PORTABLE QUADCOPTER-BASED PARTICULATE MATTER SENSOR SYSTEM FOR AIR POLLUTION MONITORING

Faith Leong[1], Soh Jun Heng[2], Justin Teng Jia Ding[3], Tan Hui Shan[3]
[1]Hwa Chong Institution (College Section) 661 Bukit Timah Rd, Singapore 269734
[2]Catholic High School, 9 Bishan Street 22, Singapore 579767
[3]DSO National Laboratories, 12 Science Park Dr, Singapore 118225

Abstract

Standalone air monitoring stations with Particulate Matter (PM) reading systems have high installation and maintenance costs. Coupled with their inability to capture the high spatial variability of PM, their inaccessibility to less developed regions of the world is exacerbated. Satellite air monitoring solutions cover large areas of Earth's surface but have low spatial resolution, providing less localised data. Deployed unmanned aerial vehicles (UAVs) fitted with low-cost PM sensors may provide both affordable and accurate methods to assess air quality information across a region, as they can be flexibly deployed and maintained from a central location. This project explores this potential application by testing the accuracy and feasibility of deploying a quadcopter to detect PM concentrations in flight.

1. Literature Review

This literature review explores existing literature regarding PM's health effects, air pollution's disproportionate harm in developing countries, the feasibility of air monitoring using quadcopters and a comparison between quadcopters and other existing air monitoring solutions.

1.1 Health Impacts of PM2.5

When inhaled, PM2.5 damages lung tissue, severely irritating the upper respiratory tracts. It also aggravates existing respiratory diseases, and in the long term, can cause permanent lung problems like asthma, chronic bronchitis, and heart disease, even resulting in premature death[1].

1.2 Disproportionate Harm of Air Pollution in Developing Countries

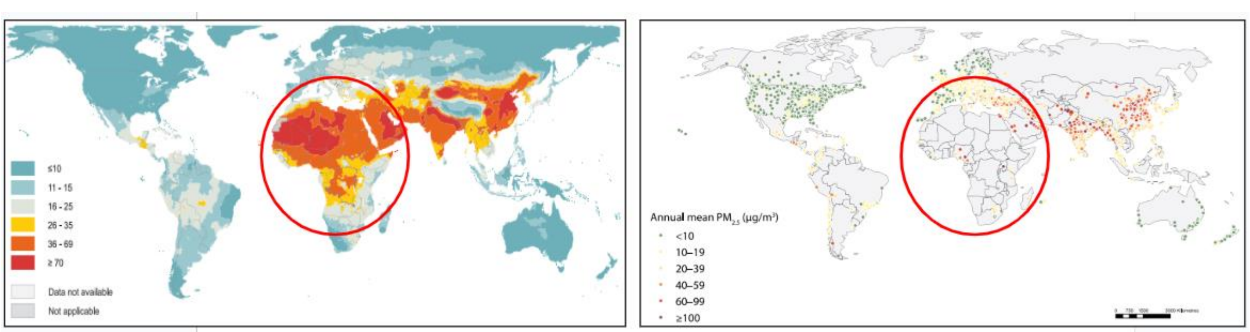


Fig 1. (left) Global Map of Modelled Annual Median Concentration of PM2.5 in µg/m^3,
(right) PM 2.5 Concentration in Monitoring Stations of Nearly 3,000 Human Settlements, 2008-2015

As shown, Western Africa and Northern Africa have the highest modelled annual median concentrations of PM 2.5, subjecting these areas to the brunt of PM exposure. However, these locations have disproportionately few monitoring stations relative to other parts of the world[2].

This unfortunately stems from the unavailability of air quality data from government sources, contributing to a lack of public awareness. Consequently, public bodies lack standards and policy guidelines to help maintain healthy air quality levels[3]. A major reason for this disparity is the high capital and operational costs of traditional ground-based air quality monitoring equipment[4].

1.3 Practical Implementations of Air Quality Monitoring with Quadcopters

From the review below, UAVs provide a cheaper alternative to existing air monitoring systems (Stationary Systems, Satellite system), while providing real-time, detailed spatiotemporal data of PM 2.5 concentration and composition at greater coverage.

Drones are also able to travel far and wide in one flight journey compared to stationary systems, decreasing cost per unit area analysed. They are also portable and can be easily transported between countries for worldwide deployment.

One possible concern in deployment of drones would be the additional manpower and efficient transportation means required, which may seem like a hassle. However, with sufficient training and possible unmanned implementations in the future, this method would be much more feasible and convenient when collecting data from rural regions.

In addition, GPS modules in drones record flight routes and coordinates. With this, drones can also identify air pollution hotspots and sources, surpassing limitations of stationary systems[5]. Air quality mapping and further actions can be derived from this concise data, leading to explosive potential in the long-term implementation of quadcopters in air quality improvement[6].

1.4 Comparison between Unmanned Quadcopters and Alternative Air Monitoring Solutions

1.4.1 Temporal Resolution Comparison

UAVs/Quadcopters

Sensor reading frequency can be adjusted to change the temporal resolution of UAV-based air quality systems. More frequent readings enhance temporal resolution for detailed and timely monitoring of rapidly changing situations. In less demanding scenarios, lower reading frequencies extend battery life and UAV operation time.

