Emerging Low-Cost Air Quality Monitoring Techniques for Smart Cities with UAV

Piyush Yadav
Department of Electronics & Communication Engineering
Delhi Technological University
Delhi, India
piyush.dcedtu@gmail.com

Tejas Porwal
Department of Electronics & Communication Engineering
Delhi Technological University
Delhi, India

Vedanta Jha
Department of Electronics & Communication Engineering
Delhi Technological University
Delhi, India

Prof. S. Indu
Department of Electronics & Communication Engineering
Delhi Technological University
Delhi, India
s.indu@dce.ac.in

***Abstract*—Air quality is a local phenomenon, that is, it changes in a significant manner from point to point, thus making air quality mapping from scarce static air quality sensors, practically insignificant. Thus, air quality monitoring using mobile sources holds enormous potential as it gives us the ability to perform spatiotemporal pollution mapping of a geographically wide region using just a few mobile sensors and at a cost that is almost negligible to ground-based static sensors. Drone technology has emerged as a very important platform to do sensing of various physical phenomena around us and by integrating low-cost and light-weight air quality sensors on a UAV, it is possible to get fine-grained spatiotemporal air quality data to have a better overview of the pollution variation and locate its source of origin. In this study, we have designed and manufactured a fixed-wing solar-powered UAV, with potential to perform perpetual flight using solar power and generate air quality data in real-time. Fixed-wing UAV design was chosen for this study due to less propeller wash on sensor readings and more flight time possible than a quadcopter. This UAV system was successfully field-tested at a low altitude and air quality data was generated on the ground, collecting, storing and transmitting data through a data fusion module consisting of low-cost OPC R1 sensor, Raspberry Pi and Pixhawk Flight controller. We do spatiotemporal analysis of the generated PM 2.5 data from the system, which could be very useful to identify pollution hotspots in urban areas, industrial region, smart cities and locate stubble burning sites.**

Keywords—Air Quality Monitoring, Solar Power, UAV, Low Cost Sensors, Satellite Sensing

I. INTRODUCTION

A balanced ambient air composition is necessary for healthy living of human beings as well as to support different activities. However, different natural and man-made activities continuously release aerosols and gas pollutants which degrades air quality. Ambient air pollution has been regarded as the ninth largest risk factor for human health globally [1]. Atmospheric pollution not only lead to adverse health conditions but also reduce agriculture yields, visibility, sunlight penetration at ground level and lead to warming of atmosphere [2, 3]. Thus to prevent these adverse impacts on lives of humans, continuous air quality monitoring has become a necessity. A lot of smart cities have started deploying new innovative technologies to monitor pollution levels [4].

A. Air Quality status of India

- India is home to 9 of the world's 10 most polluted cities and has just one air quality monitoring station for every 7 million people, while China has over eight times that number [5].
- Just a mere 5% of India's census towns are monitored currently [5].

B. Disadvantages with static Air Quality monitoring stations

Automated air quality monitoring system costs about ₹2 crore and run for seven years and is often unable to process the Air Quality readings in real-time [5]. Thus, making Air Quality Monitoring with static sensors highly ineffective.

C. Emerging Air Quality Monitoring techniques

- Air Quality is till recently done with costly static sensors only. But with the growing emergence of low cost Air Quality sensors, makes it possible to deploy these Air Quality sensors at scale, which makes it easier to do Air Quality monitoring around us with fine-granularity. A lot of work has been done recently to do Air Quality monitoring by integrating these low cost sensors on vehicles, drones and other mobile platforms [6, 7]. It makes it much easier to do real-time monitoring of Air Quality, with these mobile sensor integration, at a fraction of cost. By integrating Air Quality sensors on a vehicle as seen in Fig. 1, it becomes far easier to operate, but we are restricted to get Air Quality readings from the roads only, and the excess pollution created by the vehicle's exhaust also distorts the Air Quality readings.

Fig. 1. Air Quality sensor mounted on the top of a tram

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- Another area that is gaining great interest is Air Quality monitoring using Satellite sensing [8]. Satellite monitoring works on Aerosol Optical Depth, rather than measuring PM 2.5 values via sensors. The high-resolution camera on satellites captures the earth's image, this data is then processed and analysed. But some major challenges still remain for Air Quality monitoring with Satellite, such as when clouds block the image, lack of satellite with Air Quality measuring capabilities [9].

