A Consumer UAV-based Air Quality Monitoring System for Smart Cities

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***Abstract*—Growing concerns on air pollution in large cities urge the development of new smart cities technologies to monitor and improve air quality of the cities. Unmanned aerial vehicle (UAV) is getting attentions in air monitoring applications due to its high maneuverability in both horizontal and vertical dimensions to obtain high-spatial-resolution and near-surface vertical profiling of atmosphere pollution. Low cost micro-sensors add additional advantages to UAVs to offer numerous advantages for capturing the spatial and temporal variability of air pollutants. Despite all these exciting prospects, challenges need to be studied and addressed to exploit UAV technologies for air quality monitoring. This work designs and develops a consumer UAV-based air quality monitoring system with off-the-shelf consumer components. The design enables a UAV to carry multiple sensors to accomplish real-time monitoring of multiple air pollutants. Our prototype and experiments verify the feasibility of the system and show that it features a stable and high precision spatial-temporal platform for air sample collection.**

I. Introduction

Many people living in or near large cities are subject to poor air quality, which has been identified as a leading risk factor for global disease burden [1], [2]. In response to the growing concerns of air pollution, many cities have started exploring and deploying smart city technologies to measure and monitor air qualities [3], [4]. Industry has also been actively involved in developing such smart city technologies for air quality monitoring [5], [6]. Internet of Things (IoT), i.e. networks of connected air pollution sensors, are deployed around the cities to gather air quality data. The data is then analyzed to map areas of pollution and provided to citizens in these cities via web or apps. Providing air quality data to people in smart cities will enable them to make better and more informed choices of their daily activities and improve their life qualities. In expect, the air quality data will further help identify air pollutants and their sources, clean the air, and reduce people's exposure to harmful air pollutants.

The traditional monitoring practices [7], [8] are insufficient for reliable evaluation of public health risk, identifying emission sources, or implementing effective pollution control strategies. Latest IoT solutions [9] need to deploy massive sensors on city infrastructures. But, because sensors are fixed, they are only able to capture data with low spatial resolutions and cannot easily track the change of air pollution in the spacial dimension. Further, vertical atmospheric measurements are in critical need for air pollution forecasting and evaluation, in particular, in mega-cities with high rise buildings. Capturing the spatial and temporal variability of aerosol particles and gases between the surface and 300m is currently limited by the fixed sampling platforms. This situation significantly limits the understanding and management of air pollution, and brings increasing needs for on-site fast analysis of field samples.

Unmanned aerial vehicle (UAV) is becoming an attractive experimental platform for high-spatial-resolution, near-surface vertical profiling of atmospheric pollution in recent years [10], [11]. Recent advancements in consumer UAV technology present a low-cost solution for sampling the lower troposphere due to their abilities to maneuvers in both the horizontal and vertical dimensions and to hold a fixed position in air even under high-wind conditions. Mobile real-time low cost commercial micro-sensors equipped with new technologies of consumer UAVs offer numerous advantages for capturing the spatial and temporal variability of air pollutants and provide the ability to measure important air pollutants with high sensitivities and temporal resolutions.

While the potential of UAVs for air quality monitoring is promising, challenges still need to be addressed. These challenges are not only technological. Significant gaps exist in the real-world monitoring with the reference methods.

- *Multiple air pollutants.* Air pollutants are present as mixtures in all the air environments. Both the scientific community and regulatory agencies have been shifting from the traditional single-pollutant approach toward a multi-pollutant approach to quantify the health consequences of air pollution mixtures. Current applications mostly focus on particles, ignoring many other pollutants of concern, e.g., volatile organic compounds (VOCs).
- *Energy efficiency and flight time.* A typical consumer UAV in the price range of $500 to $2000 can fly for about 15 minutes to 30 minutes on one fully charged battery. Carrying additional devices may reduce the UAV flight time, because the on-board devices add weights to the UAV and the devices themselves consume electricity. A typical USB-powered micro-controller device consumes the power in the range of 1W to 10W. It is necessary for use to study and find a design with hardware and software to reduce the weight and the energy consumption of the UAV system.
- *Synchronization of monitoring sensor data and GPS data.* For real-time monitoring and geo-spatial data modeling,

we need to synchronize air pollutant data and GPS data, because they come from the air pollution sensor and the UAV separately. The internal clocks of the sensor and the UAV are not synchronized at all. Worse, they do not have built-in ability to implement network timing protocols. Rather than synchronizing the devices, we study and develop mechanisms to produce synchronized data within an error tolerance.

