Development of Vertical Profiling of Air Pollution Monitoring System

Sayidah Musfirah Kamarul Shukri, Arnis Asmat,
Mohd Hezri Fazalul Rahiman,
Ahmad Zia Ul-Saufie Mohamad Japeri and Zulhilmy Sahwee

August 21, 2023

Development of Vertical Profiling of Air Pollution Monitoring System

Sayidah Musfirah Kamarul Shukri[1], Arnis Asmat[1], Mohd Hezri Fazalul Rahiman[2], Ahmad Zia Ul-Saufie Mohamad Japeri[3] and Zulhilmy Sahwee[4]

[1] School of Chemistry & Environment, Faculty of Applied Sciences, Universiti Teknologi MARA Shah Alam, Selangor, Malaysia

[2] Electrical & Electronic Studies, College of Engineering, Universiti Teknologi MARA Shah Alam, Selangor, Malaysia

[3]College of Computing Informatics and Media, Universiti Teknologi MARA Shah Alam, Selangor, Malaysia

[4]Malaysian Institute of Aviation Technology, Selangor, Malaysia

[1] E-mail address musfirahqs98@gmail.com ; [2] E-mail address hezrif@uitm.edu.my ; [3] E-mail address ahmadzia101@uitm.edu.my ; [4] E-mail address zulhilmy@unikl.edu.my

Abstract

This paper presents the development of a vertical profiling air pollution monitoring system utilizing Unmanned Aerial Vehicles (UAVs), air quality sensors and a real-time monitoring system. The air quality sensor incorporates the Arduino UNO R3 board programmed by Arduino Mega, along with other essential components. These include the HPMA115S0 particulate matter sensor, ATH20 temperature and humidity sensor, BPM180 barometric pressure sensor, GPRS Module model SIM800L for data transmission, RTC DS3231 for timekeeping and synchronization, and an SD card slot for data retention. The integration of these technologies enables comprehensive and dynamic assessments of dust (PM2.5 and PM10) concentrations and meteorological parameters (humidity and temperature) at different altitudes (0-120 m). This study leverages the use of two handheld air quality detectors, the data from the Department of Environment, and the nearby stationary sensor of AiRBOX Sense within the area of UiTM for data comparison and field co-location. The obtained results demonstrate promising potential, as a comparison between the collected data and the reliable data from the three sources revealed a fair similarity. Holistically, the system empowers accurate data collection, analysis, and management, contributing to improved understanding and mitigation of air pollution.

Keywords: Air monitoring, air quality, air pollution, vertical profile, quadcopter, particulate matter.

1. INTRODUCTION

The urbanization process such as industrialization, conveyance and commercialization deteriorate the air quality of urban areas compared to the less developed area (Leh et al., 2020). Furthermore, cities with more complex shapes and higher population densities tend to have poorer air quality (Li & Zhou, 2019). According to Doreswamy et al. (2020), the high levels of particulate matter in the form of PM_{10} and $PM_{2.5}$ are exacerbating the air quality and leading to severe health implications such as lung cancer and cardiovascular disease (Fortelli et al., 2016). These are the consequences of contemporary industrialization comprised of liquid droplets, solid particles, and gas molecules, which are being dispersed into the atmosphere (Doreswamy et al., 2020). Therefore, the past decades have seen a dramatic increase amount of studies on PM distribution and its impact on public health, particularly for people living in urban areas (Anenberg et al., 2019; Molina et al., 2017; Ridzuan et al., 2022).

In Malaysia, Klang Valley is the most well-known urbanized region in Malaysia that covers the area of Selangor, Putrajaya and Kuala Lumpur (Wahap & Shafri, 2020). In 2021, it is known as the top area which contributed the highest percentage (41.5 per cent) to the economic growth of Malaysia (Department of Statistics Malaysia, 2022). This will lead to high population density in urban areas due to career factors (Department of Statistics Malaysia, 2021). This is not a good sign, as Chen et al. (2019) revealed that vertical living will be adversely affected, as the pollutant concentrations inside the buildings can be considerably influenced by outdoor air pollutants. This is because the buildings make use of outside air for their ventilation systems. Meanwhile, about 5.5 million people in Malaysia lived in strata developments as of June 2014 (New Straits Times, 2016). New Straits Times (2022) revealed that the competition for land and greater space has gotten fiercer as the number of people in need of homes has increased by 14.2 per cent. To counter this issue, Malaysian developers seek to build upwards rather than horizontally.

In order to monitor air quality, *sensor-based monitoring systems* often make use of sensor monitoring stations set up by public or commercial organisations in specific areas in a city (Liu et al., 2020). The study also revealed that, despite highly accurate results achieved by densely deployed static sensors, this method still has issues with high costs and immobility. Furthermore, the geographical resolution required to identify localised pollution hotspots and varied human exposures is not present in traditional fixed-site pollution monitoring techniques (Apte et al., 2017). Currently, the ground measuring station is designed for air quality measures on PM, which is frequently placed on surface ground permanent stations. It has been proved to not accurately represent exposure on a tiny scale. The sites are also very few, with uneven geographical intervals, resulting in less consistent air sample collection and assessment (Tian, 2008). The ground stations do provide a steady stream of high-quality data but short geographical coverage is required to generate an outstanding synoptic spatial pattern (Salahuddin & Ashaari, 2017). Furthermore, in case the stationary monitoring stations are a kilometre from the sampling point, sufficient sample data cannot be gathered reliably (Sevusu, 2015; Xiong et al., 2021). Besides, $PM_{2.5}$ monitoring at ground level (1 to 3 metres) also is insufficient in small-scale areas with strata (Jumaah et al., 2021).

Besides, the ground-based observations are inadequate for a total understanding of the transboundary transport of pollutants and the impact of atmospheric microcirculation (such as the urban heat island effect and sea-land breeze) on the distribution of pollutants in urban areas (Ding et al., 2009; Strawbridge & Snyder, 2004). Moreover, the atmospheric boundary layer (ABL) also has an impact on the particle's upward motion, dispersion, diffusion, accumulation, and deposition (Gautam & Patra, 2015; Tang et al., 2016). This is why, the measurements of ambient particles at multiple heights, rather than simply at a particular height, provide better details regarding their origins and active transport (Zhou et al., 2020). Therefore, in order to have a high ideal spatial and temporal resolution for data on air quality, three-dimensional measurements (vertical profiles and horizontal profiles above ground level) are necessary (Samad et al., 2022).

