Real-time Vertical Air Quality Monitoring System Development for Urban Scale

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Abstract

Developing air pollution monitoring systems utilizing Unmanned Aerial Vehicles (UAVs) and a real-time platform is a significant advancement in environmental monitoring. The paper described a system incorporating multiple sensors, including particulate matter, temperature and humidity sensors, and a barometric pressure sensor to assess air quality parameters using UAVs at different altitudes. The system monitors air quality parameters from 0 to 120 meters at various altitudes. This vertical profiling capability provides a more detailed understanding of air quality variations in the vertical dimension, which is crucial for identifying pollution sources and patterns. The system leverages the Internet of Things (IoT) platform for real-time data collection, transmission, and analysis. The study suggests that the developed system could serve as an alternative for particulate matter monitoring at an urban scale. Combining UAVs, air quality sensors, and IoT technologies offers a comprehensive and dynamic approach to air quality monitoring in urban environments.

Keywords: Air Quality Integrated System, Air Quality Sensor, Meteorological, Particulate Matter, Vertical Profile, Unmanned Aerial Vehicle

1. Introduction

Industrialization, transportation, and commercialize-tion contribute to poorer air quality in metropolitan regions than in less developed places [1]. According to [2], high levels of particulate matter in the form of PM_{10} and $PM_{2.5}$ are worsening air quality and posing serious health risks such as lung cancer and cardiovascular disease [3]. Many studies on PM dispersal and its impact on public health have skyrocketed during the last few decades, especially for people living in urban areas [4][5] and [6]. Malaysia had around 5.5 million individuals living in strata buildings as of June 2014 [7]. There is severe competition for land and space since demand for dwellings has increased by 14.2%. In response, Malaysian developers choose to build vertically rather than grow horizontally [8]. [9] discovered that vertical living will be negatively impacted because outdoor air pollution can significantly influence building pollutant concentrations. [10] revealed that the mean mass concentrations of $PM_{2.5}$ (26.8 $\mu g/m^3$) and PM_{10} (44.8 $\mu g/m^3$) in the Klang Valley between 2018 and 2020 exceeded the intermediate limitations set by the Malaysian ambient air quality standard 2020 (MAAQS).

Previous studies revealed that the ground measuring station is designed for air quality measures on PM, frequently placed on surface ground permanent stations [11] and [12]. It places fixed-site PM monitoring stations 7 to 10 meters above the ground.

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Despite highly accurate results achieved by densely deployed static sensors, this method still needs to improve with high costs and immobility for assessing air quality across neighborhoods and urban areas [11] and [12]. In Malaysia, the permanent stations are widely distributed due to the expensive cost of precise sensors [13]. A previous study suggested that monitoring $PM_{2.5}$ at ground level (1 to 3 meters) is insufficient in small-scale stratified areas more than a kilometer away from the sampling point [13][14] and [15]. While meteorological towers offer reliability and ease of maintenance, their effectiveness is constrained by their limited height, typically several hundred meters, and lack of flexibility in terms of location and data collection range [16][17] and [18]. Satellite-based remote sensing such as Multi-angle Imaging SpectroRadiometer (MISR), Moderate Resolution Imaging Spectroradiometer (MODIS) and Measurements of Pollution in The Troposphere (MOPITT) are highly efficient in capturing temporal and spatial changes in tropospheric air pollution across different scales. Still, its accuracy is hindered by the limited validation of data caused by factors such as cloud cover, relative humidity, and vertical distribution [16][19][20] and [21]. Light Detection and Ranging (LiDAR) and manned aerial vehicles are capable of measuring air pollutant concentration vertically but they have been proven to be high-cost alternatives [16][22] and [23]. The rapid advances in UAVs in the field of air quality measurements. Multi-rotor UAVs equipped with sensors and electronics have already been utilized by researchers to analyze atmospheric pollutants and to capture spatio-temporal variability [24] and [25]. The UAV system offers technical support for air pollution monitoring with good flexibility, convenient operation, and reliable data monitoring [17][24] and [26].