- *Safety and restrictions in city.* Importantly, UAV's flight paths need safe air space to avoid many obstacles in a city environment, such as buildings, lights, power distribution lines, trees, no fly zones and so on. In addition, UAVs cannot be deployed without restrictions. Under current aviation safety operating regulations, restrictions are placed on their use in commercial, research and private applications.

To address these challenges, we design and develop a consumer UAV-based air monitoring system. Rather than designing a customized UAV system, we target building a system with all off-the-shelf consumer components, including both hardware and software. Our contribution is a modular design that enables a consumer UAV platform to carry multiple sensors and be capable of real-time monitoring multiple air pollutants. This UAV system features a stable and high precision spatial-temporal platform for air sample collection. We also test the feasibility and capability of current consumer UAVs for the air quality monitoring applications and deploy the system in air pollution research, such as roadside air pollution profiling and emergency monitoring for air pollution episodes.

The rest of the paper include the following sections. We first discuss the design of the system in Section II. Then, we show a prototype of the UAV system in Section III. We present our field tests and experiments in Section IV. The related works on recent technologies for air quality monitoring are summarized in Section V. Finally, we conclude the paper in Section VI.

II. Design

To address the aforementioned challenges, we design a UAV system as illustrated in Figure 1. Since we use off-the-shelf products, our work is mainly focused on developing software components that synergize the existing products. Figure 1 shows the software components that are existing (in white boxes) and need to be developed (in gray boxes) in the system.

A. UAV System

A UAV system typically consists of the UAV itself, a ground station, and a few on-board gadgets (such as first person view camera). In many applications, a UAV is simply used as a carrying platform and does not intervene the operations of the on-board gadgets. The controls of the UAV and the gadgets are often separated as well. For air quality monitoring, the UAV must function beyond a simple platform that carries multiple air pollutant sensors. It is more important for the UAV to integrate the data from all on-board sensors and tag the data with geo-location information in real time. Hence, a modular

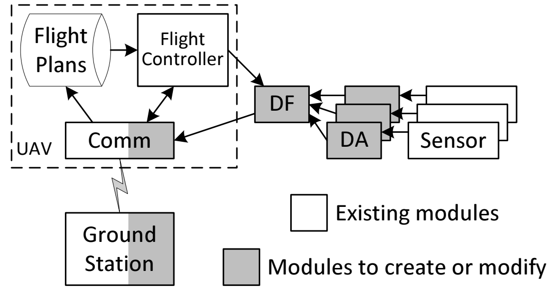


Fig. 1. Modular Design of A UAV System with Multiple Air Pollutant Sensors

design is highly desired to build a UAV system that can be easily deployed and managed in field uses.

In the modular design of Figure 1, the system has five modules: the UAV, the ground station, the sensors, the *data acquisition* modules (DA) and the *data fusion* module (DF). The operations of the UAV is usually controlled by the ground station. The UAV has a flight controller that directs the UAV to accomplish specific tasks according to a flight plan. The UAV reports its status to the ground station through its communication module. We adopt existing hardware and software of the UAV and the ground station.

The air pollutant sensors vary greatly in their working mechanisms. Each sensor is made for one specific air pollutant, such as particles or nitrogen dioxide, and produces different kinds of signals. The signals are in response to the concentrations of the pollutants and typically need to be calibrated before use. Therefore, we need to develop an individual data acquisition module that is bounded to each sensor to gather the signal and produces sensor-specific data for later processing in the data fusion module. Each data acquisition module runs its own program customized for each sensor. To save battery, the data acquisition module is built into a low cost and energy efficient micro-controller.