Hence, numerous countries have adopted various methods to aid in mitigating air quality and monitoring practices. This includes satellite remote sensing, balloon-borne instruments and tower-based measurements. 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 (Peng et al., 2015; Wang et al., 2019). In contrast to conventional observations made by meteorological towers, the UAV system offers technical support for air pollution monitoring with good flexibility, convenient operation, as well as reliable data monitoring (Wang et al., 2019). Besides, satellite-based remote sensing is highly efficient in capturing temporal and spatial changes in tropospheric air pollution across different scales, but its accuracy is compromised by the limited validation of data (Peng et al., 2015). Tethered balloons instruments offer the advantage of vertical air pollutant measurement, in reaching extreme height altitudes even up to the upper stratosphere, but their use is limited by insufficient sampling frequency and coarse resolution to resolve the detailed ABL structures and their evolutions (Lu et al., 2019). Previous methods such as piloted aircraft, Light Detection and Ranging (LiDAR) and manned aerial vehicles are capable of measuring the air pollutant concentration vertically but it is proven as high-cost alternatives (Axisa & DeFelice, 2016; Li et al., 2015; Peng et al., 2015).

The unmanned aerial vehicle (UAV) has gained popularity as a promising experimental platform for conducting high-resolution vertical and horizontal profiling of atmospheric pollution in near-surface areas due to its high manoeuvrability (Gu & Jia, 2019). UAVs also make it simple to incorporate adaptable and cutting-edge technologies. For instance, to connect with low-powered and inexpensive devices (such as smartphones) during the air contaminant sampling process, multiple sensors can be connected via Bluetooth wirelessly (Sevusu, 2015). Unmanned aircraft systems (UAS), also referred to as UAV, is an emerging technology that is expected to provide a workable substitute for current platforms for acquiring high-resolution remote sensing data with increased operational flexibility, practical option, reliable alternative, cost-effective, and a higher degree of versatility (Samad et al., 2022). By using UAV and remote sensing observations when conducting an in-situ measurement, dense resolved measurement of aerosol in the atmosphere perpendicular to the ground is possible to be acquired independently. This is a crucial factor in climate models (Mamali et al., 2018).

The past twenty years have seen increasingly rapid advances in UAVs in the field of air quality measurements. Multi-rotor UAVs equipped with sensors and electronics have already been utilised by researchers to analyse atmospheric pollutants (Samad et al., 2022). By using UAV equipped with $PM_{2.5}$ and meteorological sensors, Han et al. (2018) investigated the difference in pollutant dispersion vertically nearby the Ba River which focused on the area of urban water, green space and roads in China. By using the same platform, the vertical profiling of several pollutants had been recorded in multiple locations in the countryside of southern India (Gautam et al., 2021). Wang et al. (2019) found that the averaged relative errors for measuring $PM_{2.5}$ and PM_{10} dispersions were 6.2% and 6.6%, respectively, within the area of Hong Kong, China suggesting that the UAV system might be employed to monitor PM in an atmospheric setting.

Therefore, the study aims to develop an Air Quality Integrated System that uses unmanned aerial vehicles (UAVs) in order to measure the $PM_{2.5}$ and PM_{10} concentrations, as well as meteorological factors (temperature and humidity) vertically. The system will be designed to provide high-resolution data on the spatial and temporal distribution of air pollutants, which will enable policymakers and urban planners to develop effective strategies for reducing air pollution and protecting public health.

2. METHODOLOGY

2.1 Study Sites

The study was conducted within the area of Universiti Teknologi MARA (UiTM) Shah Alam, Selangor, Malaysia. The study sites are being divided into two which are 1) at the main entrance of Seksyen 2 (N 3°04’14” E 101°30’14”) and 2) at the main entrance of Seksyen 7 (N 3°04’35” E 101°29’29”) as shown in **Figure 5**. Study Site 1 is surrounded by house developments and residential areas. Meanwhile, Study Site 2 is known as the areas of commercial areas, residential areas, the development of the Light Rail Transit (LRT3) Station, industrialization, and major highway.

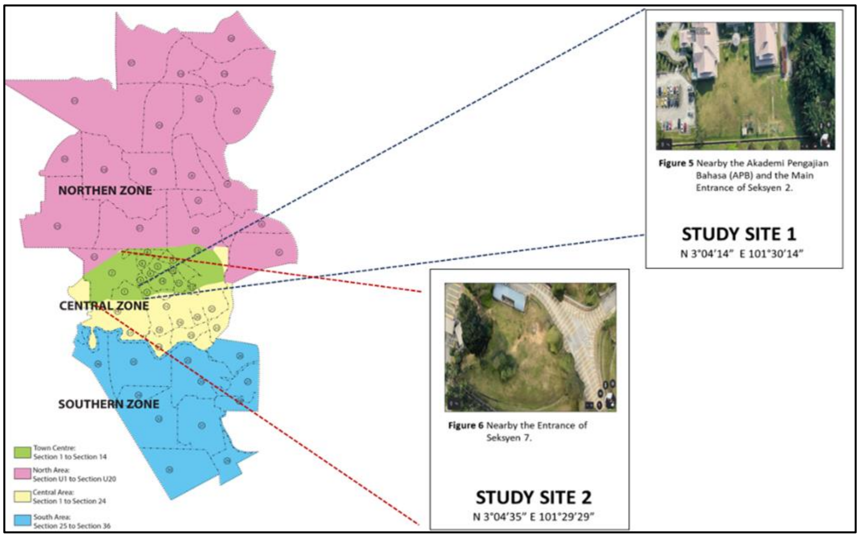

Figure 1: The study sites focus on the area of Seksyen 2 and Seksyen 7 of Shah Alam.

2.2 Vertical Air Pollution Profiling System Development

2.2.1 Air Quality Sensors

This 0.396kg portable sensor comes with dimensions of 154.5mm x 115.0mm x 77.6mm *(as shown in **Figure 2**)*. It contains a) Arduino UNO R3 board, b) Particulate Sensor Module *Honeywell* HPMA115S0, c) atmospheric pressure sensor of *Bosch Sensort*ec BPM180, d) Temperature and Humidity Sensor *Sensirion* ATH20, e) GPRS Module model SIM800L, f) a Real-Time Module, RTC DS3231 and g) SD card slot for data retention. The Arduino Software's integrated development environment (IDE) is used to programme the Arduino Uno board. The device has a battery life of 30 minutes with 3.7v and 3000mAh. The data can be stored in real-time on an IOT Favoriot platform or an SD card inserted in the sensor. The sensor interval measurements are 1 second and 10 seconds for the SD card and IOT Favoriot platform *(as shown in **Figure 3**)* for real-time respectively.

