International Journal of Recent Innovations in Academic Research

E-ISSN: 2635-3040; P-ISSN: 2659-1561
Homepage: https://www.ijriar.com/
Volume-8, Issue-10, October-2024: 1-11

Research Article

Development of an IoT-Based Hazardous Particle Detection System for Real-Time Air Quality Monitoring

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Received: September 12, 2024 **Accepted:** October 02, 2024 **Published:** October 09, 2024

Abstract
This paper introduces the development of an IoT-based hazardous particle detection system (HPDS) aimed at monitoring air quality in real time to detect harmful airborne particles, such as VOCs and CO. The system integrates sensors, a cloud-based web server, and a smartphone application to provide continuous surveillance of specific regions. Data collected by the sensors is transmitted to the web server via an LTE modem, where it is processed and presented on the application, allowing users to access real-time environmental information. The system is capable of issuing notifications when air quality levels exceed predefined thresholds, as well as logging all data for further analysis and system performance verification. The HPDS was tested in an urban environment, and experimental results demonstrated its effectiveness in tracking air quality changes and notifying users of hazardous conditions. Future enhancements to the system include the incorporation of AI to differentiate between environmental contaminants and natural events, such as dust storms, and expanding sensor capabilities to monitor larger areas. This work provides a foundation for the development of advanced air quality monitoring systems that can effectively track hazardous particles and improve environmental safety.
Keywords: IoT-Based Detection, Air Quality Monitoring, Real-Time Environmental Surveillance, North Korean Waste Balloons, VOC and CO Detection.

1. Introduction

Recent tensions between South Korea and North Korea have escalated due to the exchange of foreign aerial objects between the two nations (Oxford Analytica, 2024; Foster-Carter, 2024). South Korean balloons typically carry anti-North Korean propaganda, U.S. dollar bills, and leaflets or USB drives containing references to Western culture. In contrast, the balloons launched from North Korea pose greater concerns, often containing waste materials such as trash, human excrement, and potentially hazardous substances, including parasites (Bae and Mitsanas, 2024). For instance, on June 25, 2024, 350 waste-laden balloons were launched from North Korea, carrying soil contaminated with parasites like roundworms and whipworms, alongside damaged clothing and wastepaper (Kim and Lee, 2024; Lim and Cha, 2024). The increasing frequency of these balloon exchanges highlights the urgent need for an efficient and accurate system to detect and track these hazardous objects before they pose a risk to public safety.

The potential environmental and biological impacts of these waste balloons are significant. The balloons can carry soil and liquids contaminated with parasites or bacteria, potentially leading to environmental degradation, such as soil quality deterioration and the introduction of harmful substances into ecosystems (Mishra *et al.,* 2016; Nieder *et al.,* 2018; Yu, 2024). Additionally, the presence of human excrement and other waste materials may harbor pathogens, increasing the risk of outbreaks if these materials are not properly monitored (Oliver, 1997; Sobsey *et al.,* 2006). Furthermore, the mere presence of these balloons can heighten public fear and stress, exacerbating psychological distress and increasing tensions both domestically and internationally (Elsamadony *et al.,* 2021).

Although current detection methods, such as military radar systems, are capable of identifying large objects, they struggle to accurately detect smaller balloons, which are often only one or two meters in diameter (McCartney, 2024). The inefficacy of radar systems in detecting these smaller objects, combined with the absence of chemical, biological, radiological, nuclear, and explosive (CBRNE) materials detected thus far (Lee and Kim, 2024), necessitates the development of more advanced detection technologies. Such systems must be capable of identifying not only the balloons themselves but also any hazardous materials they may carry.

To address these challenges, an Internet of Things (IoT)-based detection system, referred to as the hazardous particle detection system (HPDS), has been developed. The HPDS integrates carbon monoxide (CO) and volatile organic compound (VOC) sensors, both of which are mounted on a developed mobile robot to detect harmful airborne substances. In addition, the system is equipped with a line tracer module, enabling it to autonomously navigate and monitor predefined areas. The HPDS underwent testing to evaluate its reliability and operational efficiency, with continuous assessments conducted to optimize its performance.

The primary objective of the system is to identify hazardous airborne particles, such as those potentially emitted from waste balloons, and to provide prompt alerts to users and authorities, thereby mitigating environmental risks.