In the modular design, the sensors do not send data directly to the ground station. Rather, we use the data fusion module to aggregate data from the sensors. Then, we use the UAV's communication module to send the aggregated sensor data to the ground station. Thereby, we can share one communication channel with all sensors to reduce the energy and cost of the system. Depending on the data throughput required by the applications, we have two kinds of communication modules. One is the telemetry radio communication between the UAV and the ground station, which is suitable for low rate data communication but has a long distance coverage. For high throughput data, we deploy WiFi as the communication mechanism, although the WiFi communication distance is limited in comparison to the telemetry radio communication. Because the sensor data is transmitted to the ground station in real time, we also add new software components in the ground station to receive, store and analyze data.

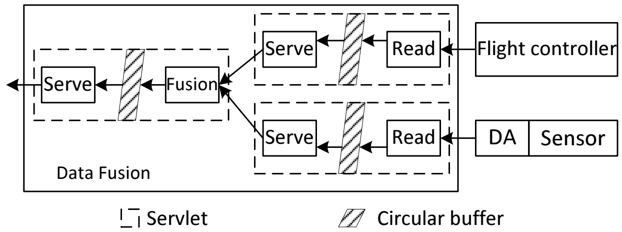


Fig. 2. Design of the Data Fusion Module

B. Data Fusion

The data fusion module is the core component in this modular design. It is responsible for integrating UAV's geo-location data, time data and sensor data. The UAV's flight controller provides the geo-location data to the data fusion module. The geo-location data often comes from a GPS device that the flight controller connects to. Because GPS data carries time information, the flight controller provides time data as well. Furthermore, the flight controller can provide the UAV's attitude data, such as orientation, velocity, acceleration and so on, to the data fusion module. Such information, accompanying the air pollutant data from the sensors, can show how the sensor data was collected by the UAV and will help us understand the context of the measurements.

Because all sensors and the flight controller provide data in different formats and at different rates, the data fusion module needs to accommodate these heterogeneous data sources. Furthermore, we may add or remove multiple different sensors in the UAV system. To support these needs, we adopt a servlet structure for the data fusion module as shown in Figure 2. The data fusion module runs several servlets to obtain data from the air pollutant sensors and the flight controller.

For each data source, a small *data source servlet* runs inside the data fusion module. Each data source servlet has a read thread and a serve thread. The read thread periodically reads from the data source at the rate specified by the data source. Then, the read thread stores the data into a circular buffer. Upon a request from the downstream fusion servlet, the serve thread reads the most recent data from the circular buffer pointed by the read thread. The serve thread can access the data in the circular buffer at a different rate than the read thread, which is necessary for the later fusion servlet to unify the data time from all the data sources.

A *fusion servlet* is placed at the downstream of the data source servlets. The fusion servlet has a similar structure as the data source servlets and includes a fusion thread and a serve thread. The fusion thread periodically reads from all data source servlets. But, different to the data source servlets, the reading rate of the fusion thread is specified by the air quality monitoring applications. The fusion thread stores data in a circular buffer for the serve thread to access.

Running these servlets decouples the fusion process from individual data sources, improves applicability of sensors, and enables quick and easy diagnostics on failed sensors. The data fusion module is implemented in a UAV's companion computer. With this modular design, we are able to use a variety of consumer UAVs to carry air pollutant sensors and obtain spatial-temporal data in real time.

Fig. 3. Prototype of the UAV-based Air Monitoring System

C. Data Format and Interface

Because all sensors produce different kinds of data in their formats and interfaces, unifying data specifics is another important aspect in the design. All data source servlets read raw data from the data sources in their specific data formats. Then, the data source servlets convert the raw data into the *packed binary data* format, which is concise and compatible to all programs. The fusion servlet processes and provides data in the packed binary data format as well.

We also include a few different types of data interfaces between the modules in the system. Because many consumer UAVs have USB interfaces and run with some variant of Linux, we build a few common data interfaces into the data acquisition module and the data fusion module, such as serial RS232, USB communications device class (CDC) or human interface device class (HID), to accommodate most UAVs.

III. PROTOTYPE

We build a prototype of the UAV system as shown in Figure 3 to test its feasibility and perform some preliminary experiments on air quality monitoring. The prototype is composed of three major components: two air pollutant sensors, a UAV, and a data fusion module.

A. Sensors and Data Acquisition Modules

For testing purpose, we use particle matter (PM) and nitrogen oxide (NO2) sensors (Alphasense, Essex, UK). Table I lists these sensors and their functions. They are both light weight and compact sensors and suitable to be carried on a UAV. These sensors have been tested by the US EPA's Office of Research and Development (ORD), and are used in their Cityspace project, in which 20 sensors are deployed in Memphis.