During this study, the use of a dust sensor model has been proposed which is known as HPMA115S0. This is because this device is a highly sensitive and accurate sensor designed to detect and count particles with sizes ranging from 0.3 micrometres to 10 micrometres in the air, particularly those with a diameter of fewer than 2.5 micrometres ($PM_{2.5}$). This sensor has a high sampling rate of up to 10,000 samples per second and can provide real-time measurement data. The sensor's power intake is typical; the power supply voltage is 5V, and the normal extreme current is about 120 milliamperes (mA). Overall, the integrated UAV platform sensors including the associated loads are 2.3 kg approximately.

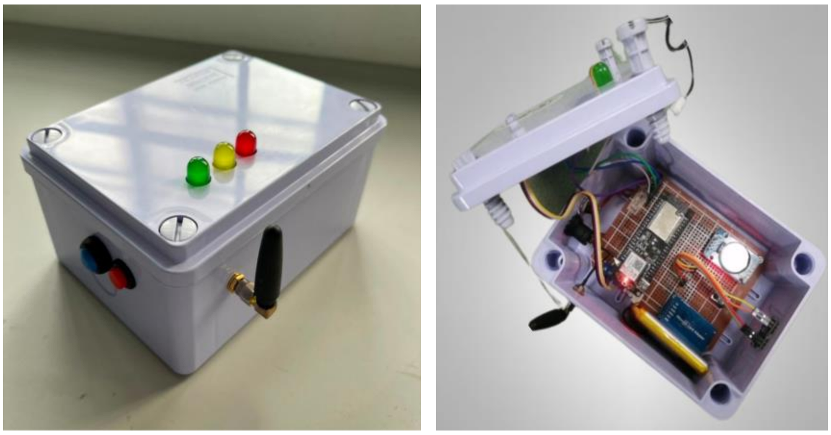

Figure 2: The ready-made dust sensors which are equipped with temperature and humidity as well as atmospheric pressure sensors.

2.2.2 The Quadrotor System of UAV

The development of a quadrotor using the Pixhawk Cube for environmental studies involves several steps, components, and technical considerations. The first stage of this research aims to develop a quadrotor system as unmanned aircraft vehicles (UAVs, or drones) for atmospheric data collection in a targeted area. The system consists of a Pixhawk flight controller, an Ublox NEO M8N GPS module with a built-in compass, a Multistar 63KV motor, a Frsky D8R receiver with a HORUS x10s remote control transmitter, a custom-made 650mm quadcopter frame, and a LiPo battery of 4000 mAh at 35°C. The system is set up and run by Mission Planner software. The sensor was designed to be attached to a rectangular box that weighs around 500 g and houses the environmental sensor and IoT system for monitoring atmospheric conditions. With a total weight of 1.8 kg, the drone is estimated to fly for around 15–20 minutes. However, for safety reasons, the drone was flown for approximately 7 minutes before landing to recharge the battery.

The drone is planned to be flown to an altitude of 120 metres in a vertical manoeuvre. **Figure 3** shows the quadcopter developed during this study as the carrier platform.

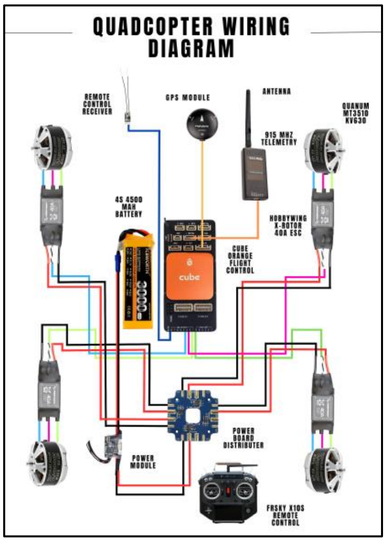

Figure 3: The quadcopter developed as the carrier platform of the portable sensors.

2.2.3 The Real-time Monitoring System

The Internet of Things (IoT) is a multi-component ecosystem that necessitates a variety of skills in order to provide a decent and lucrative solution. It needs to include several tools that enable users to operate and execute devices and data more reliably. Nevertheless, if it must be built from the ground up, the process will be lengthy and time-consuming.

Favoriot is a networking platform designed for Internet of Things (IoT) and Machine to Machine (M2M) applications (Favoriot, 2017). The data may be accessed in the dashboard's data monitoring section, which is categorized into three parts: ATH20 (temperature and humidity), BPM180 (atmospheric pressure), and Honeywell HPMA115SO (PM2.5 and PM10). Furthermore, all of this input is graphed for simple comprehension. A graph of the given height as well as the relative sea-level pressure is shown as well. These data may also be deleted and stored due to the SD cards and memory cards. The altitude, $PM_{2.5}$ & PM_{10} concentration, pressure, sea level pressure, humidity, and temperature are examples of data collected and stored by these IoT devices *as shown in **Figure 4***.

