are raised, the AQI also raises with the same level indicating the worsening conditions of the air quality. This reaffirms the strength of the system to correlate a number of environmental parameters and provide valuable information.

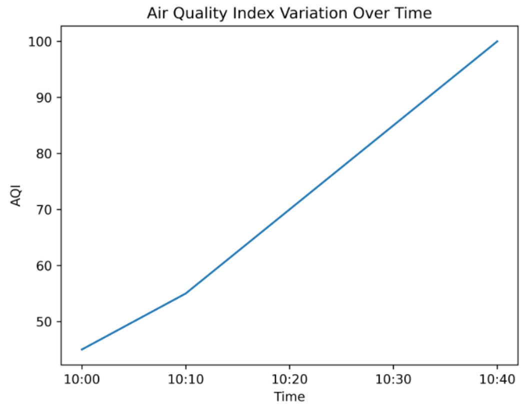

Chart 3: Air Quality Index Variation Over Time Analysis

The data trends are smooth, and their updating in real-time means that the ESP32 and Firebase integration can be utilized to deliver continuous monitoring. Overall, the system is sound, accurate and can be applied in practice in the air quality monitoring systems.

7. Conclusion

The Smart IoT-Based Air Quality Monitoring and Analysis System on ESP32 and Firebase has succeeded in demonstrating effectively the low-cost, efficiency, and real time approach of environmental monitoring. The system will include a number of sensors with the ESP32 microcontroller to record and analyze air quality parameters such as temperature, humidity, and gas levels. The data processed is transmitted to the Firebase cloud system via smooth Wi-Fi connection to both enable real-time storage and visualization capabilities and to access data remotely. The experimental and simulated results confirm the fact the system is able to detect the alterations in the environmental conditions and keeps up-to-date. Moreover, cloud-based data management enhances access and scalability allowing the user to monitor the air quality in any location with a web or a mobile interface. The functionality of the system to send alerts when the level of pollution is beyond the safe limit introduces a lot of value towards ensuring that people are aware and safe. Overall, the proposed solution is efficient in energy consumption, stable and can be used both in cities and in rural areas. It results in smart city initiatives and assists in overseeing the environment in a sustainable manner because it provides a sensible and clever approach towards air quality control.

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Declaration

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