The PM sensor OPC-N2 has a built-in data acquisition module. It transfers data through a USB emulated serial port to external devices. The sampling period is set at 1.5 seconds per sample, but can be adjusted in the range of 1 second to 30 seconds per sample. Each sample contains 62 Bytes of data.

TABLE I
AIR POLLUTANT SENSORS

Pollutant	Model	Function
Particle	OPC-N2	This sensor measures the concentrations of PM1, PM2.5, and PM10. It counts particles optically to measure PM concentrations.
Nitrogen Dioxide	NO2-B43F	This sensor is a 4-Electrode NO2 gas sensors. It produces current signals proportional to the concentration of NO2.

The NO2 sensor NO2-B43F only produces analog signals. Hence, we developed a data acquisition module that converts its analog signals to digital data. The sampling period is set at 0.25 seconds per sample, but can be adjusted in the range of 0.01 seconds to 100 seconds per sample. Each sample contains 8 Bytes of data. The data acquisition module transfers data through a USB emulated serial port as well.

B. UAV and Ground Station

We build the UAV using the S550 frame and the Pixhawk 2.1 flight controller. We adopt open source software for flight and mission control too.

1) Hardware: (i) S550 is a lightweight hexacopter frame. It is based on an upgraded design of DJI F550 hexacopter and has sufficient load space under the frame. (ii) Pixhawk 2.1 is the latest flight controller from the open hardware Pixhawk project in collaboration with 3D Robotics and Ardupilot group. It has a rich set of sensors, including GPS, magnet sensor, barometer and so on. With these sensors, it provides geo-location and attitude data in real time through serial ports to the on-board companion computer. The maximum load of the UAV (excluding UAV and battery) is above 1 kilogram, which is plentiful to carry all sensors.

2) Software: (i) We deploy Ardupilot version 3.4.6 as the UAV's autopilot software in its flight controller. Ardupilot is an open source autopilot software, designed and adopted for a variety of copters, planes, rovers and submarines. It has APIs to transmit UAV data and controlling commands. (ii) The ground station uses the open source QGroundControl version 3.3.2. It provides full flight control and mission planning for MAVLink enabled UAVs.

C. Data Fusion Module

Figure 4 shows that we use a NanoPI Neo Air board as the on-board companion computer to implement the data fusion module. The NanoPI Neo Air board is a low cost embedded computer, but has a powerful 1.2GHz quad-core CPU and 512MB memory. It has a built-in WiFi component and multiple USB ports and serial ports. We connect these ports to the data acquisition modules and the flight controller to obtain data. The NanoPI Neo Air board runs Armbian Linux and thus can import a vast pool of supporting tools and libraries. It is very suitable for developing and testing a variety of functions in

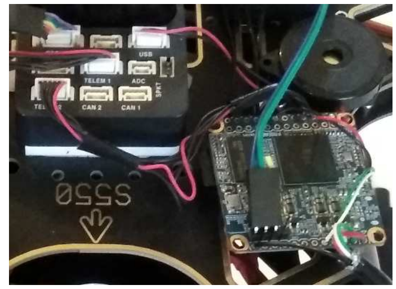


Fig. 4. Data Fusion Companion Computer

TABLE II
WEIGHTS OF UAV COMPONENTS

Components	Weight (g)
UAV (Frame, Motors, Propellers, and Flight Controller)	1711
Battery	1347
Sensors	132
Data Fusion Companion Computer	11

the data acquisition, fusion and communication modules for air monitoring applications.

Three data source servlet programs run in the on-board companion computer to collect data from the PM sensor, the NO2 sensor and the flight controller. The fusion servlet program runs as well to gather data from the three data source servlets and provide the aggregated data as a service to applications. The aggregated data includes the sensor data and the UAV data (such as GPS, attitude and so on) with synchronized time stamps.

For testing purposes, we develop two applications. One application simply saves all data into CSV files for offline data analysis. The other application runs as a web service to provide real-time air pollutant data and UAV data to smart phones and computers through WiFi.