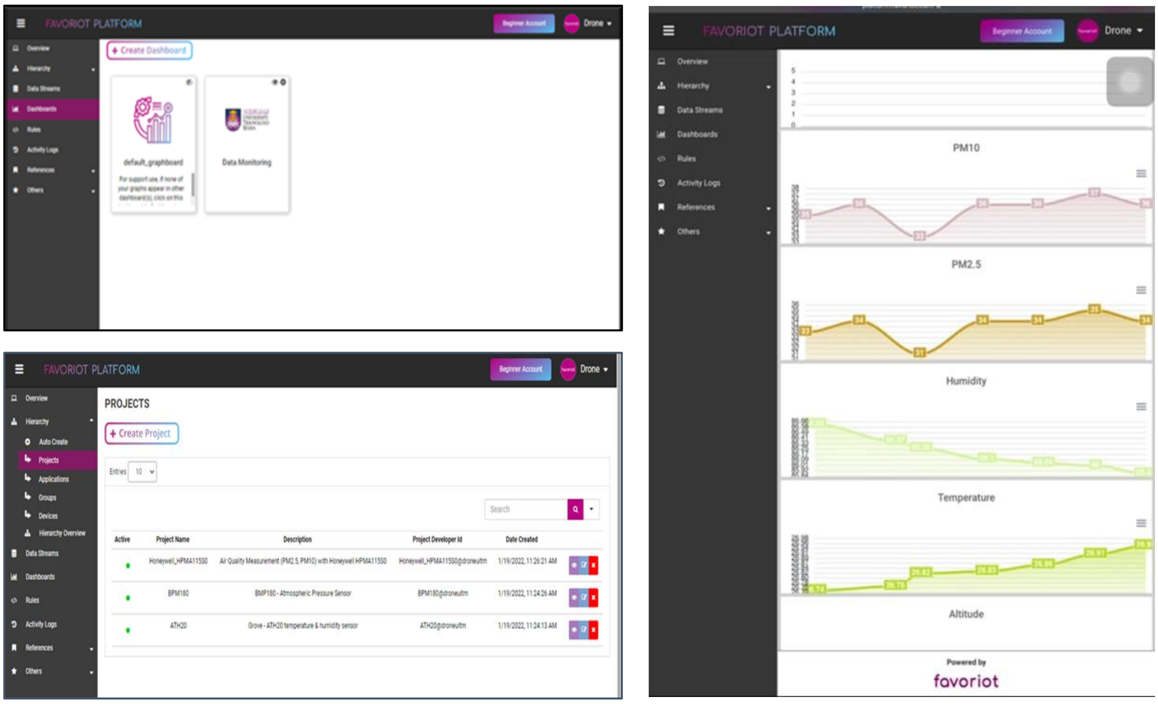

Figure 4: The User Interface (UI) and the dashboard of the IoT platform which includes the variables of the study: (a) $PM_{2.5}$ concentration (ug/m^3), (b) PM_{10} concentration (ug/m^3), (c) Altitude (m), (d) Humidity (%) and (e) Temperature (°C).

2.2.4 Schematic Diagram of Circuit

The schematic diagram for the UAV integrated system for PM and meteorological data monitoring is illustrated in **Figure 5**.

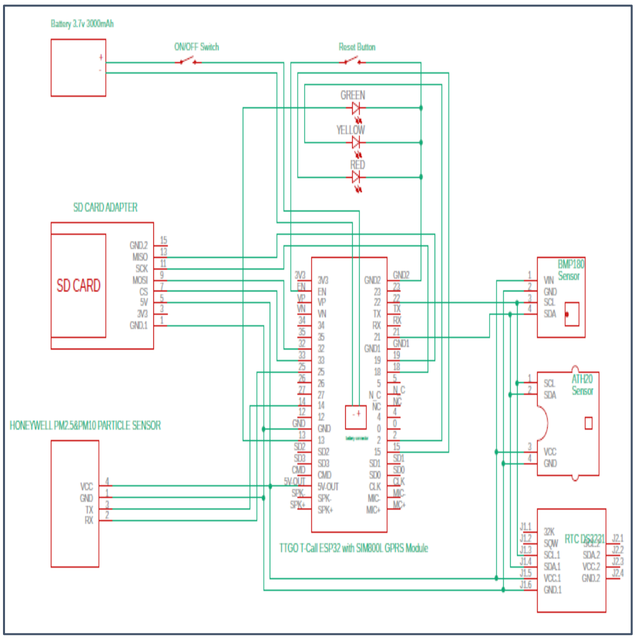

Figure 5: The UAV integrated monitoring system for PM and meteorological parameters.

2.2.5 Programming and Software

The Arduino board was interfaced with the Arduino IDE which features the Integrated Development Environment (IDE) and the core libraries. The lines of code were written in a programming language by its open-source platform (Ruslan, 2015). **Figure 6** depicts a part of the code uploaded to the Arduino Mega board via Arduino IDE 2.1.0 software.

Figure 6: A part of the code lines uploaded into the Arduino IDE 2.1.0 software.

2.3 Field Experiment

By using the sensor of a quadcopter (UAV), this study will acquire the air quality primary data directly from the two study sites proposed. The data acquisitions were carried out on 2 June 2022 (during Southwest Monsoon) and 24 December 2022 (Northeast Monsoon). The data acquisition will include the $PM_{2.5}$ and PM_{10} concentrations based on multiple altitudes (0-120 m; with an interval of 20 m), as well as the meteorological factors (humidity and temperature).

The data is collected during the morning time zone from 8.00 a.m. to 12.00 p.m. according to the previous studies (Gautam et al., 2021; Liu et al., 2018). According to Liu et al. (2020), the thermodynamics of the ABL strongly constrains the vertical distributions of PM and their evolution during the day. Meanwhile, the dependency on the ABL evolution at night is considerably less prevalent.

During the vertical data measurement *(as shown in **Figure 7**)*, the drone is flown at increasing heights (0, 20, 40, 60, 80, 100 m, 120 m) from the ground upward and from the above to the ground at the same path and rate (speed of 1 m/s) twice at each study site and each day. During the flight operation, the data that has been measured includes the PM concentrations and meteorological parameters (temperature and humidity) based on multiple altitudes as stated prior.

The reliability of the UAV monitoring system depends on the PM sensor that is integrated into it. While the sensor is initially calibrated in the laboratory, it can be influenced by real-world conditions. Hence it is important to calibrate the system in the field (Wang et al., 2019). According to Peltier et al. (2021), 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). Despite the cruciality to adhere the validation hierarchy to reach the calibration level, the researcher also revealed that it is typically impossible to reach that level.

Previous studies have conducted field calibration experiments. For instance, Jumaah et al. (2021) evaluated the result by comparing the reading measured with; i) the weather data for Malaysia obtained from NASA data using the RETScreen programme by Unit Golf Universiti Putra, including data on the country's climate history and ii) the local weather data from the state of Selangor. Besides, Wang et al. (2019) in another study, carried out a calibration test at the air-quality monitoring station on a national level. This was done to ensure that the monitoring system is accurate and reliable in real-world settings.

Therefore, the ground-based measurement is conducted prior to each flight. The measurement is conducted based on a random sampling method. 20 random points will be selected randomly within the area of each study site and the coordinates of the selected points are determined by using the Global Positioning System (GPS). The data collected includes the PM concentrations and meteorological parameters (temperature and humidity) by Air Quality Detectors *as shown in* ***Figure 8***. The device is selected as it possesses high efficiency and high responsive abilities (Jumaah et al., 2021). The PM sensor readings of the UAV platform are compared with the measurement readings (PM concentration, humidity and temperature) from the Air Quality Detectors. Besides, the data were also compared with the meteorological and pollutant data on a similar day of data acquisition, from the Department of Environment (DOE) and another stationary sensor of AiRBOX Sense within the area of UiTM.