Satellite System

Geostationary satellites and polar orbiting satellites have a revisit time of 30 minutes and 1-3 days respectively[7]. They can only capture images of the same location at half-hour intervals, limiting the effectiveness in tracking air quality changes that occur on a shorter timescale.

1.4.2 Spatial Resolution and Detail Comparison

UAVs/Quadcopters

UAVs, unhindered by cloud cover like satellites, offer high spatial resolution data due to ground proximity. Using the global positioning system (GPS) for precise deployment, they collect data from small areas and can capture centimetre-resolution imagery under most conditions at any time[8]. The drone system developed by MIT alumni that measured PM 2.5 concentration and composition had a spatial resolution of 15 metres[6], demonstrating the high spatial detail of a quadcopter-based air monitoring system.

Satellite System

Operating at significantly higher altitudes than drones, satellites provide extensive coverage but have diminished spatial detail[9]. Moreover, its view of the surface can be obscured by clouds, distorting data accuracy and making it challenging to monitor air quality[10]. Spatial resolution of satellite imagery, specifically the Multi-functional Transport Satellite 2 which is a geostationary satellite widely used in meteorological research, varies from 250 metres to 4 kilometres[11]. These large distances mean less detail and variations in air quality the satellites can detect.

Traditional Stationary Air Monitoring System

Stationary air monitoring systems cannot capture the high spatial variability of PM 2.5, as the substantial infrastructure, including power and data shelters and large size limits the flexibility in installation sites[12]. The high cost of reference equipment limits the number of units that can be deployed, resulting in regional-scale measurements, leading to data gaps at local levels, hence contributing to low spatial resolution[13].

1.4.3 Cost Comparison

UAVs/Quadcopters

Quadcopters are a cost-effective air quality monitoring solution. The low setup cost, minimal infrastructure needs, and durable design reduce initial and maintenance expenses. The use of low-cost sensors further decreases operational costs. Our complete system, consisting of the parts below, costs around S$1035.67. The dimensions of the quadcopter are 383*385*240mm. The total weight of the system with the battery is 1680g.

SN	Component	Quantity	Unit Cost/S$	Cost/S$
1	SDS011 PM Sensor	1	17.77	17.77
2	S500 Drone Frame	1	48	48
3	Brushless Motor F80 Pro KV1900	4	35.75	143
4	Gemfan Hulkie 5055S-3 Propeller	4	3	12
5	FPV 45A 3-6S 32Bit ESC	4	33.25	133
6	Tattu Lipo Battery Pack 4S 5200mAh	1	102	102
7	Pixhawk Mini 4 Flight Controller Set with PM06 PDB and GPS antenna	1	214	214

8	Raspberry Pi Model 3B+	1	64	64
9	RC controller (FUTABA T14SG)	1	-	-
10	RC Receiver Futaba R7008SB	1	217.90	217.90
11	SiK Telemetry Radio V3 (Ground and Air)	1 set	84	84
⋮	⋮	⋮	⋮	⋮

Fig 2. Partial Bill of Materials on Components of PM-Sensing Drone (Full in Appendix A)

<u>Traditional Stationary Air Monitoring System</u>

Traditional stationary air monitoring systems are relatively large (4200*3500*2500mm) [14], heavy and expensive, costing around S$121000-S$242000[15], while prices for regulatory-grade, individual pollutant analysers range between €5000 and €30,000 per device[16]. These systems are subject to strict maintenance routines to ensure accurate, reliable data[17]. This includes instrument calibration and part replacement, which is costly due to the skilled personnel needed.

In summary, our drone costs a mere ≈0.86% of that of a stationary system, while boasting a compact size 0.000968 times a traditional station. Coupled with the comparable temporal resolution, increased spatial resolution and detail of data collected, the quality of the air monitoring system is not compromised, offering an effective alternative to air monitoring.

2. Materials and methods

2.1 Materials

2.1.1 Frame

The S500 quadcopter frame was used. The frame has mounting tabs at the front and rear end of the bottom plate for attachments. It has a ground clearance of 200mm[18]. This is helpful for attaching our bulky battery, Raspberry Pi, PM Sensor and their relevant holders to the bottom of the frame. Our complete system weighs 1677g in total. The components attached to the bottom centre of the drone lowers and centralises its centre of gravity (CG), increasing the stability of the drone.

2.1.2 SOLIDWorks2023 & 3D Printing

As the motors were not matched up to the frame holes, we designed adaptors in SOLIDWorks 2023 with specific dimensions to make up for the misalignment in components. Holders for the battery, RPi and PM sensor were also designed to be screwed to the bottom part of the frame securely, without blocking the screws of other components. When 3D printing, the required tolerance and component weight were considered when deciding line thickness and density infill.

2.1.3 Lithium-polymer (LiPo) Battery, Voltage Regulator

Power supply was provided by a 4S 14.8V 5200mAh 35C Lithium Polymer battery. A Voltage Regulator was used to step down the voltage from 16.8V to 5V to avoid damaging the Raspberry Pi 3 and PM Sensor.