IV. FIELD TESTS AND EXPERIMENTS

We conducted several field tests to collect preliminary flight data and sensor data for feasibility study. The goals of the tests are to find (i) if the sensors and the data fusion module consume a significant amount of battery power and (ii) if the accuracy of sensor data is influenced by the UAV.

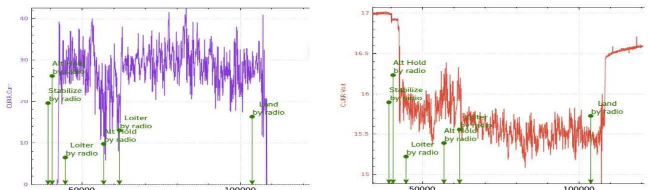
A. Settings

We set up the prototype UAV system with a 16200mAh battery. The maximum UAV flight time is around 30 minutes. The weights of the major components of the prototype are listed in Table II. The sensors and the companion computer are very light weight and only take 4.5% of the system.

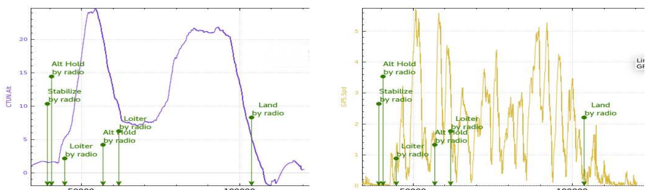
We tested the system along a local road with a speed limit of 60km/h in Austin/Travis County and a highway section in Memphis/Shelby County with a speed limit of 110km/h. The highway section has the highest traffic volume in the region with an Annual Average Daily Traffic (AADT) count of

(a) Local Road (b) Highway Section

Fig. 5. Traces of Road Side Tests

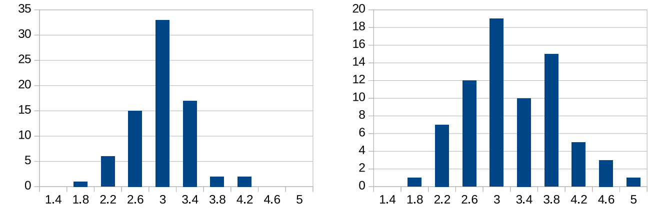


(a) Current (b) Voltage

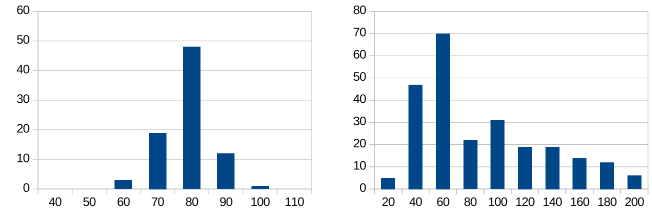


(c) Altitude (d) Speed

Fig. 6. Examples of the Flight Controller's Data



(a) PM2.5 Data On Ground (b) PM2.5 Data In Air



(c) NO2 Data On Ground (d) NO2 Data In Air

Fig. 7. Histograms of Sensor Readings Before and During Flights

TABLE III
STATISTICS OF SENSOR READINGS BEFORE AND DURING FLIGHTS

Data	Mean	Deviation
(a) PM2.5 on ground	2.78	0.43
(b) PM2.5 in air	3.03	0.66
(c) NO2 on ground	75.0	13.7
(d) NO2 in air	86.0	51.6

>150,000. The highway has near-road air monitoring stations as well for us to compare the measurements. For safety, all tests were 50 meters away from the roads. During the tests, the wind speed was below 5m/s.

As discussed in Section III-A, the sensors and the flight controller produce data at different rates. Using the servlet programs, we were able to obtain synchronized data from the data fusion module at the rate of one sample every two seconds. Figure 5 shows two examples of the test traces, which were based on the PM2.5 and GPS readings along the flight paths. Each sample has 62 Bytes and the data throughput is very low at 248bps.

B. Power Consumption

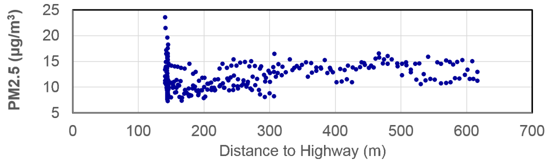
We measured the power consumption of the UAV system on ground and during flight. Figure 6 shows the flight data of a typical flight test. The flight data includes current, voltage, altitude and speed. The data was produced by the flight controller.