II. RELATED WORKS

Previous technologies [10] for monitoring the quality of air included balloons, manned aircrafts and satellites which are not manoeuvrable, involve risk to human life and are highly expensive. Nowadays, researchers use remotely controlled as well as autonomous fixed wing and rotary wing aircrafts to monitor air quality. Fixed wing Gliders offer very efficient flight and can be used to cover large areas. Owning to a large wingspan, gliders provide the flexibility to mount the air quality sensor at various mounting points, such that, the impact of propeller wash is least on the sensor output data. Many researchers have used these UAVs to monitor air pollutants [11, 12, 13] focusing mainly on particulate matters, carbon dioxide, methane and ozone. However they might require additional infrastructure for take-off and landing. Rotary wing aircrafts like quad-copters when used for monitoring air quality [14], can achieve high spatial resolution at the cost of decreased spatial diversity. They do not require any additional infrastructure for landing and take-off and also allow discontinuous trajectories such as hovering. However, in Quadcopters, propeller wash and variation in the current of the system deeply affects the sensor readings and the flight time is also very limited, thus limiting their use as a mobile source for Air Quality measurement.

III. DESIGN

A. Our Solar Powered UAV Prototype

We designed and built a 3.12 meter wingspan UAV for this study. The UAV was built with carbon fibre rods, balsa wood, aramid and glass fibre. Fig. 2 shows the XFLR5 analyses of the design parameters to provide optimum gliding ratio for the given design.

We used an EMAX MT-3515 brushless DC motor and 13*6 folding propellers. The wing had a dihedral angle of 3 degree. The angle of attack in the design was 4 degree. In the case of level flight, the lift force(L) generated by the wing compensates for the weight of the plane(W) and the thrust produced by the propeller(T) compensates for the drag force(D) [15]. So, the lift force generated by the wing was calculated as L= $\rho C_L S V^2$ which compensates the weight W=mg as shown in (1) and thrust T balances the drag force D= $\rho C_{TD} S V^2$ as shown in (2)

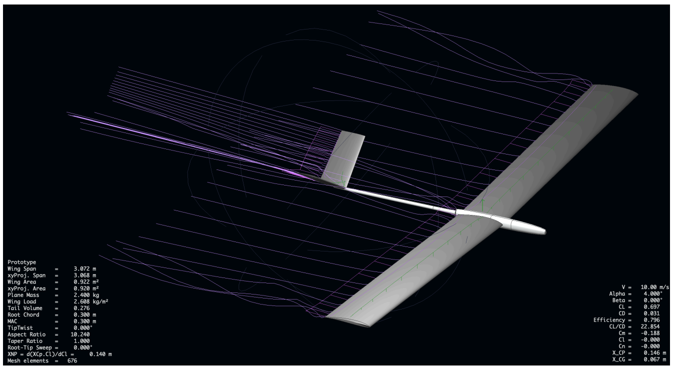

Fig. 2. XFLR5 analysis of the prototype design

$$mg = \rho C_L S V^2 \tag{1}$$

$$T = \rho C_{TD} S V^2 \tag{2}$$

Where: m is the mass of the plane (kg); g is gravity (m/s^2); S is the surface area of the wing (m^2); V is the cruise velocity of the plane (m/s); C_L is the coefficient of lift, C_{TD} is total drag coefficient.

Fig. 3. Design of our prototype

In our design, keeping the high load in mind, we used carbon fibre wing spars. The wing spar has three essential loads: the wing bending load produced by lift ; the transverse shear load caused by wing bending ; and the torque load produced by the pitching moment of the wing airfoil [16]. The tail boom is also made of carbon fibre, as it has to carry the bending loads produced by the V-Tail. The V-Tail in our design was chosen to provide better ground clearance and being lighter in weight.

We calculated the power required using (3) for level flight of the UAV [17]:

$$P_{req} = T*V \tag{3}$$

where, T is calculated using (2) as 1.95 N and using V= 8 m/s

So, P_{req} for UAV to have a level flight was calculated out as 15.6 W. The power required for hand launch of UAV was calculated by keeping the thrust to weight ratio of the UAV greater than 0.6 : 1.

