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Smart Weather Monitoring System Using ESP32 and IoT

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Abstract

The increasing unpredictability of climate conditions necessitates an efficient and real-time weather monitoring system. The following paper describes an IoT weather monitoring system using the ESP32 microcontroller, connected to various environmental sensors to gather and process atmospheric information. The system uses a DHT11 sensor to measure temperature and humidity, an MQ135 gas sensor for measuring air quality, and a PM2.5 sensor to measure the level of particulate matter. The ESP32 web server acts as the processor, forwarding accumulated information to a TFT display for real-time visualization and to the Blynk IoT platform for remote monitoring. The application of WiFi connectivity enables easy data transfer, and users can view weather data through a cloud-based app. The system aims to be low-cost, energy-effective, and scaleable to accommodate various environmental requirements, e.g., smart agriculture, air pollution control in cities, and disaster prediction. Incorporation of IoT enhances the usability and accessibility of the system via remote monitoring. Experiments results indicate that the system effectively acquires and presents live environmental parameters with the advantage of being a dependable method of weather monitoring. Future expansion can also entail the incorporation of AI algorithms for predictive analytics and anomaly detection to further improve the efficacy of the system. This research contributes to the development of smart environmental monitoring solutions that can support climate resilience and sustainability interventions.

Keywords: ESP32, IoT, Weather Monitoring, Air Quality, DHT11, PM2.5 Sensor, Remote Sensing, Smart Agriculture, Blynk, Environmental Monitoring

INTRODUCTION

Weather observation has become an integral part of contemporary society, impacting sectors like agriculture, transportation, disaster management, and urban planning. Weather prediction and understanding are very important in developing decisions that affect human life and economic activities. Conventionally used weather observation systems utilize meteorological stations that record data at distinct points. The systems are usually costly, need a huge amount of infrastructure, and do not offer localized real-time information. With the evolution of the Internet of Things (IoT), it became more affordable and accessible to monitor weather in real-time, enabling individuals and organizations to monitor environmental conditions effectively. The integration of weather monitoring and IoT brings with it a paradigm change in analysis and data acquisition. IoT-based weather stations consist of different sensors that continuously monitor parameters like particulate matter, humidity, temperature, and air quality. They upload the data to

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cloud servers, facilitating real-time access and analysis. Low-cost microcontrollers that include WiFi and Bluetooth capabilities, like the ESP32, have popularized smart weather monitoring systems.

The ESP32 microcontroller is a powerful, energy-efficient microcontroller with multiple function support that makes it the best option to implement in IoT-based weather monitoring. The ESP32 has dual-core processors, has large connectivity features, and is capable of interfacing with several sensors, hence capable of fetching and sending weather data efficiently. ESP32 is highly programmable along with having strong development environment support, e.g., Arduino IDE and MicroPython, to assist developers in designing applications based on specific requirements.

This research intends to create an IoT-based weather monitoring system using the ESP32 microcontroller and sensor integration such as the DHT11 for temperature and humidity, MQ135 for air quality sensing, and PM2.5 sensors for particulate matter level measurement. The data are shown on a TFT display for local monitoring and sent to the Blynk IoT platform for remote monitoring. This approach offers a robust and legible weather observation system that can be used in urban and rural settings.

One of the most important motivations behind this research is growing concern with climate change and pollution. Global warming, climatic change, rising levels of air pollution, and erratic weather patterns all necessitate advanced monitoring systems that report accurate and up-to-date data. The suggested system is a low-cost replacement for conventional meteorological stations and offers a power-efficient and expandable solution to numerous applications. Smart weather monitoring systems are particularly beneficial in farming, as real-time weather data is highly significant in optimizing irrigation efficiency, avoiding crop loss due to extreme weather conditions, and optimizing maximum overall crop yield. Farmers are provided with real-time temperature and humidity data, which they subsequently utilize to make the right decisions regarding water and crop management. Also, measurement of air quality using the MQ135 sensor is able to sense the level of pollution, a critical element in providing healthy conditions for living within cities.