2.1.4 PM Sensor

The Nova SDS011 High Precision Laser Dust Sensor (refer to Appendix B), was used to capture PM 2.5. It has an area of 71x70mm. The sensor's laser illuminates air particles in the sensor, which scatter light, and its photodiode detects the variation in light falling on it, generating a voltage based on the incident light. Voltage readings are fed to the microprocessor, which converts the voltage data into mass/number concentration of the PM[19].

2.1.5 Power Distribution Board, Electronic Speed Controllers (ESCs), Brushless Motors

The Holybro PM06 V2 Power Module supplies 5.2V to the flight controller from the battery. It provides current consumption and battery voltage measurements via analog signal through a 6 Pin JST-GH cable, along with integrated power distribution for 4 ESCs[20]. Attached to the propellers were four F80 PRO 3-6S KV1900 brushless motors, each producing a maximum thrust of over 2kg and a maximum power of 1122W[21]. This helps generate sufficient thrust for take-off and hovering.

2.1.6 Flight Controller

The Holybro PX4 Mini flight controller includes sensors like a GPS module, a compass, a barometer, a gyroscope, an accelerometer, and a magnetometer. QGroundControl was used to calibrate the parameters and sensors of the drone. The built-in flight map was used to track the GPS position of the drone in flight. In addition, the flight planner allows for autonomous flight from waypoint to waypoint.

2.2 Methods

2.2.1 Project Flow

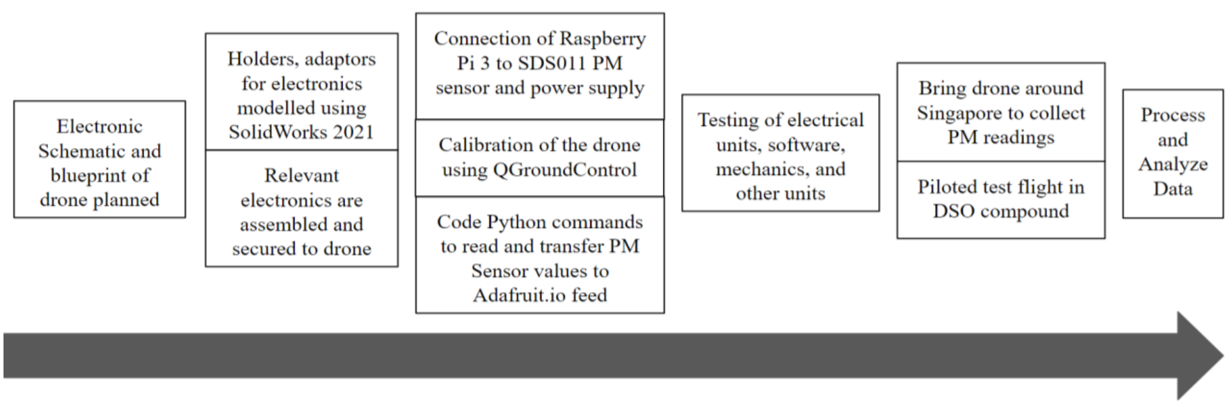


Fig 3. Overview of the Steps Taken for the Project

2.2.2 Overview of Electronics

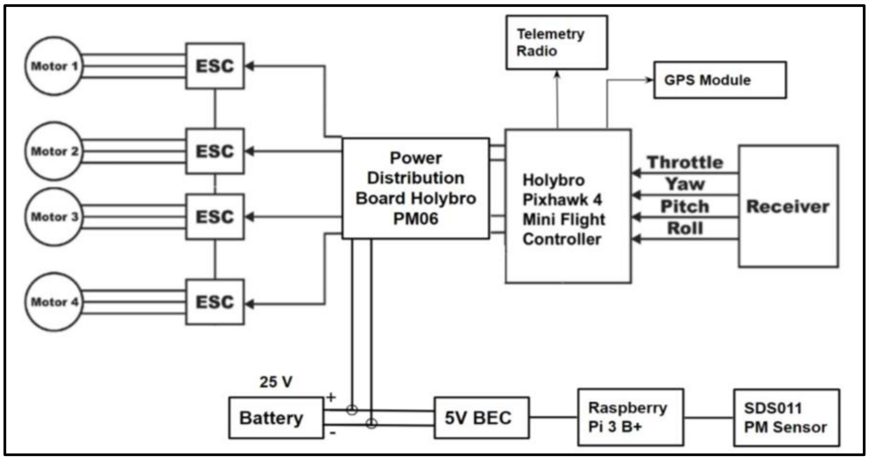


Fig 4. Electronic System Schematic of the Unmanned Quadcopter

Fig 5. Physical Arrangement of Electronics on Quadcopter Frame. PM Sensor and RPI3 attached below

The layout of these components was optimised to utilise all the space on the both frames, while lowering and centralising the CG for balance. The Pixhawk 4 Mini, RC receiver, Telemetry Unit and Voltage Regulator were attached to the top frame with dual-lock Velcro in a neat arrangement. The battery fits snugly in the holder and is connected to the 2 sub circuits via a Y-connector we created. Protruding wires were secured with zip ties to the frame. This all accounted for the restrictions of off the shelf component wires, reduced vibration, and ensured stable flight.