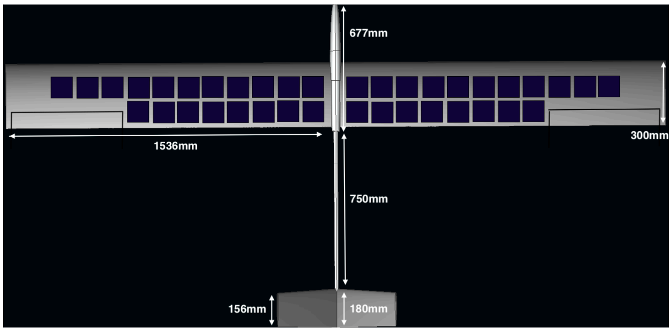

Fig 4. Conceptual design with 38 solar cells

In the design, 38 solar cells were chosen, as they would fit easily on the wing and generate around 100W of power under ideal condition. So, with this design configuration, we can completely rely on solar power during level flight.

The solar module is more than sufficient to power the UAV during level flight, thus making this solar module of 38 cells more than sufficient for our application.

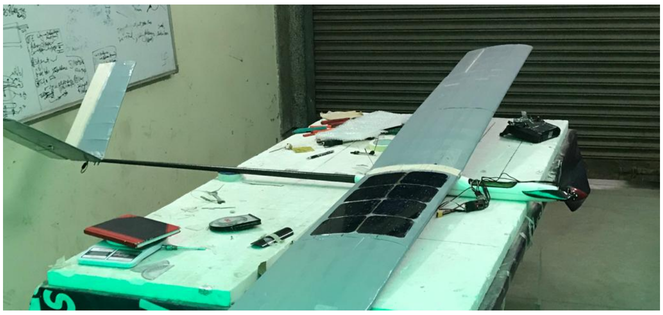

Fig. 5. Prototype with 8 solar cells integrated

We used Sunpower C-60 solar cells for this project. These are extremely light weight solar cells and are highly flexible, thus making them very favourable for our application. To make the solar module, we connected all the 38 solar cells in series and laminated the cells together. It gave the solar module sufficient strength, at the same time, making it very light weight as well. This helps to keep the power to weight ratio from the module suitable [18].

B. Data Fusion Module

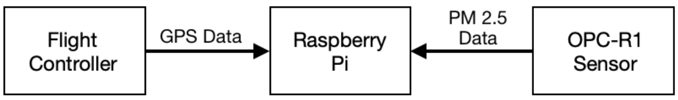

Fig. 6. Data fusion Module Design

Our data fusion module comprised of an Air Quality sensor, a companion computer and a flight controller. The data fusion module was powered with a Lipo battery. The Raspberry Pi acted as the central unit in this module, by extracting and storing GPS data from the Flight controller and Air Quality data from the OPC-R1 sensor.

- OPC-R1 sensor

For this study, we used Alphasense OPC-R1 Air Quality sensor. The OPC-R1 is very light weight and low-cost optical particulate sensor and use laser technology to measure micro-particles from 0.4 to 12.4 µm in diameter. It is capable to produce PM 1, PM 2.5, PM 10 data. It weighs about just 30 grams, and is extremely compact and lightweight in size for integrating on a UAV [19]

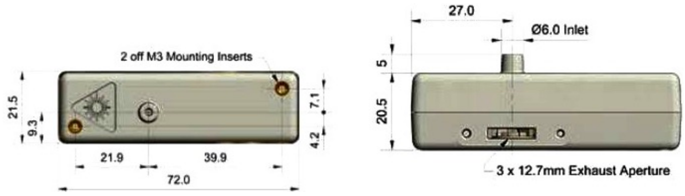

Fig. 7. OPC-R1 sensor

- Pixhawk Flight Controller

We used pixhawk as the flight controller of the UAV and Ardupilot its autopilot software. Ardupilot is an open source autopilot software, often used as onboard flight controller for planes, rovers and copters. Ardupilot comes with APIs for controlling commands and transmit UAV data. For the ground control station, we use Mission Planner, an open source ground control station with ability to provide full flight control for UAV and other platforms.