The Blynk IoT platform takes center stage in enhancing the availability of the weather monitoring system. By utilizing cloud-based data visualization and storage, users can remotely observe weather conditions using a web interface or mobile app. This functionality is most beneficial for meteorologists, researchers, and environmentalists who need constant data analysis and logging. Blynk also has the capability to designate alerts and notifications for certain weather parameters, allowing users to react promptly to serious environmental changes.

Another significant change in this study is the adoption of energy-saving techniques to prolong the life of the system operation. Since IoT weather stations are likely to be deployed in far-off areas, power consumption is a primary concern. ESP32 microcontrollers support low-power modes of operation, enabling the management of power efficiently while continuously collecting data. By reducing the power consumption, the system may be driven by renewable means of power, i.e., solar panels, and thus is an eco-friendly solution for long-term weather observation. One other field that shows a lot of potential for future development is the use of artificial intelligence (AI) and machine learning (ML) in weather monitoring systems. Predictive analytics based on AI can make weather forecasting more accurate with the help of analysis of patterns of historical data and detection of trends. Execution of these algorithms in an IoT-based platform can assist in predicting extreme weather, issuing early alerts to disaster management authorities and communities.

Though it has some advantages, the system also has certain disadvantages such as sensor calibration, accuracy of data, and network stability. Sensors also need to be calibrated periodically in order to function precisely, and there are other ambient conditions such as humidity, dust, and variable temperatures that come to impact sensor readings. Also, the connectivity should remain steady in terms of the internet, in order to deliver data continuity to cloud infrastructure. A path needs to be circumvented by these impediments with hardware safety and optimization for software, so trusted sensors could be delivered.

This paper attempts to give a thorough overview of ESP32-based weather monitoring system design, development, and functionality. The work entails the usage of various sensors, processing, and Internet of Things connectivity to create a cost-effective and scalable system. With the use of open-source technology and cloud-based platforms, the system is able to deliver an adaptable and tailored solution to weather observation to a broad range of applications in various industries.

Finally, IoT weather monitoring platforms have transformed environmental data acquisition and analysis to include real-time status reports of environmental status. With its multi-utility functionality, the ESP32 microcontroller offers a low-cost platform on which smart weather stations can be deployed and offered at cost-effective and scaleable prices. This study is one of the contributions towards climate resilience and monitoring efforts of climate and environment by presenting an actionable solution deployable to all environments. Future work will be focused on system development of the system feature through AI-enabled predictive analytics and additional sensor integration towards full-fledged environmental monitoring.

LITERATURE SURVEY

The paper by Wadne, Walke, Bhandwalkar, and Pisal (2023) [1] suggests an IoT-based weather monitoring system with the aim of helping farmers in farm planning and executing farm activities based on prevailing climatic information. The system employs a sequence of sensors such as temperature, humidity, wind speed, and moisture sensors that are interfaced to a data-processing microcontroller transmitting the data to a cloud server via Wi-Fi or cellular communication. The system provides web or mobile app remote monitoring capability for farmers to provide data-driven decisions regarding irrigation, fertilization, and pest control. The study is able to effectively identify the benefit of utilizing IoT in precision agriculture as a cost-saving and scalable weather observation solution. The paper is limited in experimental verification across various types of climatic conditions, which would increase its applicability. Future research can integrate AI-driven predictive analytics for enhanced decision support. Overall, this study contributes to the growing field of smart agriculture.

The paper by Ogunbunmi et al. (2024) [2] presents an Internet of Things (IoT)-based weather observation system designed for real-time data acquisition, analysis, and dissemination. The system uses several weather sensors for monitoring temperature, humidity, air pressure, and rainfall and transfers the data to a central node via wireless communication. The data, after processing, is available in the form of a web and mobile application, which provides real-time weather details and warning. The study is apt to illustrate the potential of IoT in improving weather forecasting and environmental monitoring leveraging cloud computing for scalability and data storage. However, the study would be better positioned with field implementation under different climatic conditions to substantiate its efficacy. Future studies can further look into combining predictive weather analysis with machine learning models. Overall, this study is a valuable addition to the creation of IoT-based meteorological systems.