2. Materials

A critical aspect of developing an advanced system for detecting harmful airborne substances lies in the selection of appropriate and precise sensors capable of accurately identifying contaminants while minimizing false detections. Furthermore, the system must facilitate rapid and reliable communication of key data to the user. Therefore, careful consideration was given to the technical specifications of both the sensors and the microcontroller system when selecting components to ensure optimal performance.

2.1. Microcontroller

The microcontroller chosen for this paper was the Raspberry Pi microcontroller, a single-board computer. It was chosen for its vast customizability and its high compatibility with different types of sensors. Its 4-core CPU, 1GB RAM capacity, and various slots that the sensors could be connected to made it the optimal microcontroller for this paper (Raspberry Pi, 2015).

Table 1. Specification of Raspberry Pi 2 model B.

Specifications	Values
Instruction set	ARMv7-A (32-bit)
CPU	4 × Cortex-A7
Memory	1 GB
SoC	Broadcom BCM 2836
Weight	45 g
Size	85.6 mm × 56.5mm

2.2. VOC Sensor

The VOC sensor is a key sensor in the system, as it can detect different particles released from the balloons. Particularly, the sensor was chosen for its H_2 detection as hydrogen was used more commonly than helium (Hunt *et al.,* 2024) to keep the balloons afloat. Also, the low inaccuracy of only 7%, and its wide tolerance in operating environments, allows the sensor to be used in most weathers for constant detections (Ogam Technology, 2009).

Table 2. Specification of VOC sensor.

Specifications	Values
Operating temperature	-10 to 50 Celsius
Operating humidity	5 to 95% RH
Sensitivity (β) for toluene	0.30≤β≤0.60 (concentration: 1.0 ppm)
Sensitivity (β) for H_2	0.35≤β≤0.70 (concentration: 100 ppm)
Sensitivity (β) for i-butane	0.20≤β≤0.60 (concentration: 100 ppm)
Accuracy	±7%

2.3. CO Sensor

Carbon monoxide (CO) is a harmful compound that can affect human bodies by binding to red blood cells and causing oxygen levels to drop. Being caused by incomplete combustion, CO can dangerously affect health, as continuous exposure can lead to fainting and death. The specifications of the CO sensor are shown in Table 3 (Ogam Technology, 2013).

Table 3. Specification of CO sensor.

Specifications	Values
Operating temperature	-10 to 50 Celsius
Operating humidity	5 to 90% RH
Sensitivity (β) for CO	0.30≤β≤0.60 (concentration: 100 ppm)
Sensitivity (β) for tobacco	β≤0.70 (concentration: 2000 ppm)
Accuracy	±7%

2.4. Network Modem

As proper connections are crucial in the HPDS for accurate measurements of air quality and communication with the web server, the RCU890L LTE modem from Woojin Networks is mounted on the device that specification is shown in Table 4. With a wide operating temperature range and high data speed, it proved to be a key aspect in the HPDS (Woojin Networks).

Table 4. Specification of the network modem.

Properties	t2.medium
Communication method	LG U+ LTE B5/B7 FDD Cat.4
Interface	4
Band	LTE FDD 850 MHz (B5)/2.6 GHz (B7)
Data speed	150 Mbps DL/50 Mbps UL
Input voltage	4.5 V to 5.5 V

2.5. Line Tracer Module

To enable autonomous movement within a predefined monitoring area, three TCRT5000 reflective optical sensors (Vishay, 2024) were integrated into the system as line tracer modules. The TCRT5000 sensors operate using infrared light to detect the contrast between the black lines and the surrounding surface, with a detection range of up to 25 mm that is described in Table 5. By following the black lines drawn on the ground, the system can navigate through the designated area with high precision. This configuration ensures that the system remains within its predefined boundaries while continuously monitoring air quality. The inclusion of these sensors allows for consistent and accurate traversal of the target area, thus optimizing real-time environmental data collection with minimal user intervention.

Table 5. Specifications of the line tracer module.

Properties	Values
Type	Reflective optical sensor
Detector type	Phototransistor
Detection range	2 mm to 25 mm
Dimensions	10.2 x 5.8 x 7mm

2.6. Web Server

The Amazon Web Services (AWS) web server was a key component in the system's presentation layer, responsible for facilitating data transfer between the IoT device and the user application. AWS was chosen for its efficient virtual CPU, scalable memory, and medium-tier networking performance (5 to 10 Gbps), ensuring reliable data transmission and real-time responsiveness that specification is shown in Table 6. Additionally, the server utilized Elastic Load Balancing (ELB) to optimize traffic distribution and minimize response times (Jo, 2019). These specifications made AWS an effective solution for managing the system's data flow under varying workloads.