- Working

We connected the OPC-R1 to Raspberry Pi using a SPI to USB converter. The Raspberry Pi was connected using a UART connection to Pixhawk flight controller. The communication between Raspberry Pi and Pixhawk took place using Mavlink protocol over serial connection [20].

OPC-R1 comes with a software to run on windows operating system. But Raspberry Pi runs on linux, so we created a python script to run the OPC-R1 with Raspberry Pi [21].

Fig. 8. shows our complete air quality data fusion module, with mission planner and Raspberry Pi running in the background.

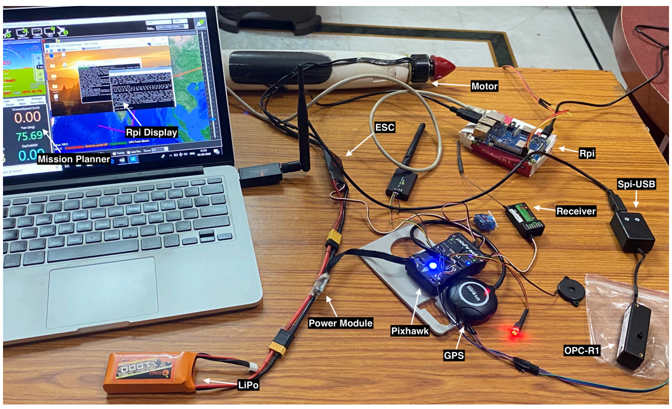

Fig. 8. Complete Data Fusion Module

On the Raspberry Pi, we are running two scripts, one to get Latitude, Longitude and Altitude data from the GPS module and one script to get PM data from the OPC-R1 sensor. This way, we can very cost-effectively plot spatiotemporal Air Quality data.

The OPC-R1 sensor is not capable to store data on an SD card or send the data directly to the ground. So, we use this data fusion module. From the GPS module connected to the Flight controller, we get the geo-location data, time data and other crucial flight aspects. From the OPC-R1 sensor, we get the PM 1, PM 2.5, PM 10 data along with time, temperature data. We set the OPC-R1 sampling rate to 1 second. So, we generate PM readings from the sensor in every second.

We created an application that saves the GPS coordinates from the GPS module and PM data from the OPC-R1 sensor to a CSV file in Raspberry Pi. We use the data generated in the CSV file and do the data analysis from it.

IV. FIELD TEST

A. UAV

Various flight tests of the UAV were successfully conducted, especially keeping in mind to improve the flight characteristics and make it capable to carry the payload of the data fusion module. For field-testing the UAV system, we used a 4s LiPo battery pack, that was capable to generate sufficient Thrust to weight ratio to fly the UAV with all the weight included. We tried to keep the altitude of the flight at 30 meters.

TABLE I

WEIGHT OF VARIOUS UAV PARTS

	Flight Parameters	
1	Motor, Propeller, Frame, Battery, Data Fusion module	2100 grams
2	Sunpower (C-60)Solar cells : Total 38 solar cells	310 grams

B. Data Fusion Module

We conducted the ground test of the data fusion module to generate Air Quality data along with geo coordinates from the GPS Module. This Air Quality data was plotted in terms of latitude-longitude. This helps us to analyse the variation in Air Quality as we move from one spot to another, thus making it possible to very cost-effectively analyse Air Quality spatiotemporally. Fig. 9 shows the PM-2.5 data linked to the Latitude-Longitude. This data is very valuable to locate pollution hotspots. Whenever we see a spike in the Pollution reading generated by our UAV, we can quickly locate that spot and take necessary action.