The paper by Budijono and Felita (2021) [3] outlines a smart temperature sensor system based on the ESP32 microcontroller and DS18B20 temperature sensor for controlling freezer temperature. The research seeks automation of food storage temperature monitoring for quality and efficiency for F&B businesses. The system makes real-time temperature measurements of freezers and stores data on the cloud, allowing remote monitoring as well as predictive maintenance. The study sufficiently realizes the benefits of IoT-based temperature management in corporate food storage through reducing the chances of human error and increasing operating efficiency. However, the study could also consider exploring real-world deployment problems like network reliability and sensor calibration under varying conditions. AI-based predictive maintenance can be incorporated in subsequent research to enhance system reliability further. Generally, this work contributes meaningfully to food industry smart monitoring solutions.

Dilna et al. (2022) [4] article is an IoT-based weather monitoring system for smart agriculture. The system employs a combination of sensors like DHT11 for temperature and humidity, an anemometer for wind speed, a GY8511 solar sensor for UV radiation, and an MQ7 sensor for the carbon monoxide level. The gathered information is then sent to the cloud for remote tracking through Wi-Fi, enabling the farmers to track real-time weather and get alerts for extreme weather. The research sufficiently anticipates the advantages of IoT in precision agriculture through the provision of an affordable and scalable model of weather observation. The use of API-based analysis by the system offers increased predictive power. Nonetheless, the study can be further supported with field testing and verification under various climatic conditions in real life. Future research can include AI-based weather prediction for better decision-making. Overall, this paper adds to the creation of IoT-based agricultural automation.

Wanogho, Ogbeide, and Agbontean (2022) [5] published a paper with an IoT-based weather system for observing atmospheric conditions on photovoltaic (PV) yield in Delta State, Nigeria. The system involves the use of ESP32 microcontrollers with DHT11 temperature and humidity sensors, an LDR for sensing light intensity, and a voltage sensor to observe PV panel performance. The acquired data is displayed on an LCD and uploaded to the Thingspeak cloud for live observation. The study sufficiently illustrates the application of IoT to maximize renewable energy systems through the provision of accurate environmental data collection for PV yield analysis. However, the study can be enhanced with long-term performance validation under various climatic conditions. Future studies can incorporate machine learning for predictive energy yield forecasting. In conclusion, this study significantly contributes to smart energy monitoring and IoT application in renewable energy systems.

The article by Rahut, Afreen, and Kamini (2018) [6] introduces an IoT-based weather forecasting and warning system that allows real-time data availability for climate and weather analysis. The system utilizes various sensors, such as DHT11 for temperature and humidity, an anemometer to measure wind speed, an LDR for measuring light intensity, a GY8511 solar sensor to detect UV radiation, and an MQ7 sensor for detecting carbon monoxide. The collected data is transferred to a web-based system for visualization and analysis with remote access. Additionally, predictive analysis based on APIs enhances the precision of weather forecasting. The study evidently depicts the feasibility of IoT in automation of weather monitoring, which is energy-efficient and low-cost. However, the study can be strengthened by the integration of AI-based weather forecasting models to enhance the accuracy of forecasting. Subsequent work must also focus on installing the system under different climatic conditions for large-scale validation. Overall, this research contributes significantly to smart environmental monitoring systems.

The Fahim et al. (2023) [7] article presents an IoT-based low-cost smart weather monitoring system that integrates air quality assessment using a fuzzy inference model and MQTT protocol. The system to be proposed gathers environmental data in real-time like temperature, humidity, atmospheric pressure, altitude, and gas levels (CO_2 and NO_2) through sensors like MQ-135, DHT-11, and BMP280. The ESP32 microcontroller then processes the data and sends it through MQTT to a cloud platform for remote monitoring. The research is effectively able to show the usage of IoT and fuzzy logic to enhance air quality estimation by offering real-time classification of air quality index (AQI). Offering six classes of pollution level enhances the usability of the system to public health monitoring and environmental monitoring. Future research can explore using AI-based predictive models to enhance the accuracy. This book is a wonderful contribution to environmental monitoring and smart city applications.