The atmospheric boundary layer (ABL) significantly influences the upward motion, dispersion, diffusion, accumulation, and deposition [17] and [18]. Research by [27] delves into the vertical patterns of $PM_{2.5}$ and black carbon (BC) in Macau, China, ranging from ground level to 500 meters above ground level (AGL). The research revealed a decreasing pattern in $PM_{2.5}$ concentrations with increasing height, marked by a vertical reduction of 0.2 μg/m^3 per 10 meters. Furthermore, the concentration was lower above the boundary layer than within it, often resulting in a sigmoid-shaped vertical profile. The presence of the vertical mixing layer notably affects the vertical distribution of PM concentrations through air advection and convection, driven by the vertical movement caused by cooler air overlying warmer air, particularly under solid instability [27] and [28]. The thermodynamics of the ABL strongly constrains the vertical distributions of PM and their evolution during the day [29] and [30]. Previous research has shown that, except in circumstances involving the thermal inversion layer, $PM_{2.5}$ concentrations tend to decrease with increasing altitude [16][27] and [31]. As a result, measuring ambient particles at many heights can shed light on their origins and active transit [24] and [32]. This study aims to develop an Air Quality Monitoring Integrated System capable of vertical real-time monitoring and data visualization on a small scale. The systems comprise of numerous components, including air quality sensors, unmanned aerial vehicles (UAVs), and IoT technologies for assessing $PM_{2.5}$/PM_{10} concentrations and meteorological parameters (temperature and humidity).

2. Material and Methodology

2.1 Study Sites

There are two study sites within the area of Universiti Teknologi MARA (UiTM) Shah Alam, Selangor, Malaysia, located at the main entrance of Section 2 (N 3°04′14″ E 101°30′14″) and the main entrance of Section 7 (N 3°04′35″ E 101°29′29″), as depicted in Figure 1. Study site 1 is surrounded by house developments and residential areas, while commercial and residential areas, industrial zones, and major highways surround Study Site 2. These areas are also undergoing developments related to the Light Rail Transit (LRT3) Station.

2.2 Air Quality System Development

The integrated air quality monitoring system comprises three main components: the air quality sensor, the UAV platform, and the IoT platform. As shown in Figure 2, each of these components plays a crucial role in the overall functionality and success of the monitoring system.

2.2.1 Air quality sensor

The air quality sensors consist of dust sensor HPMA115S0, designed for $PM_{2.5}$ detection with up to 15% accuracy [33]. The sensor can detect and count particles, offering a high sampling rate of up to 10,000 samples per second for real-time data. The sensor operates with a power supply voltage of 5 V, and the standard extreme current is approximately 120 milliamperes (mA). The integrated UAV platform sensors, including associated loads, weigh approximately 2.3 kg. Table 1 provides an overview of the air quality sensor specifications, detailing its dimensions, weight, battery life and capacity. The schematic diagram of air quality sensors for PM and meteorological data measurements is illustrated in Figure 3.

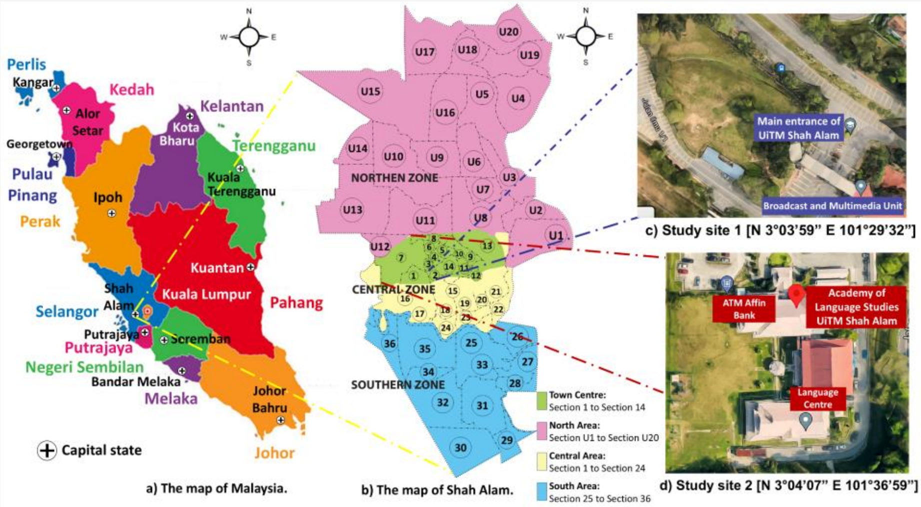

Figure 1: Study area:
(a) Malaysia (b) Shah Alam (c) Site 1 in section 2 of Shah Alam (d) Site 2 in section 7 of Shah Alam

