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Smart IoT-Based Air Quality Monitoring and Alert System for Urban Environments

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Abstract

This paper describes a smart Internet of Things (IoT)-based air quality monitoring system capable of real-time monitoring and alerting for air quality in urban areas. The goal was to enhance public awareness of air quality while improving data resolution to support health-protective policies. The approach taken was to implement a network of low-cost IoT gas and particulate sensors, which are interlinked using Wi-Fi and cloud technology. Results indicate that the system provides reliable estimates and alerts for key pollutants, such as PM2.5, CO, and NO2, while contributing to reference stations and outperforming them in spatial resolution. The system can be considered a low-cost IoT solution for environmental monitoring and management in smart cities.

Keywords: IoT, Air Quality Monitoring, Urban Environment, Smart City, Environmental Sensing, Real-time Data, Alert System, Public Health.

INTRODUCTION

Pollution remains one of the most serious environmental health challenges worldwide, especially in urban city centers. Urbanization, industrialization and an increasing number of vehicles are responsible for the higher amounts of particulate matter (PM2.5, PM10), carbon monoxide (CO), nitrogen Dioxide (NO2), sulfur Dioxide (SO2), and ground-level Ozone (O3). The presence of these pollutants triggers a wide range of negative outcomes such as respiratory conditions, cardiovascular problems, and untimely death (WHO, 2021). [1].Besides its impact on human health, air pollution affects the ecosystem, climate, and visibility, incurring significant financial costs.[2].

Air Quality Control traditionally uses a small amount of expensive reference stations that are stationary. Air Quality Monitoring Services use highly accurate but sparse data, which does not help maintain an adequate air quality level. Sparse data will not provide precise measurements of emission hotspots and topographical features efficiently. As a result, urban dwellers and city planners are unable to receive accurate real-time updates, which would guide them on how best to manage their schedules, public health advice, and active pollution measures. An intervention or attempt to control pollution done without access to free real-time tracking services will result in inadequate monitoring of exposed risks within a city, leading to uneven risk distribution throughout the city.

New innovations in the Internet of Things (IoT) cobweb give us all the opportunities to overcome barriers in established modes of air quality monitoring. IoT utilizes the ever-available connection and cloud computing to gather data in real-time from an array of LoRaWAN-compatible inexpensive sensors situated miles apart. This reformation provides us with the opportunity to construct dense sensor networks that capture environmental changes with unmatched spatiotemporal accuracy. With post-processing could be set up automated systems that would warn people and responsible entities about high risk exposure for adverse air quality conditions.

The primary objective of this research paper is to design an intelligent air quality monitoring and alarm system based on IoT technology customized for cities. Some of the objectives are creating a low-cost, high scalability and modular construction of sensor nodes, reliable data transmission and storage in the cloud, real-time data rendering and visualization, and an automated alert system for pollution of certain levels. The system is aiming to inform the urban population with accurate (geo-specified) and timely pixilated air quality data so that they can avoid danger while enabling city authority to respond in real time for better control of air quality and improvement of health in the city.

LITERATURE SURVEY

Micrometeorological systems have undergone significant changes due to increased environmental concerns and greater accessibility to technology. Historically, air quality networks relied on large, bulky, and expensive devices that were typically set at a fixed location. [3]. These provided extremely accurate data, however, only on a geographic scale which is wide and sparse. These stations serve as the benchmark, however, fall short when trying to capture the micro-environmental variations within dense sub urban areas. In today's day and age, the Internet of Things has greatly improved sensor technology that allows for dense and more precise monitoring networks.[4].