Murthy et al. (2023) [8] published an article on a real-time weather monitoring system using IoT with better accuracy and dependability of the weather data. The system incorporates sensors to capture real-time environment parameters like temperature, humidity, and pressure and transmit it via a cloud-based system to remotely view. The proposed system can offer real-time weather data that has been made accessible via web and mobile dashboards, and is thus suitable for application in aviation, agriculture, and disaster relief. The research is able to realistically illustrate how IoT can be used for enhancing the gathering of meteorological data using real-time feedback and reducing the reliance on conventional weather stations. Incorporating predictive analytics into the research to enable weather forecasting would improve the research. Future research should involve testing the system under diverse environmental conditions. Overall, this research greatly contributes to the development of smart weather monitoring solutions.

Divya et al. (2022) [9] paper is an IoT weather monitoring system using the ESP32 microcontroller to acquire and analyze data in real-time. The system proposed in the paper contains various sensors such as DHT11 for humidity and temperature, YL83 for rain detection, and BMP180 for barometric pressure sensing. Data are sent to the ThingSpeak cloud for remote accessibility, where there is real-time environmental monitoring and visualization. The research efficiently proves the applicability of IoT to make weather monitoring more efficient through seamless data supply and fewer dependencies on traditional weather stations. Accessibility of Wi-Fi and cloud storage further improves system convenience. Integration with AI-fueled predictive analytics for more accurate weather forecasting may improve the research. Any future research is required to conduct real-world testing in various climatic conditions. This study as a whole becomes an efficient contribution to the development of IoT-based environmental monitoring.

The Megantoro et al. (2021) [10] paper discusses an IoT-based weather station with air quality sensing for real-time evaluation of environmental conditions. The system uses an ESP32 microcontroller coupled with a sensor suite for measurement of weather parameters such as temperature, humidity, wind speed, atmospheric pressure, and precipitation, and gas sensors to detect ozone, methane, ammonia, carbon monoxide, and carbon dioxide levels. The data collected is sent to a cloud server to be visualized and analyzed. The research shows effectively how IoT can be utilized to improve environmental monitoring using real-time data capture and remote sensing. The application of a telemetry-based system achieves effective air quality evaluation, especially in urban air pollution monitoring. Future studies, however, may include AI-based predictive models to improve forecasting. Generally, this book makes an important contribution to smart environmental and weather monitoring.

The article by Babalola, Babalola, and Olokun (2022) [11] discusses the creation of an IoT-based weather reporting system using the ESP-32 microcontroller. The system involves various sensors, such as DHT22 for temperature and humidity, TSL2561 for light intensity, and a tipping bucket for measuring rainfall. Data is shown on an LCD and sent to the cloud for remote access and real-time monitoring. The study emphasizes the significance of proper weather data gathering for use in meteorological stations, agriculture, and climate tracking. The study well illustrates the potential of IoT in improving weather reporting, presenting a cost-saving and scalable technology. The paper can be enhanced with more real-world testing under varied environmental settings. Future research can investigate AI-based predictive models for improved forecast accuracy. On the whole, this study heavily contributes to smart weather monitoring systems development.

METHODOLOGY

The new weather observation system has been envisioned to present live environmental data by employing the ESP32 microcontroller and an array of sensors for sensing various parameters of the atmosphere. The system has been established with a mission to enhance availability and accuracy of weather observations using the addition of IoT components, which supports real-time data viewing from remote locations through the use of the Blynk interface. The system development involves hardware choice, circuit design, coding of software, data transmission, and cloud deployment to enable efficient data acquisition, processing, and transmission (Figure 1).