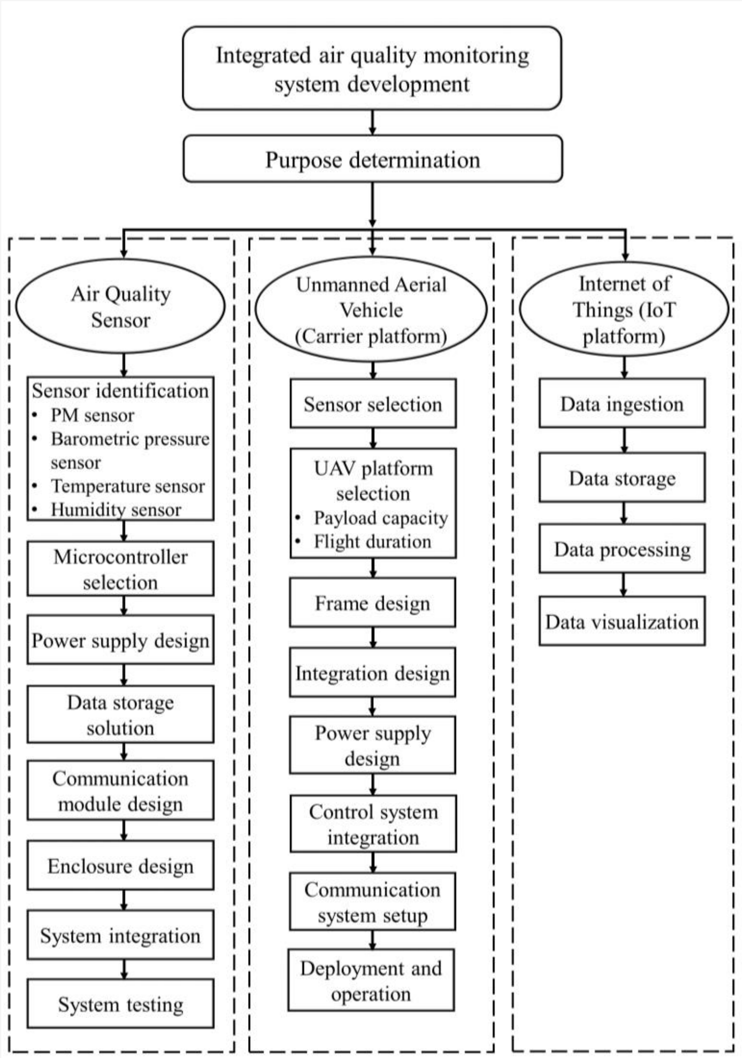

Figure 2: The conceptual framework of the three primary components of the air quality monitoring system

Table 1: The air quality sensor specifications

Specifications	Descriptions
Dimension	154.5 mm (L) x 115.0 mm (H) x 77.6 mm (W)
Weight	0.396 kg
Battery life	30 minutes
Battery capacity	3000 mAh
Battery voltage	3.7 V
Occupied with	Arduino UNO R3 board Particulate Sensor Module Honeywell, HPMA115S0 Atmospheric pressure sensor of Bosch Sensortec, BPM180 Temperature and Humidity Sensor Sensirion, ATH20 GPRS Module model, SIM800L Real-Time Module, RTC DS323 SD card slot
Sensor interval measurements	SD card: 1 second Real-time data (observed via Favoriot platform): 10 seconds