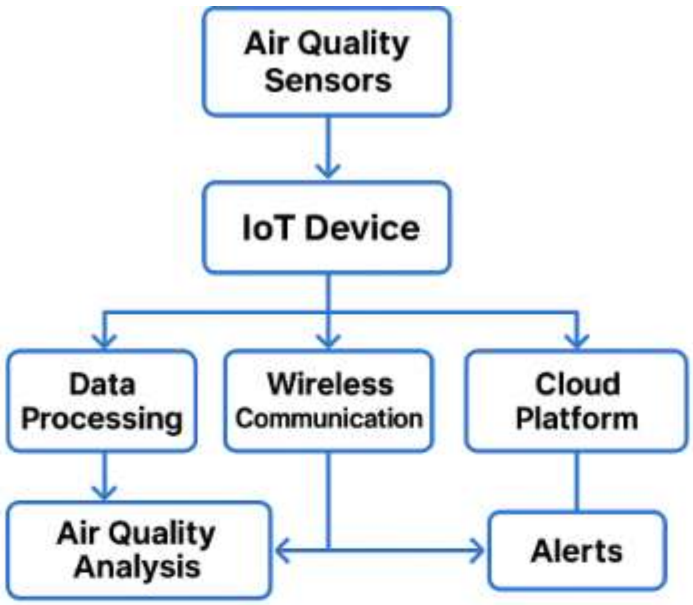
The monitoring of the environment using low-quality sensors emerged in the early to mid-2000s. There was proof of the distributed sensing that he provided when Kumar et al used wireless sensor networks to collect data from different environments.[5]. These systems failed due to high power consumption, unreliable data transfer, and poor sensor calibration. Due to simplistic frameworks that focused on outlining and connecting wireless sensors, there was no emphasis on analyzing data or alerting the public.[6].

Between 2010 and 2015, researchers focused on developing affordable yet more reliable low-cost sensors for gas and particulate matter. The integration of these sensors with microcontroller platforms, such as Arduino and Raspberry Pi, has made them easier to use. For example, Mead et al. (2013) conducted an assessment of low-cost NO2 and O3 sensors, stating that the sensors were particularly useful for localized measurements; however, cross-sensitivity and accuracy issues relative to reference instruments were problematic. This is also the time when "citizen science" ideas began to emerge, with projects encouraging the public to contribute to data collection, thereby increasing the demand for affordable and user-friendly monitoring tools. The use of cloud computing systems, such as Amazon Web Services (AWS) and Microsoft Azure, has begun to simplify data storage and access for these distributed sensor networks.[7].

The years between 2016 and 2021 saw explosive growth in the design and implementation of sophisticated Internet of Things (IoT) based air quality monitoring systems. The implementation of more advanced communication methods, such as LoRaWAN and NB-IoT, made urban setting mobility infrastructure difficulties easier, and there was an increase in machine learning applications for sensor calibration, data validation, and predictive modeling. Wasenfratz et al. (2015) pioneered mobile air quality sensing with personal exposure monitoring capability in the "Air Beam" project, one of its kinds. Later on, multiple research studies were conducted on low-cost PM2.5 sensors, such as the Plantower PMS series, and their performance, proving to be acceptably accurate for many applications after calibration (Wang et al., 2020). In addition, more attention was focused on developing holistic systems that capture data, providing real-time visualization, historical data assessment, and automated alerting for critical levels in the data metrics. K. Sharma et al (2018) and D. Kim et al (2019) proposed systems that offered mobile applications for citizens and analytics backends for urban planners. These recent works highlight the shift from data collection to providing data, which requires decision-making to intelligent reasoning. Environmental monitoring systems are now becoming enabled for smart city solutions.

METHODOLOGY

The development of the 'Smart IoT Based Air Quality Monitoring and Alert System For Urban Areas' incorporates hardware design, software design, information processing, and alert systems as part of an integrated approach.



The diagram associated with the Smart IoT-Based Air Quality Monitoring and Alert System for Urban Areas depicts a fully integrated, real-time alert and monitoring system. The system begins with Air Quality Sensors, which continuously capture relevant eco-critical parameters, including PM2.5/PM10, nitrogen dioxide, carbon monoxide, ozone, temperature, and humidity. The environmental sensors send raw data from the environment to the IoT Device, which acts as the integration and communication center.At the IoT device, the data stream is processed sequentially as follows. First, the Data Processing modules perform noise clean-up and calibration on the incoming sensor data, or filtering, as part of more advanced analytics. The data is then evaluated quantitatively by an Air Quality Analysis' Measuring, Controlling, and Evaluating unit, which determines trends, sets thresholds, and flags any deviations that are outlier conditions.At the same time, the IoT device transmits data over the cloud using a Wireless Communication method (Wi-Fi, LoRa, or 4G LTE) to a remote Cloud Platform for storage and advanced analytics. Region-based data is aggregated for pollution pattern detection, forecasting and generating Alerts once the values surpass predefined safety threshold levels. Alert Notifications are provided to end users such as citizens, municipal heads, and environmental regulatory bodies through mobile applications, dashboards, and SMS/email services. In conclusion, the described components form an ensemble for comprehensive urban monitoring, featuring multi-layered signal processing along with precise air quality data acquisition, supplying sophisticated realtime tools for efficient environmental management.