Figure 7: The UAV was flown vertically from the ground upward and from above to the ground at the same path and rate.

Figure 8: The air quality detectors used during ground-based measurement.

3 RESULTS AND DISCUSSIONS

3.1 System Architecture

As depicted in **Figure 2**, the air quality sensor is integrated into three sensors which are PM sensors, humidity and temperature, as well as the atmospheric pressure temperature. Based on the field experiment, there are a few key benefits of this monitoring system that can be recognized. These include the:

- Accessible components and a straightforward design
- Convenient, compact, and light;
- Affordable compared to other devices
- Uses a battery that may be charged externally
- Comprise built-in sensors;
- Measurement of $PM_{2.5}$ and PM_{10}, humidity and temperature, along with the time, date, altitude, absolute pressure and pressure at sea level simultaneously.
- The system can be modified (by incorporating additional sensors and determining the board model) based on the intended purpose.
- Real-time monitoring and data visualization which enables timely decision-making and response to pollution events in real-time.

3.2 Data Acquisition Results

The integrated UAV was flown twice at each study site from ground to above and from above to the ground. **Table 3.1** shows the number of times the data was captured offline (SD card) and on the IoT platform (real-time). Based on the two seasons, SD Card and the real-time monitoring system are able to capture from 79 to 126 and 81 to 102 amounts of PM and meteorological parameters data for two flights, respectively. There was not so much difference in the number of times data was captured between the SD card and the real-time holistically. Based on the table, the IoT platform captured higher amounts of data during the dry season. Meanwhile, the SD card is able to capture higher amounts of data during the wet season compared to the IoT platform.

Table 3.1: The Number of Times Data Captured at Every Study Site Based on The Season.

Seasons	Study Site	Fly	Start	End	Number of Times Data Captured	
					SD Card	Real-time
Dry Season	Study Site 1 (Seksyen 2)	1st	10:02:07	10:19:59	79	81
		2nd	10:55:48	11:05:16		
	Study Site 2 (Seksyen 7)	1st	11:39:51	11:49:45	96	102
		2nd	12:20:51	12:43:02		
Wet Season	Study Site 1 (Seksyen 2)	1st	10:09:05	10:21:02	101	97
		2nd	10:49:05	10:59:19		
	Study Site 2 (Seksyen 7)	1st	8:16:05	8:30:29	126	86
		2nd	9:12:15	9:22:56		

Figure 9 illustrates a part of the values of data captured during the data acquisition in the Dry Season (Southwest Monsoon) in Study Site 1 and Study Site 2 by offline data and IoT platform. The data shown only focuses from 10:02:00 a.m. to 10:17:00 a.m. in Study Site 1. The data captured during the period by SD card and IoT platform were 22 and 14 respectively. Meanwhile, the data shown in Study Site 2 only focuses from 10:39:00 am to 10:46:00 a.m. The data captured during the period in Study Site 2 by SD card and IoT platform were 35 and 27 respectively. At both study sites, the offline data was captured in higher amounts compared to the real-time data at a specific time.

The SD card captured lower amounts of data holistically, during the dry season in Study Site 1. Furthermore, the data numbers captured offline at the specific time from 10:02:00 a.m. to 10:17:00 a.m. were the highest. However, the number of data captured in SD card was higher than real-time during wet season. Therefore, the total number of data captured is random and does not depend on the time. Certain periods may have varied amounts of data captured. Additional errors in this situation could result from vibrations, tilting of sensors during flight, changing pressure values with altitude, electronic drone operation interference, turbulence effect on sensor inlet airflow, and changing pressure values. Besides, the Global Packet for Radio Services (GPRS) can have an impact on the data captured by the air quality real-time monitoring systems particularly due to data transmission reliability, network coverage and signal strength, data latency, data loss and packet errors as well as bandwidth limitations. This is due to the high network traffic as the sensing node continuously sends data to the cloud every 10 seconds (Jabbar et al., 2022).

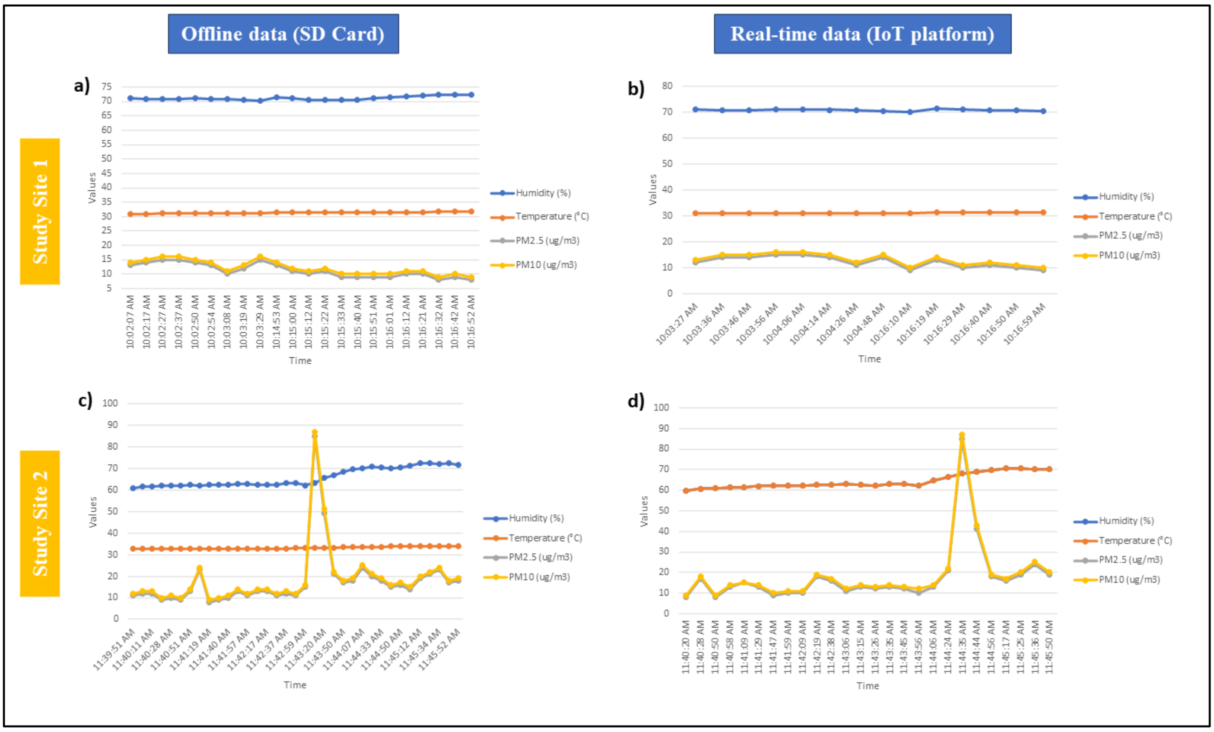

Figure 9: The Values of $PM_{2.5}$ concentrations (µg/m^3), PM_{10} concentrations (µg/m^3), humidity (%) and temperature (°C) data captured in; a) Study Site 1 by SD card, b) Study Site 1 by IoT platform, c) Study Site 2 by SD card and d) Study Site 2 by IoT platform.