2.2.3 Integrating the PM Sensor and Collecting Live Readings

The PM Sensor was connected to a Raspberry Pi 3 Model B+, which received PM 2.5 readings from the PM Sensor. Upon power on, the RPi runs a python script (Appendix C) which first waits 45 seconds for the RPi to establish a wireless connection to a cloud server. The python script then runs on loop, where the RPi sends PM 2.5 data every 4 seconds over the cloud to a feed in Adafruit IO, a cloud platform, to plot and display the data in real time. (Appendix D)

3. Test Results

To measure the feasibility of utilising drones for PM monitoring, we will analyse the maximum flight time, battery life and range of the drone, as well as comparing obtained readings to those of traditional air monitoring stations.

3.1 Flight Test

Initial flight tests of the Quadcopter were conducted. The events are as documented below:

Run	Events
1	• Drone takes off upon throttle-in input • Sensitivity of yaw, pitch and roll controls is low, slow response to input • However, XYZ values eventually reach inputted value • Good vibrations of frame
2	
3	• Drone takes off upon throttle-in input • Better response to input
4	

Fig 6. Summary of Test Runs and Assessment

In the PX4 autopilot Flight Review website, the yaw, pitch, and roll rate graphs are observed to see if the drone is stable in flight and the proportional–integral–derivative algorithm (PID) is tuned well.

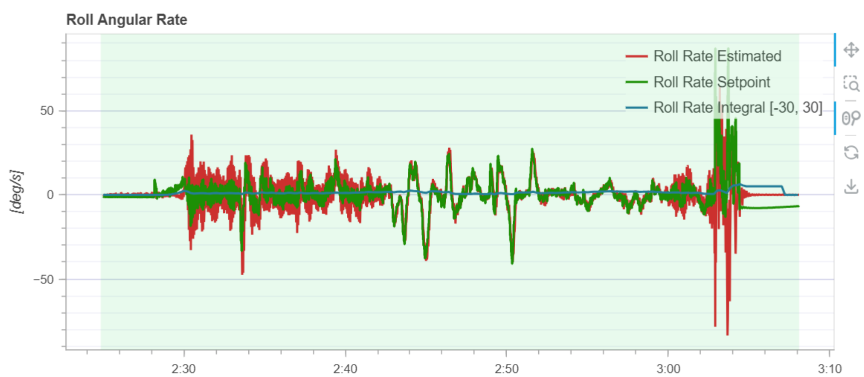


Fig 7. Roll Angular Rate Graph from Run 4

The estimated line is relatively consistent with the setpoint line. There are some overshooting and slow response time. This shows that the tracking is not consistent, but can be enhanced by further tuning the rate controller using the QGroundControl PID Tuning setup.

The inconsistencies could be due to multiple factors, including but not limited to: a low centre of gravity due to attached PM Sensor and Raspberry Pi Module below, high inertia due to great mass of drone, external factors like strong winds and inefficient motors and propellers due to poor power to weight ratio to generate optimal thrust.

In addition, it was noted that the LiPo battery was slightly bloated after the flight test, which might have caused the degradation of the flight performance.

3.2 Data Collection

3.2.1 Flight Time, Battery Endurance, Range

We analysed each flight log file on the PX4 Flight Review website. Pyulog[22], a python package that parses ULog files in PX4 autopilot middleware for conversion and display, was used to obtain .csv files which were analysed. Specific data points and parameters at point of flight were examined and graphed to form a relationship.

Values for speed during flight, as well as flight life of the drone, were derived from the PX4 ULog Flight files[23].

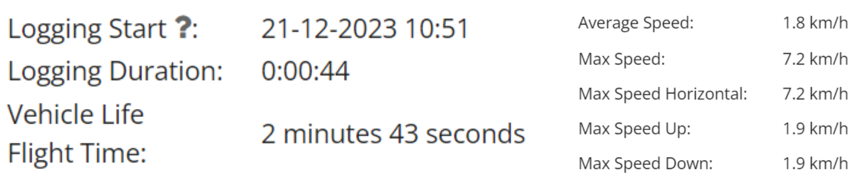


Fig 8. (Left) Vehicle Life Flight Time, (Right) Speed Values for Test Flight

Next, graphs of battery life with accordance to time in flight were plotted from data in the PX4 autopilot log to obtain approximations for maximum flight time.