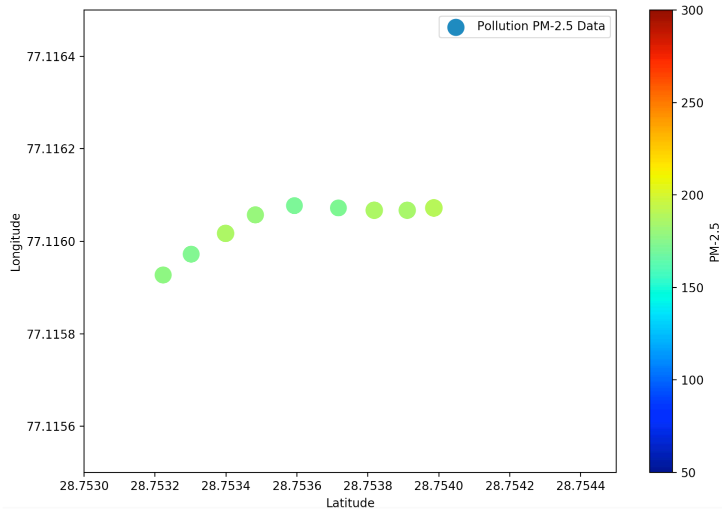

Fig. 9. PM-2.5 data and the corresponding latitude-longitude

Fig. 10 was generated using GPS and PM data stored in the CSV file of the Raspberry Pi and plotted using python Matplotlib and Pandas library [22, 23]. Fig. 9 and Fig. 10 can help us to locate sudden rise in Air Quality reading and locate pollution sources.

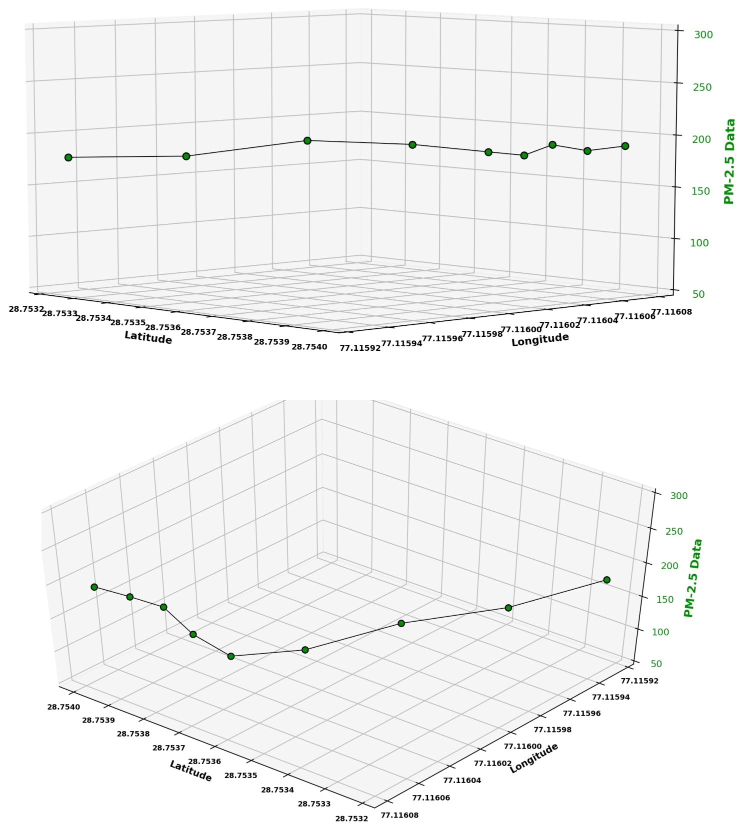

Fig. 10. 3-dimensional representation of PM-2.5 data and the corresponding Latitude - Longitude