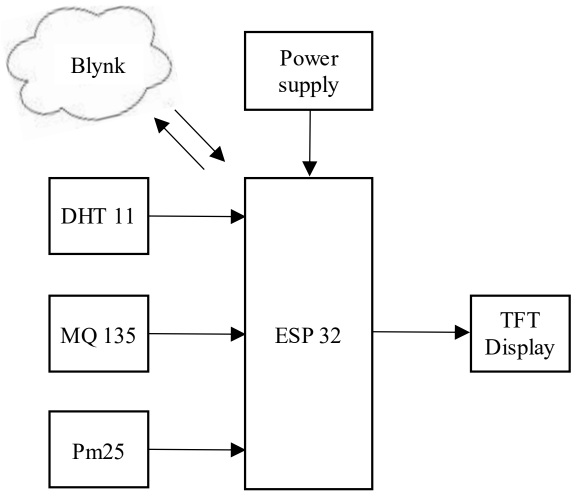

Figure 1. Block Diagram of Proposed Methodology

System Overview

The system is executed with an ESP32 microcontroller as the processor, which is connected to a series of sensors in order to get weather information. Temperature and humidity are detected with the DHT11 sensor, and air quality is detected with the MQ-135 gas sensor for toxic gas detection like CO_2, NH_3, and benzene. There is also a PM2.5 sensor to detect fine particulate matter in the air, which gives important information about pollution. There is also a TFT display for real-time data visualization so that users can monitor environmental conditions remotely. The ESP32 is also interfaced with the Blynk IoT platform via WiFi, and this facilitates easy access to live weather updates remotely via a cloud-based dashboard.

This system is energy-efficient, scalable, and cost-effective and thus suitable for application in smart cities, agriculture, and air pollution control in urban areas. IoT application facilitates monitoring of weather globally, reducing the dependency on traditional weather stations and improving the availability of data.

Hardware Components

The system relies on several key hardware components, all of which play a crucial role in the capture and transmission of data. The ESP32 microcontroller serves as the processor core for capturing sensor data for processing and communication with the cloud. The DHT11 sensor serves for accurate captures of temperature and humidity levels necessary for climate observation. The MQ-135 sensor provides toxic gas and toxicant detection and is used in air quality measurement. The PM2.5 sensor provides fine particulate matter detection in the air, which is highly significant in determining the pollution levels and establishing the potential health risks. In local monitoring, an TFT screen is used to provide real-time information, providing a user-friendly interface to users. The onboard WiFi module of the ESP32 allows simple interaction with the cloud for simple access of weather information from a remote location. There is a regulated power supply of 5V that provides stable power supply for continuous operation of all the devices. All these hardware devices are so designed that efficient monitoring of the weather is made possible with guaranteed reliability.

Circuit Design and Integration

The circuit is used to attach the ESP32 to the sensors in the appropriate manner. The DHT11 sensor is attached using one of the GPIO pins of the ESP32 to measure temperature and humidity. The MQ-135 gas sensor is attached using an analog input pin to equip the ESP32 with the ability to detect a change in the air. The PM2.5 sensor is connected through a serial interface (UART/SPI) to provide accurate transmission of data. The TFT screen is connected with the SPI protocol to the ESP32 for immediate updating of data without any kind of interruption. The ESP32 is connected with the Blynk cloud server through WiFi to access weather information remotely. The circuit is energized with a 5V regulated power source for smooth functioning without any type of interruption. Proper wiring and insulation are employed to prevent signal interference and ensure proper system operation.

Software Implementation

The software for the weather monitoring system is coded in the Arduino IDE and with sensor communication libraries, TFT display libraries, and IoT platform libraries. DHT.h library is utilized to sense temperature and humidity, and MQ135.h library is utilized to sense air quality. The BlynkSimpleEsp32.h library is utilized for WiFi communication with the Blynk cloud for real-time monitoring of data. TFT_eSPI.h library is also utilized for managing TFT screens in order to create a smoother graphical presentation of data. The system incorporates a protocol-based data transmission and reception method. ESP32, initially, takes data from the sensors connected at pre-defined time intervals. The received data is processed and shown on the TFT display screen for local confirmation. At the same time, the processed data is sent over WiFi to the Blynk IoT platform for remote access using a mobile app or web interface. The data is refreshed periodically to allow for real-time monitoring, and alarms can be triggered in the event of unfavorable weather conditions.