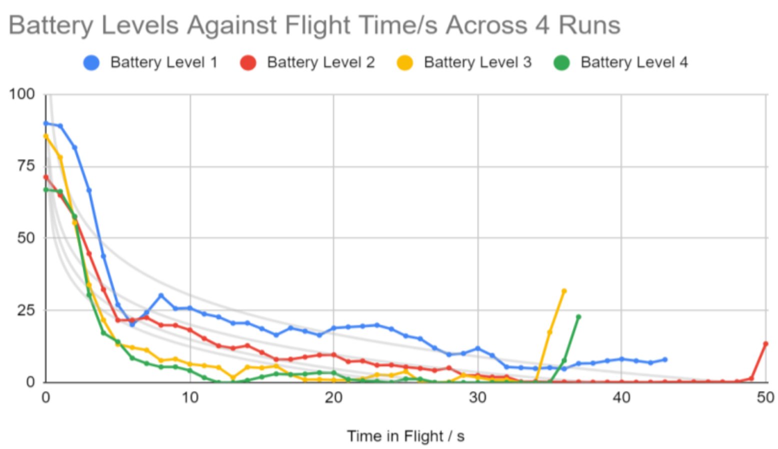


Fig 9. Graph of Battery Levels over Flight in 4 Test Runs

There is a sharp decrease in battery level around the first 6 seconds as much power is expended to first lift off. The average rate of battery decrease here is 9.58 units/s. In flight, the average rate of decrease of battery level is 0.534 units/s.

Rate of battery decrease/ units s^{-1}	Run 1	Run 2	Run 3	Run 4	Average
During take-off, for 6 seconds	9.38	6.97	12.8	9.12	9.58
During cruising	0.635	0.491	0.457	0.555	0.534

Fig 10. Rate of Battery Decrease over Flight in 4 Test Runs

By calculation, the estimated flight time of this particular drone, when the battery starts at 100 power, is 1 minute and 25 seconds. However, the average flight time, taking the average of 4 runs in the PX Autopilot Log (Fig 9) is 2 minutes and 2 seconds.

Then, the maximum speed value is multiplied by maximum flight time to find its horizontal and vertical range.

$$Horizontal\ Range = 7.2\ km/h\ \times \frac{2.03}{60} h = 0.244\ km = 244m$$

$$Vertical\ Range = 1.9km/h\ \times \frac{2.03}{60}\ h = 0.0643\ km = 64.3\ m$$

It is not ideal as we were looking for a flight time of at least 30 minutes, and a range of > 1km. However, the flight time can be easily optimised by using larger motors and propellers to generate more lift and thrust, as well as obtaining a new LiPo battery source. These measures will ensure the drone is powered optimally to fly for a long time over a long distance.

3.2.2 Comparison to PM Readings of Existing Stations

Tests were conducted in various sites of Singapore to collect data values of PM 2.5. >25 readings 4 seconds apart were taken while the drone was in both stationary and hovering mode. This tests both the accuracy of readings and the effect of altered airflow by propellers on the composition of PM around the drone. The distribution and mean of readings are compared in the figure below.

Region (Specific Location)	**NEA Readings/ μg/m³ (Appendix E)**	**Average Stationary Quadcopter Reading/ μg/m³ (Appendix F)**	**Average Hovering Quadcopter Reading/ μg/m³ (Appendix F)**
North (Khatib MRT)	5	4.7	-*
South (Mount Faber Park)	8	7.9	-*
Central (Bishan-Ang Mo Kio Park)	5	6.7	-*
East (Pasir Ris Park)	15	15.2	-*
West (Bukit Timah Old Holland Road Field)	6	5.0	4.7

*Unable to hover drone in these areas[24]

Fig 11. Obtained PM 2.5 Readings at Locations Around Singapore

As shown, the PM sensor on the quadcopter has similar readings to the NEA reference, proving that the low-cost sensor provides accurate, localised readings reflective of the air quality at a specific location. As such, we can conclude that the use of this drone sensor system is feasible.

4. Limitations/ Future Work

The quadcopter's motors and propellers were too small to efficiently produce thrust, having to operate at half of maximum speed to initiate take-off. This significantly limited the battery life and flight time. A more efficient implementation with larger motors (e.g. 2216-KV920) and propellers (e.g. Holybro S500 X500 1045) proportional to the drone size[25] would extend flying time, improving the drone's ability to collect more data at a specific point, and over a larger area.

Future work can also focus on improvements to flight endurance to improve deployment flexibility under varying weather conditions. This includes waterproofing the quadcopter and optimising the PID algorithm to improve flight stability during high winds. To improve air monitoring abilities, a greater variety of small, low-cost sensors could be incorporated into the UAV system by adapting a more efficient electronics layout. This includes other sensors for other pollutants like ozone, carbon monoxide, and sulphur dioxide to provide more comprehensive information on local air quality.

The drone could also be deployed in smaller, industrial scenes, where the above sensors are integrated to help monitor safe gas levels throughout underdeveloped or toxic workplaces[26] like factories or chemical plants. This increases workplace safety, offering lower construction and maintenance costs, and increased coverage compared to stationary sensors.

Additionally, we aim to make these drones fully autonomous. This reduces the manpower and transportation cost of manually flying drones in different geographical areas. Using GPS for autonomous navigation via waypoints can help drones autonomously cover an area and return to a ground station via preset commands. Pathfinding algorithms can improve operational efficiency in areas with lots of obstructions like high-rise buildings, and the Obstacle Avoidance feature in QGroundControl used to navigate around obstacles in the pre-planned path.

