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Research article

Autonomous monitoring, analysis, and countering of air pollution using environmental drones

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ABSTRACT

The effect of air pollution on the environment, economic and health of the people in the affected countries cannot be overemphasized. This paper investigates large scale air pollution elimination to remove pollutants that are already in existence in the environment. This method involves the use of Environmental Drones (E-drones) to autonomously monitor the air quality at a specific location. The E-drone flies up to a predetermined height (Ealtitude) every hour, measures the air pollutants at that location, implements on-board pollution abatement solutions for pollutants above the recommended threshold, and then flies back down to its location on the ground. The advantages of this system is its ability to measure air pollution concentration of CO_2, CO, NH_3, SO_2, PM, O_3 and NO_2, detect when they are too high, and implement on-board pollution abatement solutions as needed. This system's novelty lies in the fact that it not only detects when there is excessive pollution, but it also automatically deals with and abates the detected air pollution above earth. When multiple E-drones are used in different locations, a custom software generates an Air Quality Health Index (AQHI) map of the region that can be used for present and long-term environmental analysis.

1. Introduction

The effect of air pollution on the environment, economic and health of the people in the affected countries cannot be overemphasized (Anderson et al., 2012; Anenberg et al., 2010; Jian et al., 2016; Krall et al., 2013; Schwartz et al., 2017; Tao et al., 2011; www.ec.gc.ca). Some of the major air pollutants are ozone (O_3), particulate matter (PM), nitrogen dioxide (NO_2), carbon dioxide (CO_2), sulfur dioxide (SO_2), carbon monoxide (CO). Some of these pollutants occur naturally in the environment and some are generated through man-made activities.

PM pollution is a portion of air pollution that is made up of extremely small particles and liquid droplets containing acids, organic chemicals, metals, and soil or dust particles. Exposure to ground level ozone can lead to respiratory symptoms, and airway inflammation, lung epithelial damage and decrease in mucociliary clearance (www.ec.gc.ca; Lippmann, 1989; Gryparis et al., 2014). A high concentration of NO_2 can irritate airways in the respiratory system, and can aggravate and cause the development of respiratory diseases, particularly asthma (www.epa.gov; Latza et al., 2009). Some of the effects of carbon monoxide pollution include fatigue, decreased oxygen-carrying capacity, impaired perfusion from hypoxic cardiac function, and cellular hypoxia (Abelsohn et al., 2002). A high concentration of CO_2 is partly responsible for global warming, and it reduces the fertility of marine animals (Bradshaw, 2007). In humans, CO_2 pollution can cause cardiac arrhythmias and seizures, severe acidosis and anoxia (Rice, 2004). Exposure to ammonia (NH_3) can cause immediate burning of the nose, throat and respiratory tract, bronchiolar and alveolar edema, airway destruction, and respiratory distress or failure (www.ec.gc.ca). Air pollution also has a detrimental effect on climate and agricultural crops (Settele et al., 2014).

Many countries have standardized methods for reporting the level of air pollution. In Canada, the Air Quality Health Index (AQHI) is used to report the degree of pollution in different regions. Many approaches have been employed in countering the effects of air pollution. Land-use zoning and planning and infrastructure planning is used to isolate human activities that generate these air pollutants in certain regions. Pollution control devices either destroy contaminants or remove them from an exhaust stream before it is emitted into the environment. However, they cannot be used in cleaning an environment that has already been

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contaminated by these pollutants. This is because these devices require the pollutants to be gathered and contained before they can remove the pollutants. And presently, there is no known method to gather all the air pollutants in a city, province, or country, especially at high altitudes. Even if such could be accomplished, no known pollution control device can handle the removal of these pollutants on such a large scale. These techniques to combat and eliminate pollution are appropriate, but the unmanned aerial vehicle (UAV) technology has gained popularity over the years, and it has been introduced for air quality monitoring.

Drones have been investigated as a means to detect environmental air pollution (Altstadter et al., 2015; Brady et al., 2016; Chang et al., 2018; Chilinski et al., 2018; Corrigan et al., 2008; Lawrence and Balsley, 2013; Mayer et al., 2012; Ramana et al., 2007; Ramanathan 2006; Reuder et al., 2012; Smidi and Hofman, 2013; www.scmp.com; techrepublic.com; www.auav.com.au; www.nationaldrones.com.au; Villa et al., 2016; Vo et al., 2018; Watai et al., 2006). CO_2, CH_4, Particulate Matter (PM), NO_2, volatile organic compounds (VOCs), ozone, and water vapor concentrations have been successfully measured (Alvear et al., 2017; Babaan et al., 2018; Berman et al., 2012; Fladeland et al., 2011; Gu et al., 2018; Illingworth et al., 2014; Ruiz-Jimenez et al., 2019). UAV vision guided aerial-ground air quality sensing system, to monitor and forecast AQI distributions in spatial-temporal perspectives has been developed by Yang et al. (2019). Fine-grained air quality monitoring and forecasting is performed using the fusion of haze images taken by the UAV and the AQI data collected by an on-ground three-dimensional (3D) wireless sensor network (WSN) (Babaan et al., 2018). Malaver et al. (Malaver et al., 2011; Malaver et al., 2012; Malaver et al., 2015; Malaver et al., 2015b) explored the possibility of flying a solar UAV as part of solar powered wireless sensor network system (WNS) to monitor greenhouse gasses continuously, using solar energy to solve the power consumption issue that affects UAV payload and flight time capability (Villa et al., 2016). Multi-sensor data fusion is the process of combining observations from a number of different sensors to provide a robust and complete description of an environment, and has proven to be vital for UAV detection systems. (Alcarria et al., 2018; Baysal and Zhou, 2012; Yang et al., 2011).