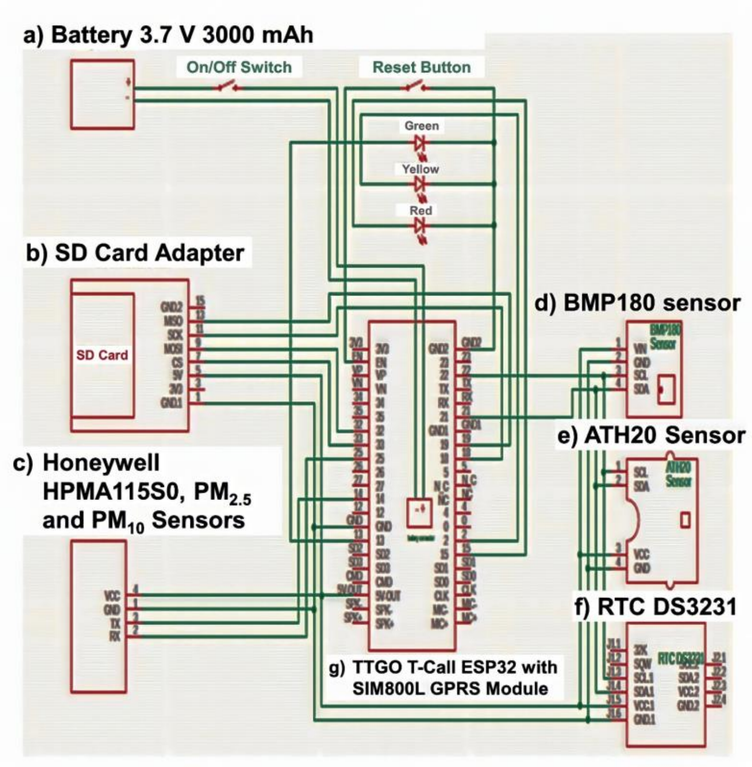

Figure 3: The schematic diagram of the developed air quality sensor

2.2.2 The quadrotor system of UAV

The quadcopter, developed as the carrier platform for the air quality sensors, includes a Pixhawk flight controller, a Ublox NEO M8N GPS module with a built-in compass, a Multistar 63 KV motor, and a Frsky D8R receiver paired with a HORUS x10s remote control transmitter. Table 2 provides a concise overview of the UAV's capabilities, dimensions, and compatible accessories, aiding in understanding its operational parameters and potential applications. Table 3 summarizes the details of a flying activity managed by Mission Planner software. Table 4 outlines the details of the conducted field experiment, including the data collection time, flight operation procedure, and speed rate of flight.

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Table 2: The quadrotor specification

Criteria	**Descriptions**
Total weight	1.8 kg
Maximum payload capacity	Rectangular box with a weight of 500 g
Frame size	650 mm
Battery capacity	4500 mAh at 35°C (LiPo battery)
Works with	a) Antenna b) FrSky 10XS remote controller c) Ground control station (Mission Planner software)

Table 3: The technical description of the aerial survey

Criteria	**Descriptions**
Set up and run by	Mission Planner software
Maximum flying estimation	15 to 20 minutes
A fly consists of	From the ground upward and from above to the ground at the same path and rate
Time taken for a vertical fly	7 minutes
Altitude	120 meters
Speed rate	1 m/s
Individual involved	2 persons

Table 4: Details of the conducted field experiment

Details	**Explanation**
Data Collection Time	8.00 a.m. to 12.00 p.m.
Flight operation	from the ground upward and from above to the ground following the same path (twice at each study site)
Speed rate of flight	1 m/s
Height intervals	0 - 20 m, 21 - 40 m, 41 – 60 m, 61 – 80 m, 81 – 100 m, 101 – 120 m
Data Parameters	Height, $PM_{2.5}$ /PM_{10} concentrations, temperature and humidity
Data Validation	20 random points of ground-based data measurement based on a random sampling method (See Figure 4 for details).

It provides an estimated 15 to 20 minutes duration for the activity, which involves ascending from the ground and descending from above along the same path and rate. A specific vertical maneuver takes about 7 minutes to complete. The flight operates at an altitude of 120 meters with a speed rate of 1 meter per second. Two individuals are involved in conducting the activity, ensuring coordinated efforts throughout. Overall, the table offers a comprehensive overview of the setup, execution, and parameters of the flying activity.

2.4 Real-time Visualization Using the Internet of Things (IoT)

The Internet of Things (IoT) is a complex ecosystem with multiple components, requiring diverse skills to deliver a robust and profitable solution. In this study, Favoriot is employed as a networking platform designed for Internet of Things (IoT) and machine-to-machine (M2M) applications [34]. The data captured is accessed in the dashboard's data monitoring section and categorized into three parts: ATH20 (temperature and humidity), BPM180 (atmospheric pressure), and Honeywell HPMA115SO ($PM_{2.5}$ and PM_{10}). The data captured is accessed in the dashboard's data monitoring section and categorized into three parts: ATH20 (temperature and humidity), BPM180 (atmospheric pressure), and Honeywell HPMA115SO ($PM_{2.5}$ and PM_{10}).

2.5 Field Experiment and Data Collection

The study collected air quality data from two study sites using air quality sensors mounted on a quadcopter (UAV). The field experiment was conducted on June 2, 2022 (during the Southwest Monsoon) with the UAV flying at altitudes ranging from 0 to 120 meters, at intervals of 20 meters. The air quality data included concentrations of particulate matter ($PM_{2.5}$ /PM_{10}) and meteorological factors (humidity and temperature). Figure 4 shows the 20 randomly selected points within the area of each study site, and the coordinates of these points are determined using the Global Positioning System (GPS).