5. Conclusion

In conclusion, the use of drones in non-stationary air monitoring is feasible due to the accessibility of equipment, ease of assembly, maintenance and accurate data collection. Drones are a cheaper alternative which can provide additional details on each reading, like specific GPS locations, and mapping of high-concentration areas and sources. Such a system has significant potential to initiate meaningful policy changes in resource-limited regions that lack the infrastructure and information necessary to tackle the issue of air pollution.

However, further strides have to be taken to improve the effectiveness of such a drone system, by optimising the electronic and physical design to maximise battery endurance, and incorporate weather proofing properties. This will improve the total distance covered and environmental data collected, to provide a more comprehensive view of local air quality.

6. Acknowledgements

We would like to express our sincerest gratitude to Justin and Hui Shan, our mentors that have guided us throughout the process of this research; Desmond, the Playground Supervisor, and, the

DSO National Laboratories (DSO) and the Young Defence Scientists Program (YDSP) for granting us this opportunity to carry out this project.

7. References

[1] Karmakar, A. (2020, September 13). Particulate Matter monitoring | Know about PM2.5. Oizom. Retrieved December 4, 2023, from https://oizom.com/knowledege-bank/particulate-matter-monitoring/
[2] World Health Organisation. (2016). Ambient air pollution: A global assessment of exposure and burden of disease. Retrieved December 05, 2023, from https://iris.who.int/bitstream/handle/10665/250141/?sequence=1
[3] Alvarez, C. M., Hourcade, R., Lefebvre, B., & Pilot, E. (2020, December 7). A Scoping Review on Air Quality Monitoring, Policy and Health in West African Cities. MDPI. Retrieved December 7, 2023, from https://www.mdpi.com/1660-4601/17/23/9151
[4] Malings, C., Westervelt, D. M., Hauryliuk, A., Presto, A. A., Grieshop, A., Bittner, A., Beekmann, M., & Subramanian, R. (2020, July 17). Application of low-cost fine particulate mass monitors to convert satellite aerosol optical depth to surface concentrations in North America and Africa. Atmospheric Measurement Techniques, 13(7), 3873–3892. https://doi.org/10.5194/amt-13-3873-2020
[5] Petersen, K. (2021, June 24). Tackling air pollution with autonomous drones. MIT News. Retrieved December 4, 2023, from https://news.mit.edu/2021/tackling-air-pollution-with-autonomous-drones-0624
[6] Rohi, G., Ejofodomi, O., & Ofualagba, G. (2020, January 1). Autonomous monitoring, analysis, and countering of air pollution using environmental drones. ScienceDirect. Retrieved December 04, 2023, from https://www.sciencedirect.com/science/article/pii/S2405844020300979
[7] NASA. (2018, September 4). About ARSET Slides. NASA Applied Sciences. Retrieved December 12, 2023, from https://appliedsciences.nasa.gov/sites/default/files/Geo_week1.pdf
[8] Sun, Z., Wang, X., Wang, Z., Yang, L., Xie, Y., & Huang, Y. (2021, August 20). UAVs as remote sensing platforms in plant ecology: review of applications and challenges. Journal of Plant Ecology, 14(6), 1003–1023. https://doi.org/10.1093/jpe/rtab089
[9] Satish, S. (2021, September 8). Satellite VS Drone Imagery: Knowing the Difference and Effectiveness of SuperVision Earth's…. Medium. Retrieved December 12, 2023, from https://medium.com/supervisionearth/satellite-vs-drone-imagery-knowing-the-difference-and-effectiveness-of-supervision-earths-90e98b78777c
[10] Riebeek, H. (n.d.). Satellite Observations | Terra. NASA's Terra. Retrieved December 12, 2023, from https://terra.nasa.gov/citizen-science/air-quality/part-ii-track-pollution-from-space
[11] Zhao, Y., & Huang, B. (2017, July). Integrating modis and MTSAT-2 to generate high spatial-temporal-spectral resolution imagery for real-time air quality monitoring. ResearchGate. Retrieved December 12, 2023, from https://www.researchgate.net/publication/321785400_Integrating_modis_and_MTSAT-2_to_generate_high_spatial-temporal-spectral_resolution_imagery_for_real-time_air_quality_monitoring
[12] Randle, A. (2016, October 5). The challenges and benefits of local air quality monitoring. Envirotech Online. Retrieved December 4, 2023, from https://www.envirotech-online.com/article/air-monitoring/6/environmental-instruments/the-challenges-and-benefits-of-local-air-quality-monitoring/2104
[13] Clarity. (2021, August 4). What is Air Quality Monitoring 2.0 & Air Sensing Technology. Clarity Movement. Retrieved December 18, 2023, from https://www.clarity.io/blog/air-quality-monitoring-2-0-how-different-types-of-air-monitoring-technologies-are-contributing-to-a-more-holistic-understanding-of-air-pollution