Table 6. Specifications of the instance for AWS.

Properties	t2.medium
vCPUs	2
Memory (GiB)	4
Clock speed (GHz)	Maximum 3.3
Networking performance	Low to medium

2.7. Reliability Testing

As sensors are a critical component of the hazardous particle detection system (HPDS), their accuracy is essential for effective waste balloon monitoring. To ensure reliability, the VOC and CO sensors were tested according to protocols set by the Korea Testing Laboratory under the Ministry of Environment guidelines (Ministry of Environment, 2019).

2.7.1. VOC Sensor

The Korea Testing Laboratory protocols require the VOC sensor to undergo calibration prior to reliability testing. Calibration was performed in a controlled environment-a 1m x 1m x 1m chamber with regulated humidity and temperature. The sensor was placed inside an acrylic chamber alongside a MiniRAE 3000, a photoionization detector (PID)-type VOC sensor, to facilitate comparative data analysis. VOCs were introduced into the chamber by burning incense, following the method described by Zhang (2015), allowing for simultaneous measurements from both sensors. The data obtained from the PID sensor were used as a reference to calibrate the VOC sensor, ensuring alignment in measurement accuracy and establishing the sensor's reliability for subsequent testing.

Following calibration, the accuracy of the VOC sensor was assessed by injecting hydrogen (H_2) into the test chamber at three predefined concentrations: 500 μg/m^3, 1000 μg/m^3, and 1500 μg/m^3. The sensor's output was then compared to the known injected concentrations to evaluate its reliability. When 500 μg/m^3 of H_2 was introduced at 15:30, the sensor displayed accurate readings starting at 15:35. Similarly, for the 1000 μg/m^3 concentration injected at 16:00, the correct reading was observed at 16:20. Finally, when 1500 μg/m^3 of H_2 was introduced at 17:00, the sensor showed an accurate reading at 17:15, with a slight delay due to the time required for the gas to diffuse uniformly within the chamber. These results indicate that the sensor demonstrates reliable performance, providing accurate and consistent VOC detection, making it suitable for the purposes of this study.

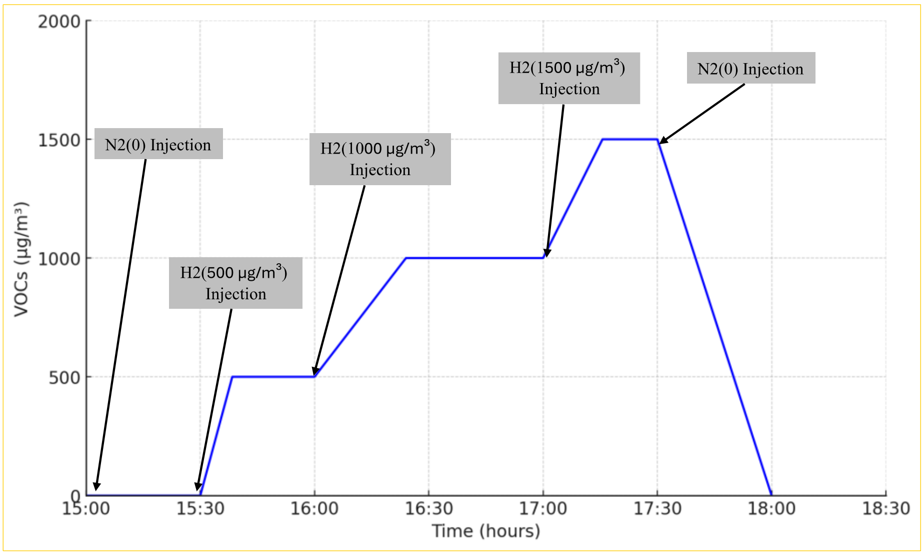

Figure 1. Reliability testing of the VOC sensor.

2.7.2. CO Sensor

The CO sensor shares the reliability testing method with the VOC sensor. This was due to the CO sensor being a semiconductor type, which is not an official standard CO sensor for air quality measurements. TES-132 was used in the reliability testing experiments as it was an NDIR-type measurement device, recommended according to the reliability testing guidelines. As mentioned previously, the same methods were used for the VOC sensor testing, including the calibration. The devices, being placed into the sample chamber, were tested by burning an inch long incense inside the chamber. Then, the sensor from the HPDS system and the NDIR-type sensor began measuring the amount of CO inside the chamber. The values from the NDIR-type sensor and the sensor inside the HPDS system showed a linear relation, showing that the CO sensor in the HPDS system was calibrated properly.