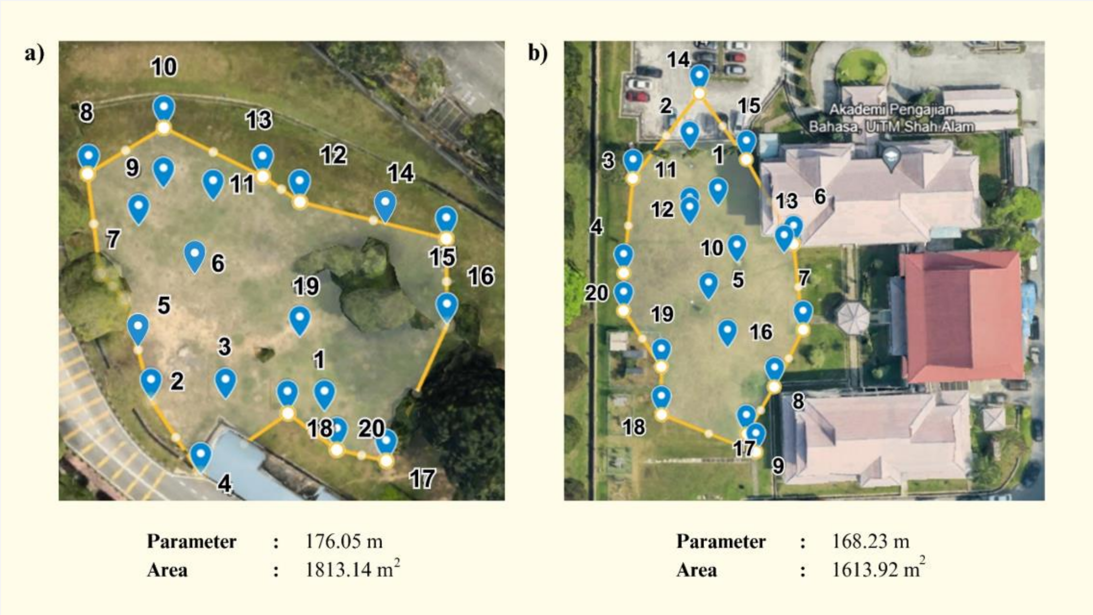

Figure 4: Locations of data collection points (a) study site 1 (b) study site 2

Figure 5: The handheld air quality detectors

The collected data includes PM concentrations and meteorological parameters (temperature and humidity) measured by Air Quality Detectors, as depicted in Figure 5. The air quality sensor readings obtained using the UAV platform are compared with the measurements (PM concentration, humidity, and temperature) from the Air Quality Detectors and the secondary data from the Department of Environment (DOE) on a similar day of data acquisition.

3. Experimental Setup and Results

3.1 System Design

Figure 6 displays the portable sensor with a dust sensor, atmospheric pressure sensor, temperature and humidity sensor, and an Arduino UNO R3 board. Arduino Software's integrated development environment (IDE) is employed to program the Arduino UNO board. The key benefits of the monitoring system include:

- Accessible components and a simple design
- Convenient, compact, and lightweight
- Affordable
- External battery charging
- Comprising built-in sensors
- Measurement of $PM_{2.5}$ and PM_{10}, humidity and temperature, along with time, date, altitude, absolute pressure, and pressure at sea level simultaneously
- Incorporation of additional sensors based on the intended purpose

Real-time data monitoring and visualization enabling prompt decision-making and response to air quality issues.

3.1.1 The quadrotor system of UAV

The quadrotor using the Pixhawk Cube development involves several steps, components, and technical considerations. Figure 7 illustrates the quadcopter used during this study as the carrier platform. As the UAV used is categorized under a small drone system, it can only legally be flown up to 121.93 meters, as mandated by the Civil Aviation Authority of Malaysia (CAAM) [35][36] and [37].

3.1.2 Real-time data visualization by the Internet of Things (IoT)

Integrating Internet of Things (IoT) technologies into the vertical air quality monitoring system signifies a significant advancement in environmental research and management. IoT integration provides real-time visualization capabilities, allowing us to analyze air quality patterns during UAV flights [38]. This feature enables on-the-spot assessments and enhances understanding of air quality dynamics [39]. Figure 8 is the dashboard showing the real-time collected data such as altitude, $PM_{2.5}$ and PM_{10} concentrations, humidity, and temperature.