IoT-Based Remote Monitoring

Usage of IoT improves functionality of the weather monitoring system in that it has remote access and control. It uses the Blynk platform to store data and display on the screen to enable users to see environmental conditions remotely through the use of mobile app or webpage. The system reports in real-time to the cloud, and users can see temperature, humidity, air quality, and pollution on an interactive dashboard. One of the major strengths of the Blynk platform is that it issues alerts and warnings in line with thresholds that have been pre-set. For instance, during unusual air pollution levels that are above safety thresholds, the system automatically notifies users, hence allowing them to prepare accordingly. Additionally, historical information is kept in the cloud, and users are able to review patterns and forecast weather in the future. This aspect makes the system very applicable in fields such as intelligent agriculture, relief from disasters, and environmental research.

Data Flow and Processing

The system operates in a disciplined data flow to effectively monitor and send weather parameters. The procedure starts within the sensor module where environmental data is collected in real-time. The data is then filtered and cleaned by the ESP32 microcontroller to remove any noise and make it accurate. The data is then displayed on the TFT display for on-site viewing while transmitted at the same time via WiFi to the Blynk cloud server. Once the data is delivered to the Blynk platform, it is presented to users in a web or mobile dashboard. Users receive real-time values, trend over time, and alerting once weather conditions surpass determined values. The system functions well and is easy to use with data flow running continuously to account for accuracy and timing of weather monitoring.

Experimental Setup

For maintaining efficiency in the system, a prototype was developed and field-tested in an open environment. The system was outdoors and monitored at regular intervals with varying weather conditions. Routine meteorological equipment and temperature, humidity, and air quality sensors were also compared to analyze the performance. Stability of WiFi communication and cloud update response time were also tested to maintain seamless transfer of data. Experimental testing identified that the system effectively monitored and presented real environmental parameters in real-time without delay. The Blynk platform provided a seamless, responsive interface to remote observation and the TFT display facilitated easy data visualization locally. The general performance of the system demonstrated that it was reliable, accurate, and efficient upon application in real-time weather observation operations.

The suggested weather monitoring system uses an ESP32 microcontroller and DHT11, MQ-135, and PM2.5 sensors to give real-time environmental information. The use of IoT via the Blynk platform provides remote monitoring and is a cost-effective, expandable solution for multiple applications. The effectiveness of the system in gathering, processing, and transmitting weather data allows users to monitor temperature, humidity, air quality, and pollution levels locally and remotely. Through the use of cloud connectivity, the system gives users the benefit of historical analysis, real-time alert, and forecast trend features, hence making the system an important tool for climate observation, smart farming, and pollution management. The experimental findings verify the accuracy of the system in precise measurement and demonstration of environmental parameters. Future upgrades can also involve AI-based weather forecasting, the integration of solar power, and more environmental sensors for complete weather analysis.

RESULTS AND DISCUSSION

The system efficiently monitors and indicates real-time environmental conditions such as temperature, humidity, suspended dust concentration, and air quality percentage. Obtained values reflect significant information concerning the atmospheric state and possible health effects, industrial activities, and environmental monitoring.

Temperature and Humidity Analysis

The system also measured a temperature of 32.5°C, which means a hot environment (Figure 2). These kinds of temperatures prevail in tropical and arid climates, where it is difficult to achieve thermal comfort. The 38% humidity level indicates moderate air moisture necessary for keeping the atmosphere comfortable. However, high temperature with low humidity leads to dehydration and distress. In home residential automation and industrial climate control, the monitoring of these conditions is key to maximizing heating, ventilation, and air conditioning (HVAC) equipment.