After the calibration, the device was again placed in the chamber, also with the NDIR-type sensor for reliability testing. The data shown in the Figure 2 shows that the level of CO, measured by the TES-13, inside the chamber increased greatly after the incense was burned, and then again dramatically dropped after the burning of the incense ended. The data also shows that the CO sensor used in the HPDS system is reliable, as the two graphs show high levels of resemblance to each other, signifying that the CO sensor is reliable for testing the effectiveness of the HPDS system.

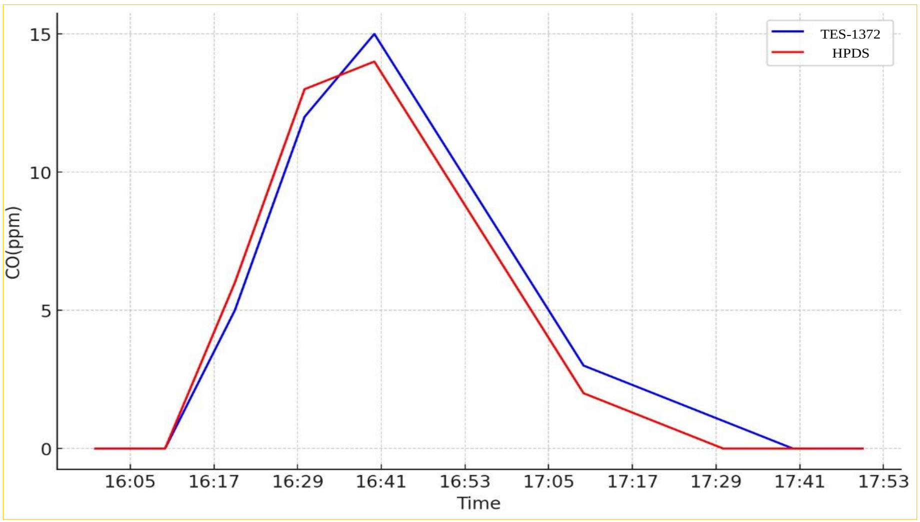

Figure 2. Reliability testing of the CO sensor.

3. IoT Based Particle Detection Platform

The hazardous particle detection system (HPDS) platform is comprised of three main components: the detection device (HPDS), a smartphone application, and a cloud-based web server, as illustrated in Figure 3. The HPDS device captures air quality data, which is transmitted via an LTE modem to the smartphone application. The smartphone component receives the surveillance data and enables additional functionalities, such as calculating GPS coordinates, controlling radar operations, and allowing manual system control when necessary. This ensures real-time access to environmental data, along with enhanced operational control for monitoring and managing air quality threats. Also, the web server, integrated with cloud computing, processes the data and supports high-speed transmission, essential for handling large volumes of real-time information. The cloud infrastructure also allows remote configuration and system monitoring, ensuring flexibility and performance in the event of any system issues.

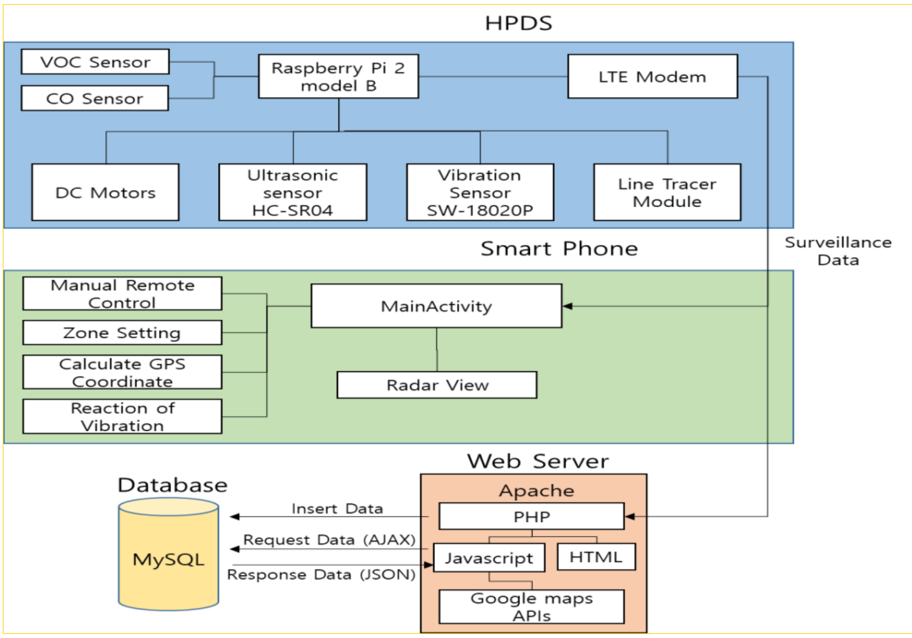

Figure 3. Configuration diagram for the HPDS platform.