3.2 UAV-based Air Quality Monitoring System Evaluation Results

3.2.1 Field test study site 1

Figure 9 shows the $PM_{2.5}$, PM_{10}, temperature, and humidity data measurements for study site 1, along the 120-meter track flown by the UAV. $PM_{2.5}$ concentration values range from 11 to 79 µg/m³, whereas PM_{10} falls within the ranges of 12 to 81 µg/m³. Meanwhile, temperature and humidity were with the ranges of 31.60 to 35.25°C and 53.38 to 70.87%.

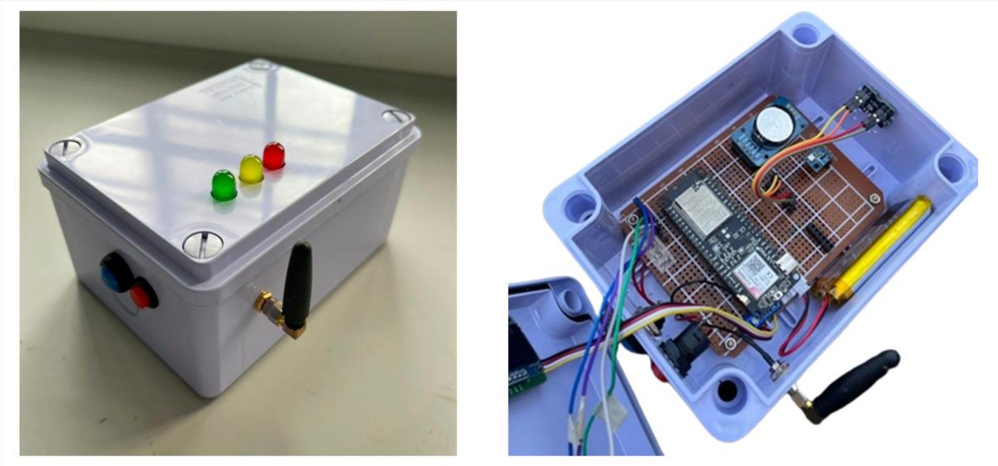

Figure 6: The dust sensors are equipped with temperature, humidity, and atmospheric pressure sensors.