Environmental Drones (E-drones), as defined by the authors, are programmed autonomous drones used for pollution monitoring, detection, and abatement at altitudes above ground level in a specific geographic region. E-drones produce Air Quality Health Index (AQHI) maps of covered regions for environmental data monitoring and long-term analysis. E-drones are the first aerial systems (especially drone-wise) designed to conduct aerial pollution abatement following successful pollution detection. This paper investigates the use of E-drones for air pollution detection and elimination to remove pollutants already in existence in the environment. This experiment is designed to test the hypothesis that E-drones can be used to conduct automated pollution detection and abatement.

2. Materials and methods

2.1. Materials

The Environmental drone is an aerial robotic system designed to automatically obtain relevant weather data, especially AQHI data, at a particular station or location. The E-drone has a base station at the location where environmental data is to be acquired. The base station consists of a compact solar panel with power connections running down the side to provide continuous power supply to the drone in between weather data acquisition.

- *Chassis*

The frame for the system needs to be durable, sturdy and have sufficient space to incorporate all sensors and modules. The chassis of the E-DRONE system was made from carbon fiber, extremely durable and light-weight, 550 mm × 550 mm in size and weighs about 460 g. Power supply was provided by an 11.1 V 3200 mAh Lithium Polymer battery. After mounting all the required accessories, sensors and modules, the total weight of the system was approximately 1.5 kg.

- *Brushless Motors*

Four brushless motors were used to convert the battery electrical power to mechanical power to spin the propellers for system flight. Each motor was mounted on a quadcopter arm and fastened with screws and nuts.

- *Propellers*

Four propellers (a clockwise pair and anticlockwise pair), 10 × 5 inches, were mounted on the four brushless motors. Care was taken to ensure the propellers were securely fastened to the motors to prevent them from slipping off mid-flight.

- *Electronic Speed Controllers (ESC)*

Electronic Speed Controllers (ESC) are used for varying the speed of electric motors. Four ESCs were connected to the onboard Lithium Polymer battery. Each ESC was connected to a motor. By varying the values sent to each ESC, the E-DRONE system can be autonomously.

- *Development Board*

The development board used to program the E-DRONE system to perform autonomous pipeline surveillance was the Arduino Uno Rev 3.

- *Gyrometer*

The GY-521 Gyrometer was used to stabilize the E-drone system during take-off, aerial patrol of the crude oil pipeline and landing. It is capable of providing acceleration, orientation, and gyrometric data for the E-DRONE system in 3-axis.

- *Altitude Sensor*

The sensor used to determine the barometric altitude of the E-DRONE system was the BMP085. This was important because the system was autonomously programmed to fly to a certain altitude before commencing pipeline surveillance.

- *Global Positioning System* (*GPS*)

The GPS is used in locating the position of the E-Drone.

- *Xbee*

A pair of Xbee Pro 900HP wireless modules helps establish wireless communication between E-DRONE system and host PC at remote base station. With a 2.1 dB antenna, this module can establish a wireless connection between the E-drone system and host PC up to a distance of 15.5 km. With a high gain antenna, this distance increases to 45 km. This wireless connection is used to relay the GPS location and images of detected oil spill sites to the remote PC of the surveillance team. The Xbee is mounted on an Xbee shield, which is stacked on the Arduino Uno (see Figure 1).