As the HPDS is an Internet of Things (IoT)-based system, it operates across three essential layers: the perception layer, the network layer, and the presentation layer. The perception layer consists of data-collecting devices, such as sensors, which gather environmental information. This data is transmitted to the network layer via a wireless module or TCP server, where it is processed on a web server. Subsequently, the processed data is sent to the presentation layer, where it is displayed to users in various formats, including text, notifications, graphs, or maps (Chaudiri, 2018; Jo, 2018; Alam, 2022). In the HPDS, the presentation layer consists of an iOS application developed by Apple, designed to enable real-time tracking of waste balloons from any location. The application features a map that visualizes the detection areas and a monitoring system capable of receiving data from multiple devices simultaneously, facilitated by the cloud-based web server. Users can select which system to track on the map, providing flexible and efficient monitoring capabilities.

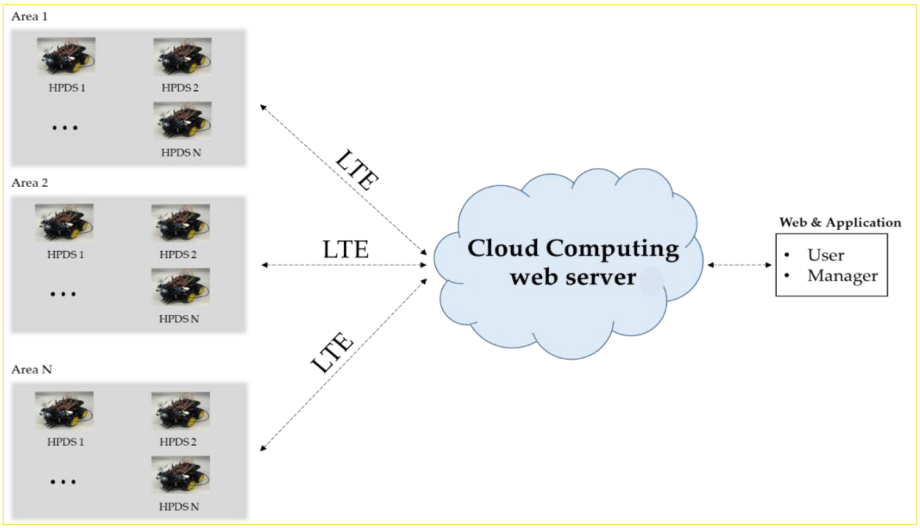

Figure 4. Block diagram of the hazardous particle detection system.

3.1. Hazardous Particle Detection System

The hazardous particle detection system (HPDS) is designed to detect hazardous particles released from balloons, allowing for early detection and minimizing potential harm to people. The system is mounted on a mobile platform equipped with sensors capable of detecting particles that may pose a risk to human health. By conducting surveillance in areas where these harmful particles may be present, the HPDS helps reduce the impact of potential exposure. In this study, a prototype was developed, which includes sensors for detecting volatile organic compounds (VOC) and carbon monoxide (CO), both of which are potentially harmful substances that could be released from the balloons. A line tracer module was also integrated into the mobile platform to enable the system to autonomously monitor designated areas and detect hazardous zones in advance. When the VOC or CO levels exceed predefined thresholds, the HPDS device communicates the detected risks to an application and web server via an LTE modem, alerting users to the presence of dangerous particles and ensuring timely intervention.

A critical component of the HPDS is the algorithm that determines whether the air quality levels detected by the sensors are sufficient to trigger an alert. The algorithm was designed to efficiently process sensor data and accurately identify contaminated areas. It continuously monitors sensor readings through an iterative loop and employs a conditional check to assess whether the detected air quality exceeds the threshold for issuing an alert. The algorithm ensures that low levels of detected contaminants do not result in false alarms, allowing the system to operate smoothly. A detailed description of the algorithm is provided in Figure 5.