Based on the result, during the dry season, the highest concentration of PM in Seksyen 2 was analysed at 41-60m ($PM_{2.5}$: 48 ug/m3, PM_{10}: 49 ug/m3). Furthermore, the highest concentration of PM concentration in Seksyen 7 was recorded at 61-80 m ($PM_{2.5}$: 61 ug/m3, PM_{10}: 63 ug/m3). Overall, the highest $PM_{2.5}$ and PM_{10} concentration from both study sites were analysed within the area of Seksyen 7 at 61-80m which are 61 ug/m^3 and 63 ug/m^3 respectively.

On the other hand, during the wet season, the highest concentration of PM in Seksyen 2 was analysed at 61-80m ($PM_{2.5}$: 36 ug/m3, PM_{10}: 38 ug/m3). Furthermore, the highest concentration of PM concentration in Seksyen 7 was recorded at 41-60 m ($PM_{2.5}$: 66 ug/m3, PM_{10}: 61 ug/m3). Holistically, the highest $PM_{2.5}$ and PM_{10} concentration from both study sites were analysed within the area of Seksyen 7 at 41-60m which are 66 ug/m^3 and 61 ug/m^3 respectively.

By utilizing the convenient, compact, and light air quality sensors device, the $PM_{2.5}$ and PM10 concentrations, as well as meteorological factors (temperature and humidity) had been measured vertically. This is because, this integrated UAV device is also equipped with the PM, temperature, humidity and atmospheric pressure sensors. Therefore, the system has proven to be a successful and efficient method to answer the objective of the study in order to measure the PM concentration in urban regions vertically. This system can be conveniently programmed using Arduino's IDE software, enabling easy manipulation of input and output. Additionally, this system incorporates an SD card and real-time monitoring system in order to measure and store the readings either offline or online.

The utilization and integration of the sensors makes air quality monitoring more accessible to individuals, communities, and organizations that may not have the financial resources to invest in expensive monitoring equipment. This increased accessibility empowers citizens to actively engage in monitoring their local air quality and raises awareness about pollution issues. The widespread use of low-cost sensors contributes to the generation of large datasets, which can support research and analysis of air quality trends and patterns over time. These datasets can also be utilized to raise public awareness, advocate for policy changes, and foster collaborations between researchers, policymakers, and the public.

While low-cost sensors have significant advantages, it is important to note that they 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, motion, and environmental conditions such as temperature and humidity variations, which can affect sensor performance. Hence, proper calibration, validation, and quality control measures are necessary to ensure the reliability and validity of the collected data. Nonetheless, the benefits of low-cost sensors in air quality monitoring make them a valuable tool in expanding our understanding of PM concentrations and promoting actions towards cleaner and healthier environments.

Besides, weather conditions, such as strong winds, rain, or fog, can affect UAV flights and the accuracy of PM measurements. Adverse weather conditions may limit UAV operations or introduce errors in the measurements, especially when sensors are exposed to precipitation or high winds that can disperse or alter the PM particles. It also has limited payload capacity, which restricts the type and number of sensors that can be carried on board. This limitation may prevent the simultaneous measurement of multiple PM fractions or the integration of advanced reference-grade instruments, resulting in a trade-off between sensor capabilities and payload constraints. It is observed that the system requires a clear line of sight to receive GPRS signals and maintain stable flight, which can be impacted by tall buildings, trees, and other obstacles. Therefore, the SD card is compulsory. As the UAV takes 7 minutes to fly off and fly back to the ground, the duration of data acquisition is also limited due to the limited battery life. Furthermore, operating UAVs for air quality monitoring involves compliance with aviation regulations and safety guidelines. UAV flights must adhere to airspace regulations, obtain necessary permissions, and ensure safety protocols are followed to avoid accidents or conflicts with other airspace users. Moreover, the use of UAVs for air quality monitoring can involve significant costs, including the acquisition, maintenance, and operation of the UAV platform and associated equipment. Training and expertise in UAV operations and data analysis are also necessary, adding to the operational complexity and resource requirements.

Nevertheless, the sensor measurements showed strong agreement with the measurements obtained from the Air Quality Detectors at the corresponding locations. Furthermore, the integrated system utilizing UAVs enabled fast, accurate, and consistent assessment of extensive areas at various altitudes above the ground. The accurate measurements obtained are able to tell the PM concentrations, humidity and temperature based on multiple heights by using the system developed.

CONCLUSION

In conclusion, this scientific paper presents the development of a vertical profiling air pollution monitoring system using a combination of Unmanned Aerial Vehicles (UAVs), air quality sensors, and a real-time monitoring system. Traditional ground-based monitoring stations have limitations in terms of cost, mobility, geographical coverage, and capturing the full complexity of air pollution dynamics. The integration of these technologies offers a novel approach to air quality monitoring, allowing for comprehensive and dynamic assessments of pollutant concentrations at various altitudes in urban areas. Overall, the development of the vertical profiling air pollution monitoring system using UAVs, air quality sensors, and real-time monitoring represents a significant advancement in the field of air quality monitoring. It contributes to the continuous improvement of monitoring technologies and lays the foundation for effective pollution control strategies and sustainable urban development.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support and assistance of Universiti Teknologi MARA under the research grant "Geran Insentif Penyelidikan (GIP): 600-RMC/GIP 5/3 (024/2022) " and “Geran Penyelidikan Khas: 600-RMC/GPK 5/3 (051/2020)”. This research would not have been possible without the financial support provided by the university. This transdisiplinary research is part of a dissertation which was submitted as partial fulfilment to meet requirements for the Master at Universiti Teknologi MARA.