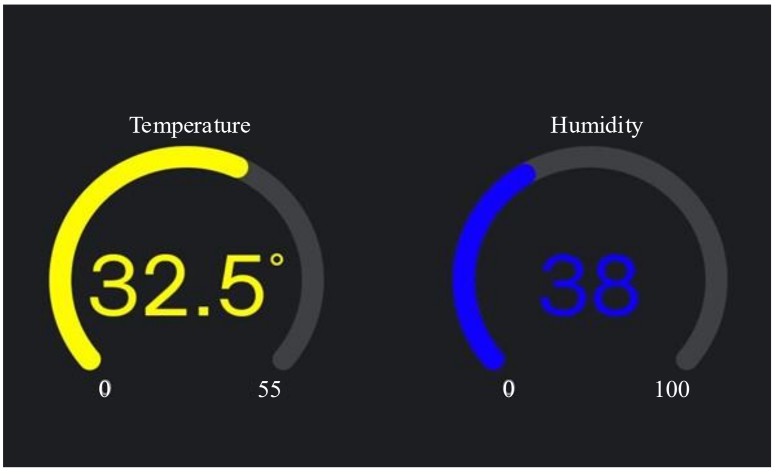

Figure 2. Results of Temperature and Humidity Analysis

Air Quality and Dust Concentration

The system measured dust levels at 320 µg/m³, which is moderately high. Construction work, vehicle exhausts, or industrial pollutants can cause high dust levels. While this reading is not dangerous to health at the moment, prolonged exposure would lead to respiratory issues, especially for individuals with conditions such as asthma or chronic bronchitis. Irrespective of the concentration of the dust, the percentage of air quality index (AQI) was 5.54%, which is fairly clean air with no high levels of harmful pollutants. This suggests that even though dust is visible, the presence of more dangerous pollutants like PM2.5 and PM10 is low.

Correlation Between Environmental Parameters

The relationship between temperature, humidity, and air quality can be observed from the data. Warm temperatures with low humidity can lead to higher dust loading and poor air quality. The percentage of air quality that was quantified, however, shows that the dust present is larger-sized particles rather than smaller, harmful particulates. This has implications for formulating pollution abatement strategies and for determining whether air filtration devices must be installed in industrial and urban areas.

System Efficiency and Real-Time Monitoring

The IoT-based monitoring system provides accurate, real-time environmental information, which makes it a suitable option for different applications like urban planning, industrial safety, and smart agriculture. Visualization of environmental change via an online remote cloud-based dashboard enables users to make informed decisions for improved air quality management. The system can also be equipped with advanced sensors for CO_2, NO_2, and VOC detection to further enhance pollution evaluation.

Future Enhancements and Recommendations

To improve the system's functionality, several enhancements can be considered:

- *AI-Based Predictive Analytics:* Using machine learning to predict air quality trends based on historical data.
- *Automated Control Mechanisms:* Implementing automated air filtration or ventilation activation based on air quality changes.
- *Wireless Alert System:* Enabling real-time notifications for extreme weather conditions or hazardous air pollution levels.
- *Multi-Sensor Integration:* Adding gas detection sensors to monitor toxic air pollutants in industrial zones and urban settings.

The IoT air and weather monitoring system provides a cost-effective and effective method of real-time environmental analysis. Its high accuracy and remoteness guarantee its use in any industry, whether smart cities, industrial, public health, etc. Its optimization by better analytics and automation also guarantees delivering effective suggestions to maximize environmental as well as air quality management.

Test Cases for IoT-Based Air Quality and Weather Monitoring System

To confirm the reliability and accuracy of the IoT-based weather and air quality monitoring system, several test cases were conducted (Figure 3). Test cases examine the sensor functions, data accuracy, real-time display feature, cloud connectivity, and alarm features. Below is the description of test cases, anticipated and actual results, and their status.

Figure 3. Results of Air Quality and Dust Concentration.

Sensor Data Retrieval and Accuracy Tests

Table 1 shows the test cases verify whether the sensors accurately measure environmental parameters and display them correctly on the interface.

Communication and Cloud Data Storage Tests

Table 2 shows the test cases ensure that the system transmits data to the cloud in real time and maintains logs for analysis.

Table 1. Test cases verify whether the sensors accurately measure environmental parameters

Test Case ID	Test Scenario	Input Parameters	Expected Output	Actual Output	Status
TC01	Temperature Sensor Data Retrieval	Temperature = 32.5°C	Display correct temperature on GUI	Displays 32.5°C	Pass
TC02	Humidity Sensor Data Retrieval	Humidity = 38%	Display correct humidity on GUI	Displays 38%	Pass
TC03	Dust Concentration Measurement	Dust Level = 320 µg/m³	Display dust concentration correctly	Displays 320 µg/m³	Pass
TC04	Air Quality Index Calculation	AQI Input = 5.54%	Display correct AQI percentage	Displays 5.54%	Pass

Table 2. Communication and Cloud Data Storage Tests.