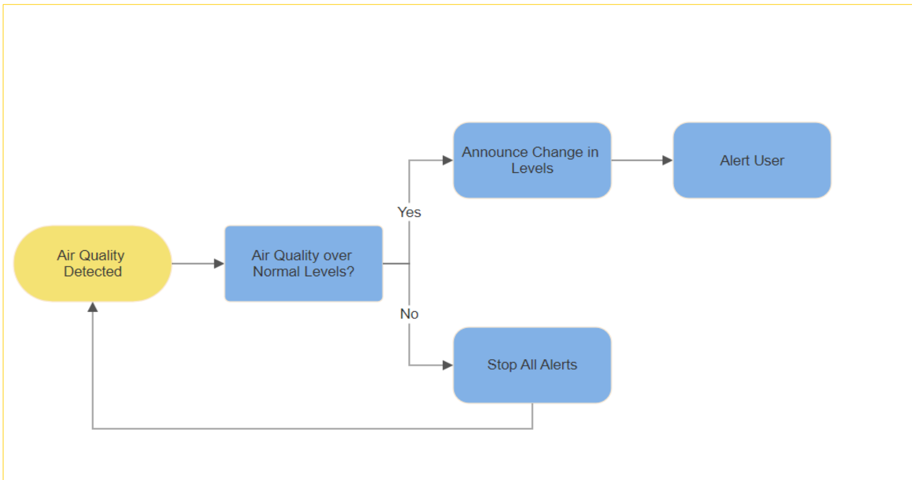

Figure 5. IoT algorithm description.

3.2. IoT Modem

A critical component of the HPDS system is its internet communication, facilitated by an IoT network. The system employs an LTE modem mounted on the device to transmit and receive data between the sensors and the cloud-based web server. Data is transmitted in TCP/IP packets (Tarik, 2015) via the LTE modem, ensuring reliable and efficient communication between the web gateway and the server. This connection enables the system to operate seamlessly and remotely, allowing real-time monitoring and control of the HPDS device from any location.

3.3. HPDS Web Server

As another key part of the HPDS, handling data processing and updating the application in real-time. Utilizing the system's algorithm, the web server receives sensor data and calculates the current location of the device to display the location of hazardous particles. This processing is performed on the web server rather than the application, as the high volume of data from the microcontroller would significantly slow down the application, impairing its functionality. By centralizing data processing on the web server, the system ensures fast, efficient calculations while presenting the results through the application. Furthermore, all data transmitted from the microcontroller is stored on the web server, allowing administrators to monitor the system for quality assurance and maintenance purposes. To assist in system management, a notification feature has been implemented, enabling the web server to send alerts regarding key information, such as device status and functionality.

3.4. Air Quality at Normal Times

The HPDS requires accurate assessment of ambient air quality, which necessitates the use of standardized reference values. To this end, air quality benchmarks established by the Ministry of Environment, Korea (2018) were adopted that is described in Table 7 below. These benchmarks classify air quality into three categories: good, moderate, and poor. This classification allows the HPDS to assess the presence of potentially harmful airborne contaminants in real-time. Furthermore, the system utilizes these standards to provide timely alerts to users when significant changes in air quality are detected, thereby enhancing situational awareness and enabling prompt responses to environmental hazards.

Table 7. Standards for air quality.

Conditions	Type of pollutants	
	CO ($\mu g/m^3$)	VOC ($\mu g/m^3$)
Good	≤10	≤400
Moderate	10<α*≤25	400<α*≤500
Poor	>25	>500
*α = measured value		

3.5. Application

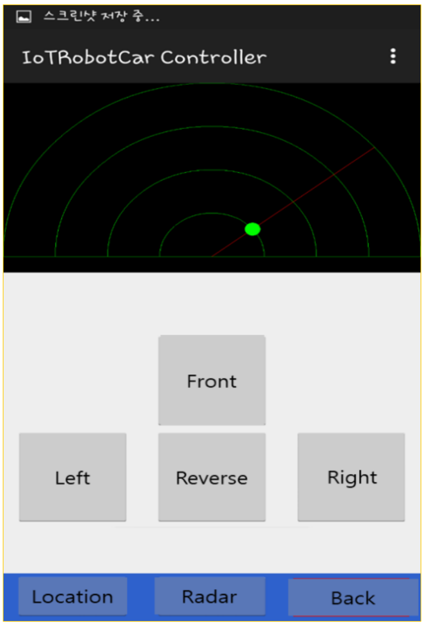

Figure 6. User interface for manual control and radar operation in HPDS mobile application.