REFERENCES

Anenberg, S. C., Achakulwisut, P., Brauer, M., Moran, D., Apte, J. S., & Henze, D. K. (2019). Particulate matter-attributable mortality and relationships with carbon dioxide in 250 urban areas worldwide. *Scientific Reports 2019 9:1*, *9*(1), 1–6. https://doi.org/10.1038/s41598-019-48057-9

Apte, J. S., Messier, K. P., Gani, S., Brauer, M., Kirchstetter, T. W., Lunden, M. M., Marshall, J. D., Portier, C. J., Vermeulen, R. C. H., & Hamburg, S. P. (2017). High-Resolution Air Pollution Mapping with Google Street View Cars: Exploiting Big Data. *Environmental Science and Technology*, *51*(12), 6999–7008. https://doi.org/10.1021/ACS.EST.7B00891/SUPPL_FILE/ES7B00891_SI_002.XLS

Axisa, D., & DeFelice, T. P. (2016). Modern and prospective technologies for weather modification activities: A look at integrating unmanned aircraft systems. *Atmospheric Research*, *178–179*, 114–124. https://doi.org/10.1016/J.ATMOSRES.2016.03.005

Chen, J., Brager, G. S., Augenbroe, G., & Song, X. (2019). Impact of outdoor air quality on the natural ventilation usage of commercial buildings in the US. *Applied Energy*, *235*. https://doi.org/10.1016/j.apenergy.2018.11.020

Department of Statistics Malaysia. (2021). *Migration Survey Report, Malaysia, 2020*. https://www.dosm.gov.my/site/downloadrelease?id=migration-survey-report-malaysia-2020&lang=English

Department of Statistics Malaysia. (2022). *Gross Domestic Product (GDP) By State 2021*. https://www.dosm.gov.my/portal-main/release-content/gross-domestic-product-gdp-by-state-2021

Ding, A., Wang, T., Xue, L., Gao, J., Stohl, A., Lei, H., Jin, D., Ren, Y., Wang, X., Wei, X., Qi, Y., Liu, J., & Zhang, X. (2009). Transport of north China air pollution by midlatitude cyclones: Case study of aircraft measurements in summer 2007. *Journal of Geophysical Research: Atmospheres*, *114*(D8), 8304. https://doi.org/10.1029/2008JD011023

Doreswamy, Harishkumar, K. S., Km, Y., & Gad, I. (2020). Forecasting Air Pollution Particulate Matter (PM2.5) Using Machine Learning Regression Models. *Procedia Computer Science*, *171*, 2057–2066. https://doi.org/10.1016/J.PROCS.2020.04.221

Favoriot. (2017). *Favoriot Platform Tutorial*. Favoriot. https://platform.favoriot.com/tutorial/v2/

Fortelli, A., Scafetta, N., & Mazzarella, A. (2016). Influence of synoptic and local atmospheric patterns on PM10 air pollution levels: a model application to Naples (Italy). *Atmospheric Environment*, *143*, 218–228. https://doi.org/10.1016/j.atmosenv.2016.08.050

Gautam, S., & Patra, A. K. (2015). Dispersion of particulate matter generated at higher depths in opencast mines. *Undefined*, *3*, 11–27. https://doi.org/10.1016/J.ETI.2014.11.002

Gautam, S., Sammuel, C., Bhardwaj, A., Shams Esfandabadi, Z., Santosh, M., Gautam, A. S., Joshi, A., Justin, A., John Wessley, G. J., & James, E. J. (2021). Vertical profiling of atmospheric air pollutants in rural India: A case study on particulate matter (PM10/PM2.5/PM1), carbon dioxide, and formaldehyde. *Measurement: Journal of the International Measurement Confederation*, *185*(May), 110061. https://doi.org/10.1016/j.measurement.2021.110061

Gu, Q., & Jia, C. (2019). A Consumer UAV-based Air Quality Monitoring System for Smart Cities. *2019 IEEE International Conference on Consumer Electronics, ICCE 2019*. https://doi.org/10.1109/ICCE.2019.8662050

Han, L., Zhao, J., Zhang, J., Gao, Y., & Xin, K. (2018). Vertical distribution of urban near-surface pollutant

PM2.5 based on UAV monitoring platform. *Chemical Engineering Transactions*, *71*, 25–30. https://doi.org/10.3303/CET1871005

Jabbar, W. A., Subramaniam, T., Ong, A. E., Shu'Ib, M. I., Wu, W., & de Oliveira, M. A. (2022). LoRaWAN-Based IoT System Implementation for Long-Range Outdoor Air Quality Monitoring. *Internet of Things*, *19*, 100540. https://doi.org/10.1016/J.IOT.2022.100540

Jumaah, H. J., Kalantar, B., Mansor, S., Halin, A. A., Ueda, N., & Jumaah, S. J. (2021). *Development of UAV-Based PM 2 . 5 Monitoring System*. 1–12.

Leh, O. L. H., Marzukhi, Marlyana Azyyati, Kwong, Q. J., & Mabahwi, N. A. (2020). *Impact of Urban Land Uses and Activities on the Ambient Air*. *18*(4), 239–258.

Li, F., & Zhou, T. (2019). Effects of urban form on air quality in China: An analysis based on the spatial autoregressive model. *Cities*, *89*, 130–140. https://doi.org/10.1016/J.CITIES.2019.01.025

Li, J., Fu, Q., Huo, J., Wang, D., Yang, W., Bian, Q., Duan, Y., Zhang, Y., Pan, J., Lin, Y., Huang, K., Bai, Z., Wang, S. H., Fu, J. S., & Louie, P. K. K. (2015). Tethered balloon-based black carbon profiles within the lower troposphere of Shanghai in the 2013 East China smog. *Atmospheric Environment*, *123*, 327–338. https://doi.org/10.1016/J.ATMOSENV.2015.08.096

Liu, C., Huang, J., Wang, Y., Tao, X., Hu, C., Deng, L., Xu, J., Xiao, H. W., Luo, L., Xiao, H. Y., & Xiao, W. (2020). Vertical distribution of PM2.5 and interactions with the atmospheric boundary layer during the development stage of a heavy haze pollution event. *Science of the Total Environment*, *704*, 135329. https://doi.org/10.1016/j.scitotenv.2019.135329

Liu, F., Zheng, X., & Qian, H. (2018). Comparison of particle concentration vertical profiles between downtown and urban forest park in Nanjing (China). *Atmospheric Pollution Research*, *9*(5), 829–839. https://doi.org/10.1016/j.apr.2018.02.001