Figure 7: Devices involved in the fly mission

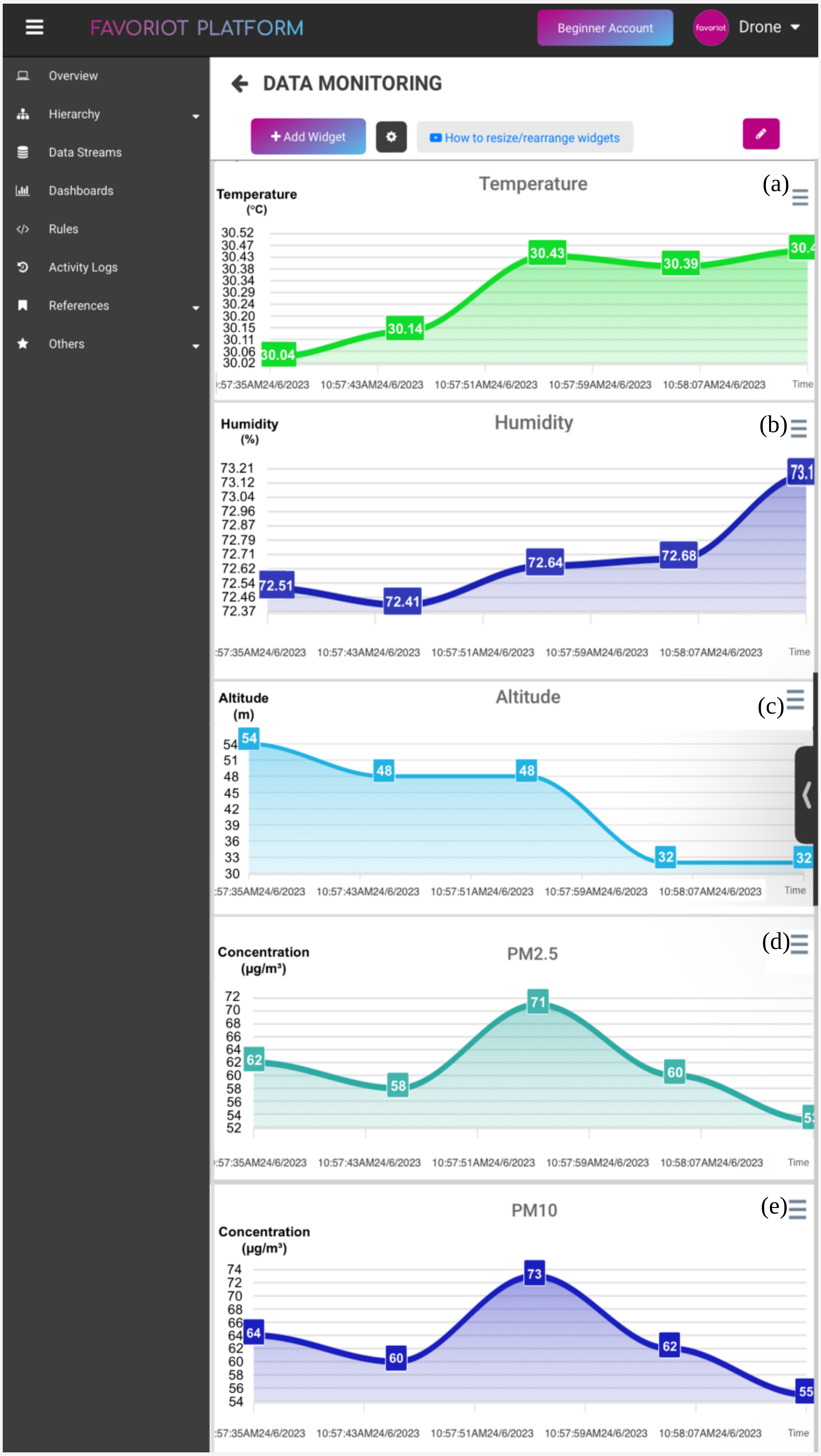

Figure 8: The User Interface (UI) and the dashboard of the IoT platform
(a) temperature (b) humidity (c) altitude (d) $PM_{2.5}$ concentration (e) PM_{10} concentration