The HPDS system includes a dedicated smartphone application, developed to provide real-time monitoring and control capabilities. The application allows users to view data collected by the HPDS, including air quality levels and the location of hazardous particles, on an interactive map. This enables users to track the system's performance and respond to environmental threats in a timely manner. Additionally, the application has been designed to support system administrators by enabling manual control of specific devices when necessary as shown in Figure 6. Through the application, administrators can remotely operate the device, including activating the radar to survey the surrounding environment, ensuring comprehensive situational awareness. This integration of manual control further enhances the system's flexibility, allowing for more targeted responses to potential hazards.

4. Experimental Testing

Following the reliability testing outlined in the previous section, a functional testing experiment was conducted to evaluate the system's effectiveness and accuracy. The objective of this test was to verify the operational performance of the HPDS and ensure the system functioned as intended. The testing was carried out in an apartment complex in Seocho, where a designated monitoring area was established using black tape to define a small region. This setup allowed the HPDS device to continuously monitor the marked area for hazardous particles. The HPDS device, sensors, a web server, and a mobile application, was tested under real-world conditions to ensure seamless data collection, processing, and transmission, confirming the overall functionality and reliability of the system.

4.1. Cloud Computing-Based Web Server

The HPDS is designed to send an alert to the web server whenever VOC or CO levels detected in the vicinity exceed the threshold values specified in Table 7. Simultaneously, the system logs these changes on the web server, allowing users to monitor air quality fluctuations in real-time. The changes are presented both as notifications and through a data log, with VOC and CO levels color-coded according to the corresponding thresholds, providing a clear visual indication of air quality status as shown in Figure 7. The logged data can be reviewed later to analyze previous instances of air quality changes, offering a comprehensive historical record for monitoring environmental conditions.

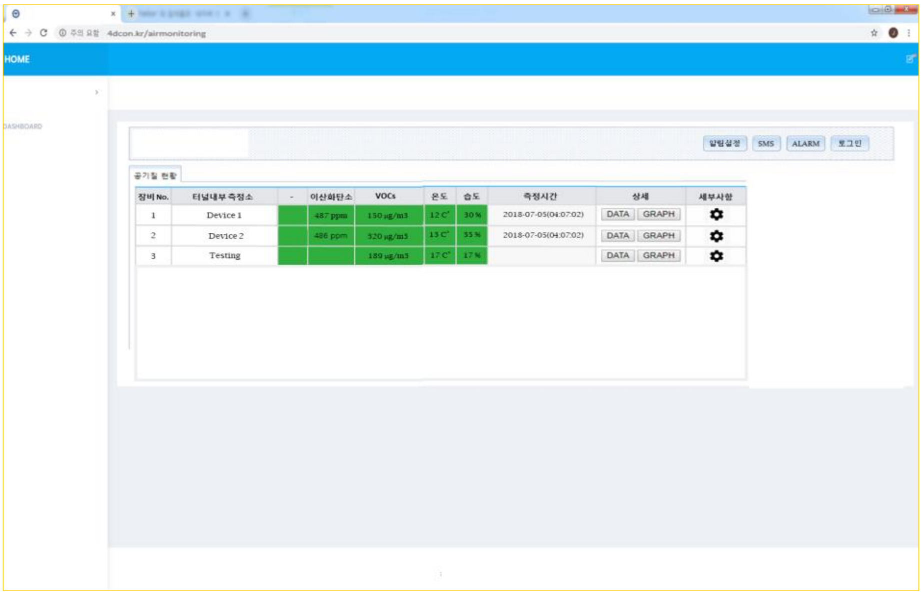

Figure 7. User interface for the web server.

4.2. Application

The application was tested to evaluate its effectiveness and accuracy in delivering timely notifications. This testing involved verifying that notifications were correctly transmitted to users. A comparison was made between the web server and the application to ensure that when the web server detected a change in air quality, the application received the notification under the following conditions: 1) the message was delivered within a time interval of less than 10 seconds, and 2) the notification contained accurate details, including the specific particles detected and the location. Additionally, the application was designed to visually display environmental conditions based on VOC and CO levels, with color-coded indicators corresponding to the thresholds outlined in Table 7. This color-coding allows users to quickly assess the air quality and the level of potential hazard in real-time as described in Figure 8.