Liu, Y., Nie, J., Li, X., Ahmed, S. H., Lim, W. Y. B., & Miao, C. (2020). Federated Learning in the Sky: Aerial-Ground Air Quality Sensing Framework with UAV Swarms. *IEEE Internet of Things Journal*, *8*(12). https://doi.org/10.1109/JIOT.2020.3021006

Lu, Y., Zhu, B., Huang, Y., Shi, S., Wang, H., An, J., & Yu, X. (2019). Vertical distributions of black carbon aerosols over rural areas of the Yangtze River Delta in winter. *The Science of the Total Environment*, *661*, 1–9. https://doi.org/10.1016/J.SCITOTENV.2019.01.170

Mamali, D., Marinou, E., Sciare, J., Pikridas, M., Kokkalis, P., Kottas, M., Binietoglou, I., Tsekeri, A., Keleshis, C., Engelmann, R., Baars, H., Ansmann, A., Amiridis, V., Russchenberg, H., & Biskos, G. (2018). Vertical profiles of aerosol mass concentration derived by unmanned airborne in situ and remote sensing instruments during dust events. *Atmospheric Measurement Techniques*, *11*(5), 2897–2910. https://doi.org/10.5194/AMT-11-2897-2018

Molina, C., ToroA, R., MoralesS, R. G. E., Manzano, C., & Leiva-Guzmán, M. A. (2017). Particulate matter in urban areas of south-central Chile exceeds air quality standards. *Air Quality, Atmosphere and Health*, *10*(5), 653–667. https://doi.org/10.1007/S11869-017-0459-Y/METRICS

New Straits Times. (2016). *Malaysian house buyers increasingly drawn to high-rise living*. https://www.nst.com.my/news/2016/07/161815/malaysian-house-buyers-increasingly-drawn-high-rise-living

New Straits Times. (2022). *The case of vertical buildings for quality living*. https://www.nst.com.my/opinion/columnists/2022/12/858354/case-vertical-buildings-quality-living

Peltier, R. E., Castell, N., Clements, A. L., Dye, T., Hüglin, C., Kroll, J. H., Lung, S.-C. C., Ning, Z., Parsons, M., Penza, M., Reisen, F., & von Schneidemesser, E. (2021). *An Update on Low-cost Sensors for the Measurement of Atmospheric Composition, December 2020*. https://library.wmo.int/doc_num.php?explnum_id=10620

Peng, Z. R., Wang, D., Wang, Z., Gao, Y., & Lu, S. (2015). A study of vertical distribution patterns of PM2.5 concentrations based on ambient monitoring with unmanned aerial vehicles: A case in Hangzhou, China. *Atmospheric Environment*, *123*, 357–369.

https://doi.org/10.1016/J.ATMOSENV.2015.10.074

Ridzuan, N. A. M., Noor, N. M., Rahim, N. A. A. A., Jafri, I. A. M., Saufie, A. Z. U., Zainol, M. R. R. M. A., Kamaruddin, M. A., & Deák, G. (2022). *MODELING OF PARTICULATE MATTER (PM10) DURING HIGH PARTICULATE. October*.

Ruslan, N. (2015). *Air polution index (API) real time monitoring system*.

Salahuddin, M. M., & Ashaari, Z. H. (2017). *Application of Remote Sensing Instruments in Air Quality Monitoring in Malaysia*.

Samad, A., Florez, D. A., Chourdakis, I., & Vogt, U. (2022). Concept of Using an Unmanned Aerial Vehicle (UAV) for 3D Investigation of Air Quality in the Atmosphere—Example of Measurements Near a Roadside. *Atmosphere 2022, Vol. 13, Page 663*, *13*(5), 663. https://doi.org/10.3390/ATMOS13050663

Sevusu, P. (2013). *Real-Time Air Quality Measurements Using Mobile Platforms*. 1–168.

Sevusu, P. (2015). REAL-TIME AIR QUALITY MEASUREMENTS USING MOBILE PLATFORMS. *Rutgers The State University of New Jersey, School of Graduate Studies*.

Strawbridge, K. B., & Snyder, B. J. (2004). Daytime and nighttime aircraft lidar measurements showing evidence of particulate matter transport into the Northeastern valleys of the Lower Fraser Valley, BC. *Atmospheric Environment*, *34*(38), 5873–5886. https://doi.org/10.1016/J.ATMOSENV.2003.10.036

Tang, G., Zhang, J., Zhu, X., Song, T., Münkel, C., Hu, B., Schäfer, K., Liu, Z., Zhang, J., Wang, L., Xin, J., Suppan, P., & Wang, Y. (2016). Mixing layer height and its implications for air pollution over Beijing, China. *Atmos. Chem. Phys*, *16*, 2459–2475. https://doi.org/10.5194/acp-16-2459-2016

Tian, J. (2008). *Ground-Based Measurements for Modelling the Spatiotemporal Distribution of Fine Particlate Matter at A regional Scal*.

Wahap, N. A., & Shafri, H. Z. M. (2020). Utilization of Google Earth Engine (GEE) for land cover monitoring over Klang Valley, Malaysia. *IOP Conference Series: Earth and Environmental Science*, *540*(1). https://doi.org/10.1088/1755-1315/540/1/012003

Wang, T., Han, W., Zhang, M., Yao, X., Zhang, L., Peng, X., Li, C., & Dan, X. (2019). Unmanned Aerial Vehicle-Borne Sensor System for Atmosphere-Particulate-Matter Measurements: Design and Experiments. *Sensors 2020, Vol. 20, Page 57*, *20*(1), 57. https://doi.org/10.3390/S20010057

Xiong, X., Shah, S., & Pallis, J. (2021). *Balloon/Drone-based Aerial Platforms for Remote Particulate Matter Pollutant Monitoring*. 6604.

Zhou, S., Wu, L., Guo, J., Chen, W., Wang, X., Zhao, J., Cheng, Y., Huang, Z., Zhang, J., Sun, Y., Fu, P., Jia, S., Tao, J., Chen, Y., & Kuang, J. (2020). Measurement report: Vertical distribution of atmospheric particulate matter within the urban boundary layer in southern China - Size-segregated chemical composition and secondary formation through cloud processing and heterogeneous reactions. *Atmospheric Chemistry and Physics*, *20*(11), 6435–6453. https://doi.org/10.5194/acp-20-6435-2020