[14] Delhi Central Pollution Control Board. (2015). TECHNICAL SPECIFICATIONS FOR CONTINUOUS AMBIENT AIR QUALITY MONITORING (CAAQM) STATION (REAL TIME). Environment Surveillance Centre & Emergency Response Centre, Bhopal. Retrieved December 22, 2023, from https://erc.mp.gov.in/Documents/doc/Guidelines/CAAQMS_Specs_new.pdf
[15] Mayuga, J. L., & Schumacher, H. J. (2023, September 27). DENR pushes more air quality monitoring stations in Metro Manila, other urban areas | Jonathan L. Mayuga. Business Mirror. Retrieved December 12, 2023, from https://businessmirror.com.ph/2023/09/27/denr-pushes-more-air-quality-monitoring-stations-in-metro-manila-other-urban-areas/
[16] Castell, N., Dauge, F. R., Schneider, P., Vogt, M., Lerner, U., Fishbain, B., Broday, D., & Bartonova, A. (2016, December 28). Can commercial low-cost sensor platforms contribute to air quality monitoring and exposure estimates? ScienceDirect. Retrieved December 12, 2023, from https://www.sciencedirect.com/science/article/pii/S0160412016309989
[17] Curtis, D. (03 2014, April 03). EN14181 Stationary Source Emissions - Quality Assurance of Automated Measuring Systems. Environtech. Retrieved December 12, 2023, from https://www.envirotech-online.com/article/air-monitoring/6/source-testing-association/en14181-stationary-source-emissions-quality-assurance-of-automated-measuring-systemsnbsp-nbsp/1596.
[18] S500 Quadcopter Frame & Landing Skids – Hobby Square Singapore. (n.d.). Hobby Square Singapore. Retrieved December 5, 2023, from https://hobbysquare.com.sg/products/s500-quadcopter-frame-landing-skids
[19] Zxz_100@163.com. (2021, October 29). What Is PM2.5 Particulate Sensor? | How Does It Work? CALT. Retrieved December 6, 2023, from https://caltsensor.com/what-is-pm2-5-particulate-sensor-how-does-it-work/
[20] Holybro. (n.d.). PM06 V2 Power Module – Holybro Store. Holybro. Retrieved December 18, 2023, from https://holybro.com/products/micro-power-module-pm06-v2
[21] T-MOTOR. (n.d.). F80 PRO 3-6S Fpv Racing Drone Motor KV1900_F Series_Motors_FPV Model_T-MOTOR Official Store - UAV Power System, Robot Power System, Model Power System. T-MOTOR Store-Official. Retrieved December 6, 2023, from https://store.tmotor.com/goods.php?id=748
[22] bkueng, b. (2017). PX4/pyulog: Python module & scripts for ULog files. GitHub. Retrieved December 19, 2023, from https://github.com/PX4/pyulog
[23] PX4 Autopilot. (2019, June 24). PX4 Quadrotor Flight Review. review.px4.io. Retrieved December 22, 2023, from https://review.px4.io/plot_app?log=a5efdc8e-379f-4558-8e51-0572cd3cd601
[24] Singapore Government Agency. (2010). OneMap. OneMap. Retrieved December 19, 2023, from https://www.onemap.gov.sg/v2/dronequery
[25] Holybro. (2020). S500 V2 Kits – Holybro Store. Holybro. Retrieved December 20, 2023, from https://holybro.com/products/s500-v2-kit
[26] Agence France-Presse. (2023, April 30). Gas leak in India's Punjab kills at least 11 people. South China Morning Post. Retrieved December 20, 2023, from https://www.scmp.com/news/asia/south-asia/article/3218915/factory-gas-leak-indias-punjab-kills-least-11-people

ANNEX

Appendix A

Bill of Materials of PM Sensing Drone

SN	Component	Quantity	Unit Cost/S$	Cost/S$
1	SDS011 PM Sensor	1	17.77	17.77
2	S500 Drone Frame	1	48	48
3	Brushless Motor F80 Pro KV1900	4	35.75	143
4	Gemfan Hulkie 5055S-3 Propeller	4	3	12
5	FPV 45A 3-6S 32Bit ESC	4	33.25	133
6	Tattu Lipo Battery Pack 4S 5200mAh	1	102	102
7	Pixhawk Mini 4 Flight Controller Set With PM06 PDB and GPS antenna	1	214	214
8	Raspberry Pi Model 3B+	1	64	64
9	RC controller (FUTABA T14SG)	1	-	-
10	RC Receiver Futaba R7008SB	1	217.90	217.90
11	SiK Telemetry Radio V3 (Ground and Air)	1 set	84	84
12	Bullet Connectors (M & F per set)	12 sets	-	-
13	XT 30 Connectors (M & F per set)	2 sets	-	-
14	M3 Threaded Inserts	5	-	-
15	Wires & Heat sleeves	-	-	-
16	Dual Lock Velcro	6	-	-
17	M2.5 x 8mm Cap Head Screws	20	-	-
18	M2.5 x 6mm Countersunk Screws	16		
19	M3 x 6mm Countersunk Screws	4		
20	M3 x 10mm Cap Hexagon Screws	20		
21	M3 x Hexagon Nut Socket	23		
22	M3 x 6mm Cap Hexagon Screws	19	-	-
23	M3 x 20mm Standoffs MtF	20	-	-