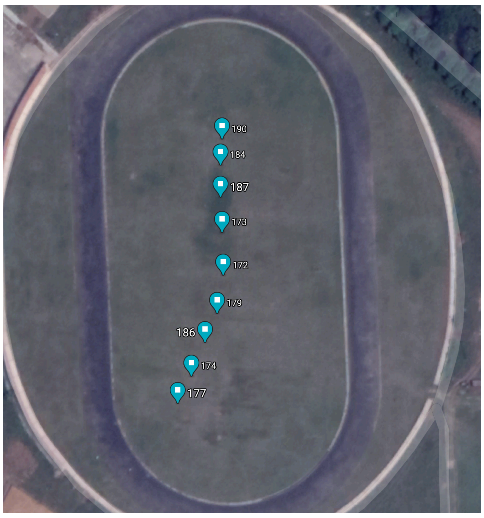

Fig. 11. PM-2.5 data using geo-coordinates plotted on a map

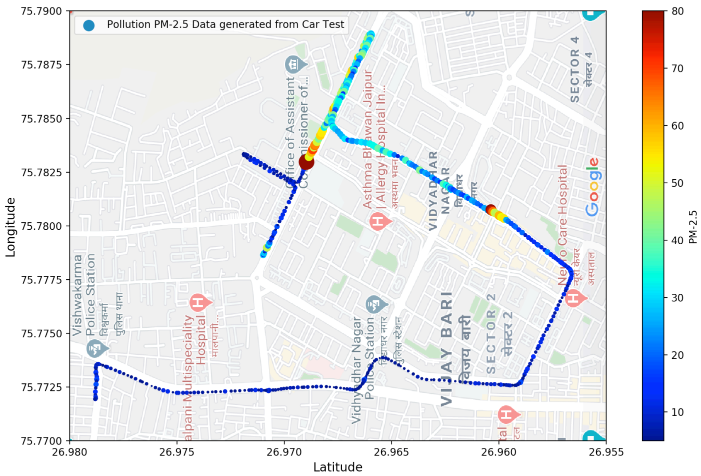

Fig. 12. PM-2.5 data generated by integrating Data Fusion module on a car

The Data Fusion module was also tested by integrating it on a car to show its capability as a low-cost mobile monitoring system that can be integrated on various public transportation systems. Fig. 12 shows the path that the car followed and the PM-2.5 data generated from the sensor linked to the Latitude-Longitude obtained from the GPS module and plotted on a map. This shows the potential to deploy such a low-cost monitoring system rather than just relying on very expensive ground based monitoring stations.

V. CONCLUSION & FUTURE SCOPE

In our work, we built a fixed wing UAV and plotted the Air Quality data with geo-coordinates using our data fusion module. We tested the UAV with sufficient payload to carry the data fusion module. The Data Fusion module we built is very low-cost, with capability to perform spatiotemporal sensing of Air Quality levels. It is significantly cheaper than extremely expensive ground based Air Quality stations that often lack the capability to produce pollution data in real-time, and due to their very high costs are very scarcely distributed and cannot be deployed at scale.

We also integrated our Data Fusion module on a car to generate PM-2.5 data with it to show its capability to act as a low-cost mobile monitoring station that can be deployed at scale on public transportation systems in cities to get fine-grained real-time Air Quality data. This fine-grained data could be used to locate pollution hotspots in cities and very precisely predict future Air Quality levels. This could be used to better manage smart cities by restricting vehicle movement in areas which are predicted to have very high future Air Quality levels and permit only public transportation during that time in that region.

In the future flight tests, we will run the prototype using solar power and try to achieve perpetual flight using autonomous flight along with real-time Air Quality sensing capabilities. This will generate Air Quality with fine-granularity and at a very low cost which could be very valuable and cost-effective for smart cities, industrial areas, glaciers and stubble burning monitoring. The key advantage of such a system is its ability to generate Air Quality data by reaching areas that are often inaccessible to vehicles or ground based static sensors. One such very crucial application is for Stubble Burning Monitoring in India, which is the key source of pollution in Delhi region. Currently such Stubble Burning Monitoring is done using human land inspection and using satellite data, which are both ineffective due to lack of real-time data. Our prototype can be the right alternative to detect such Stubble Burning sites in real-time.

The biggest advantage of this system is the ability to cover almost all geographic locations, and thus we are not just restricted to areas covered by scarce static sensors or even by sensors integrated on vehicles. This way, we can locate pollution creating hotspots in any location, which is one of the most crucial aspect of reducing pollution levels. Our low cost data fusion module could be integrated to not just UAV, but other mobile sources as well, such as public buses, vehicles to generate Air Quality data in real-time and due to its very low cost, this system could be deployed at scale for smart cities. Although, there are many limitations as well, such as issues of data quality of these low cost air quality sensors. In order to run the system completely on solar power, there will be a lot of issues due to high temperature at flight altitude, that drastically reduces the solar cell performance. So, it will be important to work on these issues in future flight tests. Our future work will include comparing air quality data between our UAV and Quadcopters, using multiple sensors in our UAV and integrating a thermal camera to the data fusion module to get infrared signatures for detecting methane leakage from Oil & Gas industry, which is very harmful for ozone layer depletion and also detect fire sites from the UAV prototype.

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