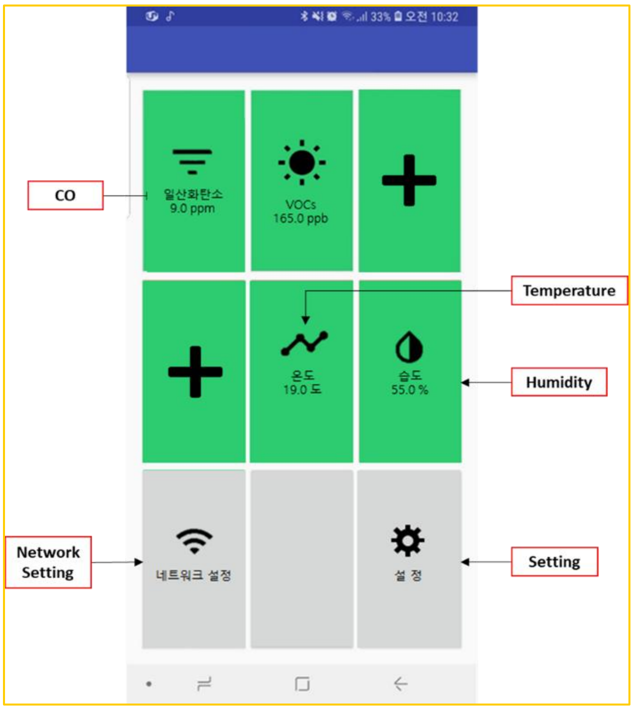

Figure 8. User interface for monitoring particles in HPDS mobile application.

5. Results

The effectiveness of the HPDS was evaluated based on its ability to monitor air quality and track hazardous particles within specific regions. The system successfully transmitted data wirelessly to the web server, as evidenced by the real-time graphing of live air quality data during its movement around the apartment complex. Additionally, the data collected by the HPDS was accurately logged into a database on the web server. The system displayed dynamic changes in air quality, updating in real-time to reflect the current environmental status. The integrity of the logged data was confirmed by processing it to identify and exclude any outliers, such as sudden spikes or drops, ensuring that the system provided reliable information.

Furthermore, the experimental results demonstrated that the application successfully sent alerts to users when air quality exceeded the threshold values outlined in Table 7. Notifications were triggered as soon as the system detected VOC or CO levels surpassing the established limits. The accuracy of these alerts was verified by confirming that the air quality levels met or exceeded the threshold, and that notifications were sent through the web server and accurately displayed on the application. The successful coordination between the web server and the application allowed administrators to efficiently monitor air quality in the apartment complex and detect potential hazards from waste balloons.

Overall, the experiments validated that the HPDS is an effective system for detecting hazardous air quality levels and identifying foreign objects that release harmful particles into the atmosphere. The system also effectively transmitted alerts to users and administrators when air quality exceeded normal levels, with the application accurately displaying data and notifying users of any significant environmental changes.

6. Conclusion

This paper presented the development of an IoT-based hazardous particle detection system (HPDS) designed to measure real-time air quality and provide data accessibility "anywhere, anytime." The system's components, including the physical sensors, web server, and mobile application, were detailed to enable reproducibility for further research or system enhancement. Experimental testing was conducted to validate the system's accuracy and effectiveness in monitoring air quality and ensuring the reliability of its notification system. The results confirmed several key findings: (1) the HPDS can effectively monitor air quality in real time within a specific region; (2) the system can accurately alert users and administrators in the event of significant changes in air quality; and (3) the system provides reliable data, ensuring optimal performance and ease of debugging if needed.

Future research is needed to refine the HPDS, particularly in distinguishing between foreign particles and broader environmental factors such as yellow dust storms or other atmospheric changes. One potential approach is the integration of artificial intelligence (AI) to differentiate between environmental changes and the presence of hazardous foreign objects. Additionally, further system scaling could be achieved by incorporating sensors with greater range, allowing for the monitoring of larger areas and the detection of waste balloons or air quality changes over extended distances.

Declarations

Acknowledgments: The author wishes to thank the Seoul Innovation Research Institute.

Author Contribution: The author confirms sole responsibility for the following: study conception and design, data collection, analysis and interpretation of results, and manuscript preparation.

Conflict of Interest: The author declares no conflict of interest.

Consent to Publish: The author agrees to publish the paper in International Journal of Recent Innovations in Academic Research.

Data Availability Statement: The data presented in this study are available upon request from the author.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Research Content: The research content of manuscript is original and has not been published elsewhere.

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Citation: Steve Rho. 2024. Development of an IoT-Based Hazardous Particle Detection System for Real-Time Air Quality Monitoring. International Journal of Recent Innovations in Academic Research, 8(10): 1-11.