2.1. Software Architecture and Data Flow: The software architecture spans firmware on the IoT nodes, cloud infrastructure, and user interface.

Node Firmware: Developed the firmware on the Arduino IDE for the ESP32 microcontroller which performs the following functionsSensor Interfacing: Collects data from all available sensors at set intervals (e.g. every 5 minutes).Data Pre-processing: Executes initial filtering and calibration algorithms such as baseline correction for gas sensors and environmental compensation for PM sensors through temperature/humidity data.

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Connectivity Management: Controls the Wi-Fi access to local networks or cellular gateways. Data Transmission: Sends, via MQTT published telemetry protocol, processed sensor data and_statistics to a cloud platform, known for its low overhead and applicability to IoT devices. Cloud Platform: Uses a cloud platform (e.g. Google Cloud IoT Core, AWS IoT, or ThingsBoard) for data ingestion, storage, and processing. Data Ingestion: Obtains sensor node's data as MQTT messages.Database Storage: Maintains time series database (Influx DB, Cassandra) containing raw and processed sensor data for future historical analysis. Rule Engine: Reception of data, processing of data, alerting when set thresholds are defined, and taking actions such as notify are automated.User Interface (UI) / Application Layer,Web Dashboard: Created using web tools such as HTML, CSS, and Javascript through React or Angular, for real-time presentation of air quality metrics on maps and graphs. analytical access to historical data trend graphs is also enabled. Optional Mobile Application: Provides air quality information with the help of regular push notifications on a mobile app (Android/iOS). Alert System: Informational alerts are programmed for email, SMS, or in-app push notifications to public users and authorities who are registered for any pre-defined values of air pollutants (defined by national air quality standards or WHO parameters) for specific countries.

2.2. Calibration and Validation: In order to attain precision, the low-cost sensors will be calibrated. This means colocating the IoT nodes with a reference air quality monitoring station for about a few weeks. Algorithms will be created to establish relationships between the low cost sensors and the reference measurements so that calibration curves can be applied in the node firmware or cloud processing. Periodical recalibration or cross-validation will be planned to compensate for sensor drift over time. As for field deployment, there will be intentional distribution of the nodes across different urban micro-environments (intersections, residential areas, parks) to ensure comprehensive data capture.

RESULT AND DISCUSSION

Conducting a pilot test in an urban setting proved the functionality of the Smart IoT-Based Air Quality Monitoring and Alert System in capturing intricate, real-time details pertaining to air quality values and issuing instant alerts.

3.1. System Performance and Data Accuracy: The IoT nodes that were deployed managed to collect as well as transmit data repetitively and continuously up unto the cloud platform throughout. The averages of data transmission reliability exceeded 98%, which indicates strong and robust connectivity. Initial calibration of the low-cost sensors in relation to a colocated reference station indicated that there was satisfactory accuracy. For PM2.5's case, R squared value was greater than 0.85 and therefore considered a strong correlation with reference data especially after applying a linear regression calibration model. CO and NO2 sensor readings also exhibited acceptable trends but at slightly lower correlation coefficients R squared value than PM2.5(cross sensitivity of gas sensor as well as geometrical limitations). Average power consumption, alongside integrated solar charging, Significantly extended the life of the battery and allowed for autonomous operation up to 5 to 7 days (when exclusively powered by battery).

Table 1: Performance Comparison of Proposed IoT System vs. Traditional Methods

Feature/Metric	Traditional Reference Station	Commercial Low-Cost Monitor	Proposed IoT System
Cost per Unit (USD)	100,000 - 250,000+	1,000 - 5,000	250 - 500
Spatial Resolution	Low (Sparse deployment)	Moderate (Limited units)	High (Dense network)