When the UAV was in air, the consumed current reached about 30Amp regardless its maneuvers and speed. In contrast, when the UAV was on ground, the consumed current was only about 1Amp. Because the battery voltage is around 16V, the power consumption was about 480W during flight but only 16W on ground. We also measured the power consumption of the sensors and the companion computer. They consumed about 5W in total, which is almost negligible to the UAV's power consumption. Hence, carrying the air pollutant sensors on the UAV does not degrade the flight time and operations of the UAV in our prototype.

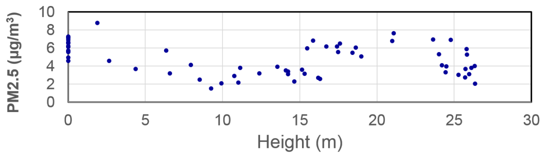
C. Air Pollutant Data Accuracy

The air pollutant sensors are designed and manufactured mostly for use in a stable environment, for example, installed onto a post or used inside a lab. Many sensors are very sensitive to the changes in the environment. It is thus necessary to examine if the sensors may operate differently when being carried on a UAV. We conducted experiments to read data from the PM sensor and the NO2 sensor on the same location before and during a flight. Figure 7 shows the histograms of the data and compares the data before and during the flight. Table III shows the means and the standard deviations of the four sets of data.

When the UAV was on ground, both PM2.5 data and NO2 data show a normal distribution in Figures 7(a) and 7(c). The central points of the histograms are the means of the readings and the widths of the histogram are the deviations in the readings. When the UAV was in air, Figures 7(b) and 7(d) show that their histograms were changed during the flight. Table III shows that both means and deviations were changed to larger values. We observe that the histograms during flight are shifted to the right and are widened. Because NO2 data



(a) PM2.5 Data By Distance To Highway



(b) PM2.5 Data By Height

Fig. 8. Examples of Road Side Test Data

shows more changes than PM2.5 data, the NO2 sensor was more affected by the UAV.

We conducted further experiments to find the causes of such influences. We learned that the UAV consumes a very large current than the sensors and the data acquisition modules. Because we let the UAV and on-board devices share the same power source, the ripple in UAV's current produced a significant noise into the sensors and the data acquisition modules, which resulted in the changes of sensor readings. Because the PM sensor uses an optical mechanism and has a built-in data acquisition module, it is more noise-resistant than the NO2 sensor.

Since the PM sensor was less affected by the UAV operation, we further compared the PM2.5 data with the data obtained from near-road particle concentration stations deployed by EPA. As shown in Figure 5(b), we let the UAV fly perpendicularly to the high way so that we can measure PM2.5 by distance to the highway. Figure 8 shows the PM2.5 data by distance and by height. The data matches the data obtained from the near-road stations, and no clear concentration gradient was observed near sources that emitted fine particles in our experiments.

V. Related Works

The UAV has been an attractive experimental platform for high-spatial-resolution, near-surface vertical profiling of atmospheric pollution in recent years [10], [11]. Previous technologies [7], [8] used balloons, aircraft and satellite remote sensing which are unmaneuverable or expensive. Recent advancements in UAV technology present an attractive, low-cost alternative for sampling the lower troposphere due to their ability to translate in both the horizontal and vertical dimensions and to hold a fixed position in the atmosphere even under high-wind conditions. An extensive literature review [12] only identified a small number of air pollution studies that utilized UAVs to measure single air pollutants with a focus on particulate matters, carbon dioxide, methane and ozone. This relatively small number of works show that the field is still in its early stages of development.

VI. Conclusion and Future Work

In this work, we designed a consumer UAV-based air quality monitoring system. The modular design enables the system to carry multiple different air pollutant sensors and integrate the data from all the on-board sensors with geo-location information in real time. Our preliminary field tests with the prototype show that the on-board devices did not affect the UAV's power consumption and flight time. However, the UAV operations influence the sensor readings to some extent due to the electronic interference from the UAV. Our future work will include the investigation of how to shield on-board sensors from UAV's electronic interference and the development of area coverage air monitoring UAV flight missions.

Acknowledgment

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