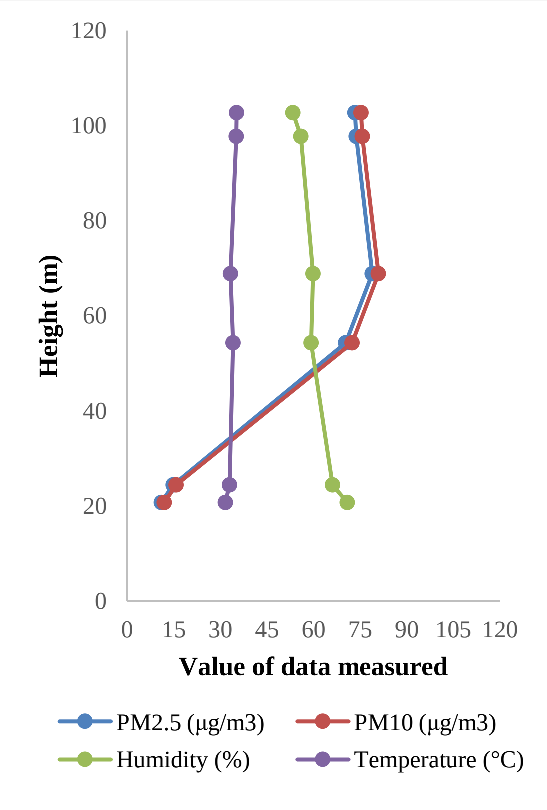

Figure 9: The measurement values at site 1

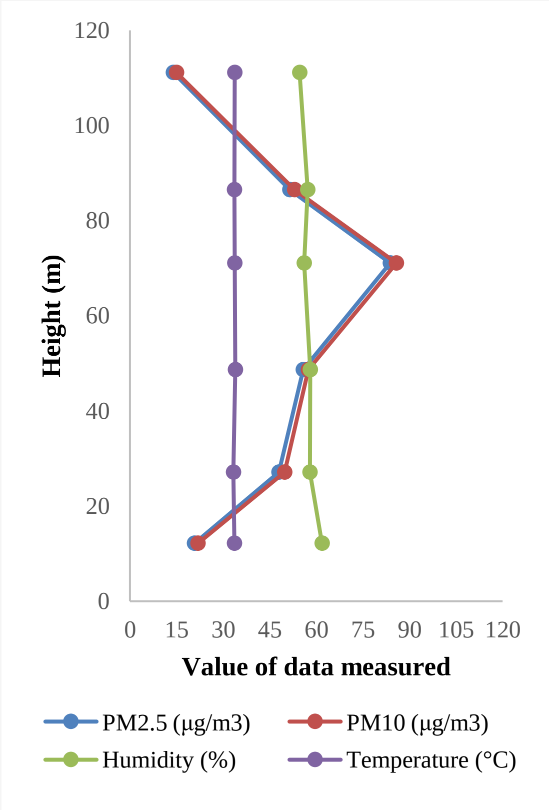

Figure 10: The measurement values at site 2

3.3.2 Field test study site 2

$PM_{2.5}$, PM_{10}, temperature, and humidity data measurements for study site 2, along the 120-meter track flown by the UAV, are as shown in Figure 10. $PM_{2.5}$ concentration values range from 14 to 84 µg/m³, whereas PM_{10} falls within the ranges of 15 to 86 µg/m³. Meanwhile, temperature and humidity were within the respective ranges of 33.29 to 33.92°C and 54.62 to 61.83%. Furthermore, the highest concentration of PM concentration in study site 2 was recorded at 61 to 80 m ($PM_{2.5}$: 61 µg/m³, PM_{10}: 63 µg/m³,). Overall, the highest $PM_{2.5}$ and PM_{10} concentration from both study sites were analysed within the area of study site 2 at 61 to 80 m which are 61 µg/m³, and 63 µg/m³, respectively.

4. Discussion

Vertical air quality monitoring using drones and IOT integrated offers several key advantages and is becoming increasingly important in environmental monitoring and research. With IoT integration, the system can provide real-time data visualization of air quality parameters and can store data both via the cloud and offline through an SD card.

The modular design allows the system to accommodate various sensors simultaneously and integrate real-time data from all onboard sensors. This continuous monitoring can capture short-term fluctuations in air quality and provide detailed insights into pollution patterns over time. The system is equipped with not only air quality sensors (Honeywell HPMA115SO), but also temperature and humidity (ATH20), as well as atmospheric pressure (BPM180) sensors, to measure multiple air quality parameters simultaneously. This multi-sensor approach enhances the quality and depth of data collected, leading to a more comprehensive understanding of air quality dynamics.

Previous studies revealed that the development of air quality sensors may have limitations regarding accuracy, calibration requirements, and potential interferences from environmental and external factors. Integrating and calibrating PM sensors on UAVs can be challenging as it is subject to vibration, pressure fluctuations, and environmental conditions such as temperature and humidity variations [17] and [40], which can affect sensor performance.

Besides, a calibration test of the air-quality monitoring station on a national level was conducted. This was done to ensure that the monitoring system is accurate and reliable in real-world settings [17]. According to [41], two approaches can be adopted to improve the measurement confidence and data quality of Low-Cost Sensors (LCSs) which are comparison (by measuring the data from the sensor with the nearby data to evaluate whether the sensors are measuring sensible values and changes) and field co-location (by comparing the measurements data with those of another sensor that is known to be accurate, usually located close to the first sensor to evaluate the performance of sensor).

Nonetheless, the benefits of low-cost sensors in air quality monitoring make them valuable in expanding our understanding of PM concentrations and promoting actions towards cleaner and healthier environments. Besides, the system requires a clear line of sight to receive GPRS signals and maintain stable flight, which tall buildings, trees, and other obstacles can impact. Therefore, an alternative to providing another offline data storage, such as the SD card is needed. In addition, integrating IoT technologies into vertical air quality monitoring offers a transformative approach to environmental monitoring. Critical evaluation of real-time visualization and validation methods is crucial to maximize the system's effectiveness in informing evidence-based decision-making for urban environmental management. Upgrading to a bigger energy capacity battery would allow the UAV to collect data for longer periods of time during flights [42], which are currently restricted by battery life. This update would allow for more extensive monitoring of air quality parameters by extending flight length, making it easier to collect and analyse comprehensive data.

5. Conclusion

In conclusion, this scientific paper presents the development of a vertical air pollution monitoring system with integration of Unmanned Aerial Vehicles (UAVs), air quality sensors, and IOT real-time visualization. Overall, the development of the integrated vertical air pollution monitoring system provides significant advancement in the field of air quality monitoring. As technology continues to evolve, vertical profiling is expected to play an increasingly pivotal role in our efforts to combat air pollution comprehensively. It contributes to the continuous improvement of monitoring technologies and lays the foundation for effective pollution control strategies and sustainable urban development.

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