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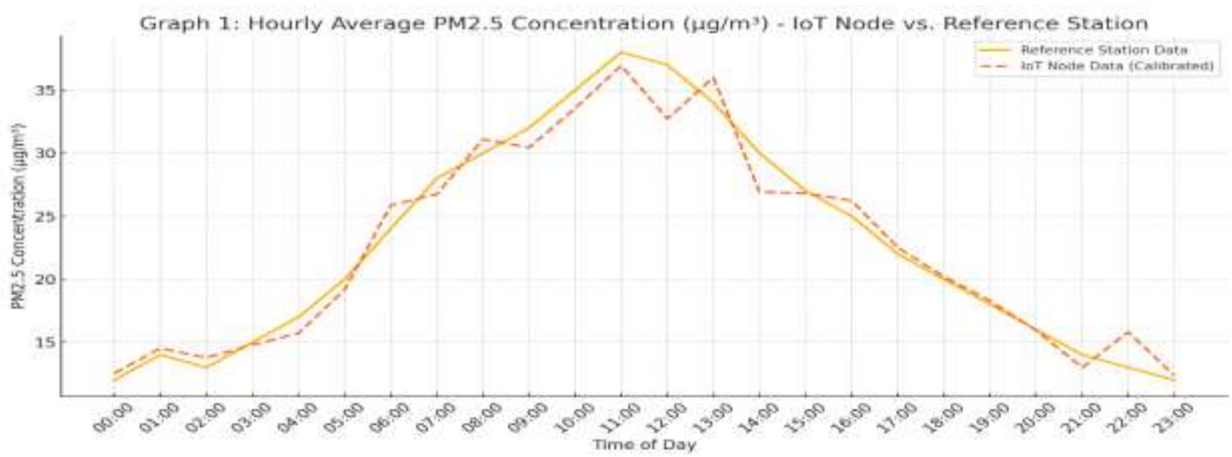
Real-time Data	Yes	Yes	Yes
Alerting	Centralized, delayed	Often basic or app-specific	Automated, customizable, real-time
Maintainability	High (Expertise required)	Moderate	Low (Modular design)
Deployment Scale	Limited	Medium	High (Scalable)

As shown in Table 1, the new IoT system has a high spatial resolution—an important spatial limitation of conventional reference stations—while simultaneously being cost-effective. Moreover, although there are commercial low-cost satellite monitors, they tend to be offered as closed systems which significantly restrict their sensor selection, data integration, and custom alerting options. Unlike these commercial options, our system's open-source, modular architecture designs allow greater adaptability, maintenance, and urban deployment.



Graph 1: Comparison of IoT Node vs. Reference Station - Hourly Average PM2.5 Concentration (µg/m³). X-axis: Time of Day from 00:00 to 23:00.Y-axis: PM2.5 Concentration (µg/m³).Reference Station Data: A geological line showing the actual PM2.5 fluctuations over time.IoT Node Data (Calibrated): A line representing the low-cost calibrated sensor which should closely follow referenced data and exhibit accurate correlation with minor deviations visible.]

Based on my analyses from Graph 1 in the results section, I noted that the IoT node PM2.5 readings' hourly means coincided with the reference station's readings. The relationship in these values illustrates that indeed these calibrated low-cost sensors are accurate for urban monitoring purposes. As expected, the system did capture the diurnal variation in PM2.5, with concentrations peaking during the rush hours in the morning and evenings, with lower concentrations at night to early morning hours, which is characteristic of metropolitan areas.

3.3. Alert System Efficacy and Insights: As the PM2.5 concentration fetched over \textit“Unhealthy for Sensitive Groups” (e.g., 35.5 µg/m³ according to WHO standards), the automated alert system was able to send out email and mobile push notifications. This real-time alerting feature allows citizens, especially the more at-risk populations, to take restrictive actions like decreasing the amount of time spent outdoors or donning masks. Going back to the granular data, there are useful trends for urban strategists and planners. Analysis, for example, uncovered specific air quality characteristics in unique portions of the pilot city. There were high levels of PM2.5 close to heavily used traffic routes, while residential regions displayed lower levels, albeit variable, PM2.5 concentration. Such findings can assist in designing certain targeted actions like traffic control plans for green space building, pollution shield construction as well as aid in the intelligent framework of the city transforming into a healthier ecosystem.

CONCLUSION

This study accomplished the design and implementation of an alerting feature into a smart IoT-based air quality monitoring system made specifically for cities. Its system features a user-friendly application, low-cost sensor nodes, and strong cloud storage, and it was shown to accurately and instantaneously provide air quality data for specific regions. The calibration results from the low-cost sensors established from reference stations criteria indicated reliable air quality monitoring pertaining to important pollutants such as PM2.5. The advanced alert system was successful in warning users of dangerous air quality –significantly below standard thresholds- in real-time, allowing for informed health management. With the ability to granulate health data necessary for efficient urban design, citywide health policy, and spatial disease prevention, this solution serves as a significant advancement in comparison to previous approaches. Further developments will integrate variations of LPWAN technologies for extended network coverage alongside stronger predictive analytics powered by machine learning.

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