24	M3 x 10mm Standoffs MtF	4	-	-
25	M3 x 10mm Standoff FtF	4		
26	M3 x 5mm Nylon Spacers	4		

Appendix B

Nova SDS011 High Precision Laser Dust Sensor

maximum relative error of ±15% at 25 • C and 50% relative humidity
+ location

Appendix C

Python Script Running on Raspberry Pi Model 3B+ when Powered On


```python
import serial, time
from Adafruit_IO import Client
aio = Client('', '')

ser = serial.Serial('/dev/ttyUSB0')
time.sleep(45)

while True:
    data = []
    for index in range(0,10):
        datum = ser.read()
        data.append(datum)

    pmtwofive = int.from_bytes(b''.join(data[2:4]), byteorder='little') / 10
    aio.send('twofivepm', pmtwofive)
    pmten = int.from_bytes(b''.join(data[4:6]), byteorder='little') / 10
    aio.send('tenpm', pmten)
    time.sleep(1)
```

Appendix D

Real Time View of PM 2.5 Data Received on Adafruit IO, from RPi

Appendix E

PM2.5 Readings (NEA) Across Singapore

1-hr $PM_{2.5}$ ($\mu g/m^3$) Readings from 26 Dec 2023 12AM to 26 Dec 2023 11PM

Region/Time	12am	1am	2am	3am	4am	5am	6am	7am	8am	9am	10am	11am
North	10	9	9	6	6	5	6	6	4	8	6	4
South	9	9	11	4	7	7	5	6	7	6	6	10
East	11	8	9	7	12	12	10	7	4	6	8	7
West	8	9	4	7	9	5	5	6	4	5	6	6
Central	11	9	9	4	7	7	9	7	9	7	6	5

Region/Time	12pm	1pm	2pm	3pm	4pm	5pm	6pm	7pm	8pm	9pm	10pm	11pm
North	4	5	4	5	5	4	5	3	4	5	5	**6**
South	11	8	5	7	7	7	6	4	3	4	4	**14**
East	7	10	9	12	8	8	8	8	8	5	4	**5**
West	5	5	6	4	3	3	4	5	4	3	4	**5**
Central	5	7	8	12	6	10	11	4	7	7	7	**5**

Region/Time	11am	12pm	1pm	2pm	3pm	4pm	5pm	6pm	7pm	8pm	9pm
North	6	5	6	5	6	4	4	8	6	13	9
South	6	6	4	18	9	9	9	6	10	10	12
East	17	6	9	16	12	5	7	10	14	15	11
West	4	5	8	9	5	9	5	5	4	5	6
Central	5	8	8	9	8	9	8	8	11	12	12

Appendix F

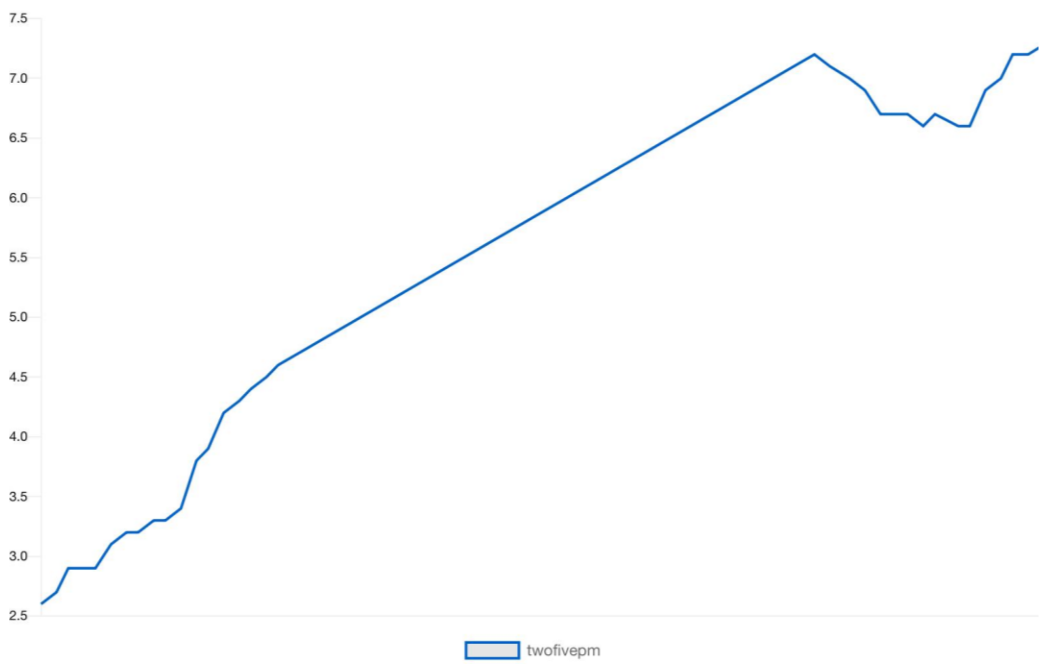
PM2.5 Readings (Drone) Across Singapore

Bukit Timah Old Holland Road Field (hovering (top) in flight (bottom))

faitherpie / Feeds / twofivepm

Bishan Park

Pasir Ris Park



Mount Faber

Khatib MRT