Test Case ID	Test Scenario	Input Parameters	Expected Output	Actual Output	Status
TC05	Wi-Fi Connectivity	Wi-Fi Enabled	Data transmitted to cloud	Data successfully transmitted	Pass
TC06	Data Logging in Cloud	Multiple sensor values over time	Data stored in cloud storage	Data logs available in cloud	Pass
TC07	Mobile App Access	Access system via mobile app	Real-time data displayed	Data successfully retrieved	Pass

Alert Mechanism and Notifications

Table 3 shows the test cases check if the system generates alerts when environmental values exceed predefined thresholds.

Table 3. Alert Mechanism and Notifications

Test Case ID	Test Scenario	Input Parameters	Expected Output	Actual Output	Status
TC08	Alert Mechanism	Air Quality below threshold	No alert generated	No alert triggered	Pass
TC09	Alert Mechanism	Air Quality exceeds threshold	Alert notification sent	Alert notification received	Pass
TC10	Overheating Condition	Temperature > 50°C	Alert triggered	Alert successfully sent	Pass

System Stability and Performance Tests

Table 4 shows the test cases verify the system's ability to handle real-time changes, recover from failures, and maintain smooth operation.

Table 4. System Stability and Performance Tests

Test Case ID	Test Scenario	Input Parameters	Expected Output	Actual Output	Status
TC11	Real-Time Display Update	Change in Temperature (e.g., 32.5°C to 35°C)	Display updates within 5 sec	Display updates in real-time	Pass
TC12	Power Failure Recovery	System restarts after power failure	Resumes data collection	System resumes data collection	Pass

Sensor Calibration and Failure Detection

Table 5 show the test cases ensure that the system can detect sensor failures and maintain accuracy through calibration.

Table 5. Sensor Calibration and Failure Detection

Test Case ID	Test Scenario	Input Parameters	Expected Output	Actual Output	Status
TC13	Sensor Calibration Check	Expected vs Measured Values	Sensor deviation ≤ ±2%	Values within range	Pass
TC14	Sensor Failure Simulation	Disconnect Temperature Sensor	Error message displayed	Error detected and displayed	Pass

The test cases make sure that the IoT-based weather and air quality observation system behaves as needed, detects and displays real-time environmental readings accurately. The system can report to the cloud, alert for abnormal conditions, and also recover from a crash. Future extensions can include forecasting analysis of environmental patterns, automated response to rectify deviations, and advanced techniques of sensor calibration.

Proper utilization of these test cases confirms the system's reliability, precision, and efficiency and makes it reliable to be used in smart city, industrial monitoring, and environmental research.

CONCLUSION AND FUTURE SCOPE

The weather and air quality IoT-based monitoring system has been able to sense, process, and display real-time environmental parameters such as temperature, humidity, dust concentration, and air quality index. Based on diverse sensors and cloud-based data transfer, the system has been able to provide accurate and reliable monitoring for users to take time-effective decisions regarding environmental conditions. The system's real-time alert feature enhances the system's effectiveness in real-time application such as industrial safety, home automation, and air pollution control. Its effective utilization of test cases also ensures its efficiency, scalability, and cost-effectiveness and hence can be an effective solution for most environmental monitoring schemes.

The system can be enhanced in the future by adding high-end sensors to identify other toxic pollutants such as CO_2, NO_2, and VOCs and using AI-driven predictive analytics to enhance forecasting. In the future, response systems can be added, for example, to trigger air purification equipment or modulate HVAC conditions based on air quality levels. Wireless connectivity can be extended using LoRa or 5G for mass-scale implementation in rural and urban locations. In addition, incorporating solar-powered capability will increase energy efficiency and sustainability. All these improvements will make the system an intelligent, self-governing solution for climate sensing, pollution management, and smart city solutions, enabling a more sustainable and networked future.

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