- *Ultrasound Sensor*

The HC-SRO4 is an ultrasound sensor used for obstacle detection and avoidance and was mounted on the front of the E-DRONE system. If the system detects an obstacle less than 35 cm in front of it during flight, it

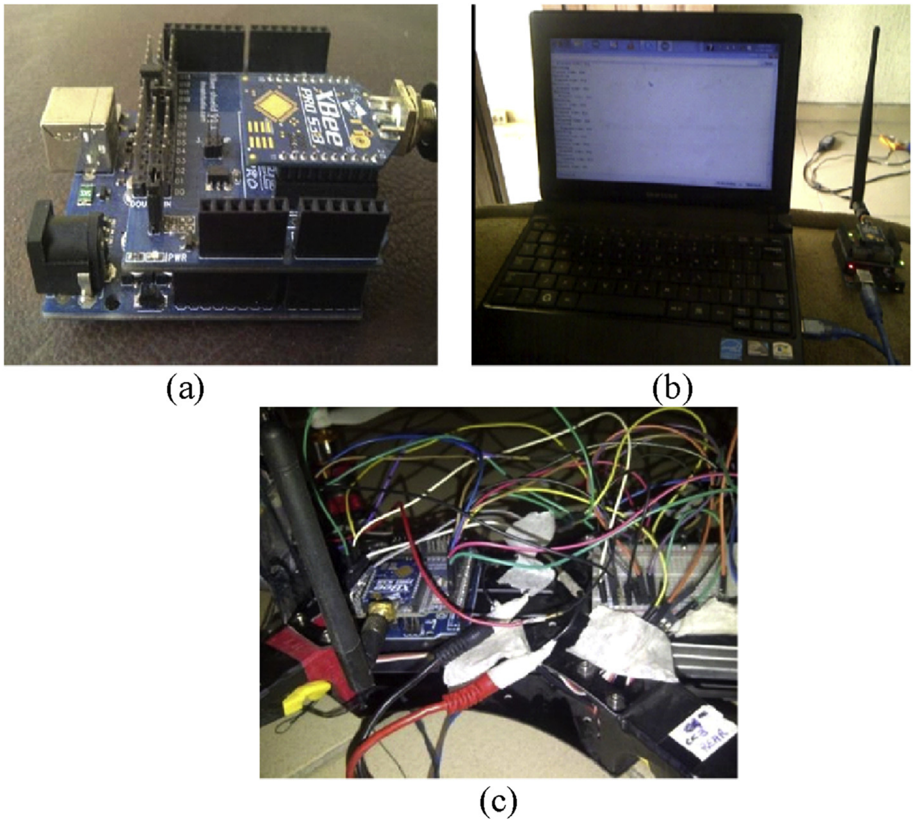

Figure 1. (a) Xbee Pro 900HP on Xbee Shield stacked on Arduino Uno. (b) First Xbee connected to host PC at remote station. (c) Second Xbee mounted in E-DRONE system.

takes a detour route to avoid the object before continuing along its patrol route.

- *Air Pollution Sensors*

The primary method by which the E-drone measures the air pollutants is by use of gas sensors such as the one shown in Figure 2. Each of the air pollutant concentrations are measured by individual and different sensors. Figure 3 shows the pictures of the gas sensors used to take measurements of CO_2, CO, NH_3, SO_2, PM, O_3 and NO_2 in the E-drone system. Calibration for each sensor will be done weekly. The E-drone system keeps track of time automatically and sends recalibration commands to the sensors once a week in between weather data acquisition. Air pollutant sensors are designed and manufactured mostly for use in a stable environment (e.g. stationary on the ground), and are extremely sensitive to changes in the environment (Gu et al., 2018). Improvements will need to be made to shield the onboard air pollution sensors from the UAV's electronic interference to ensure accurate AQHI measurements.

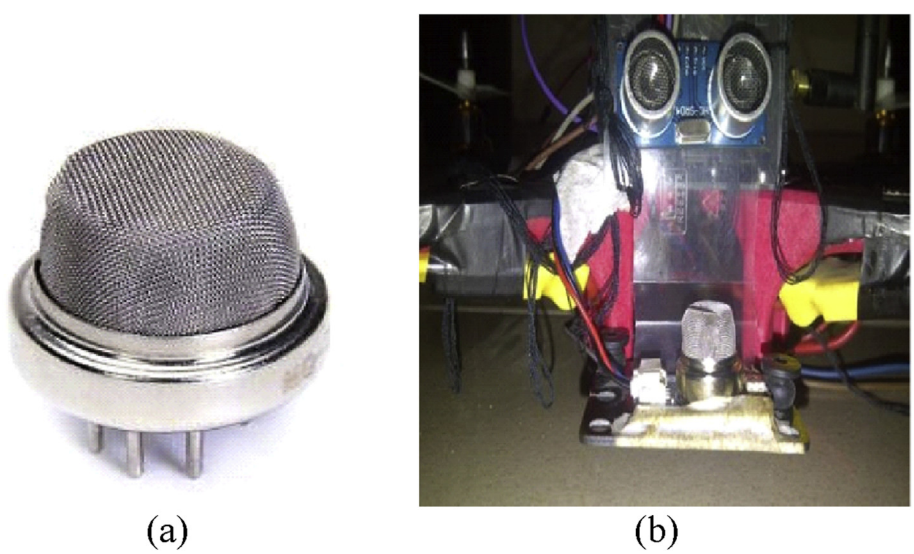

Figure 2. (a) Gas sensor. (b) Sensor mounted in front of E-DRONE system.

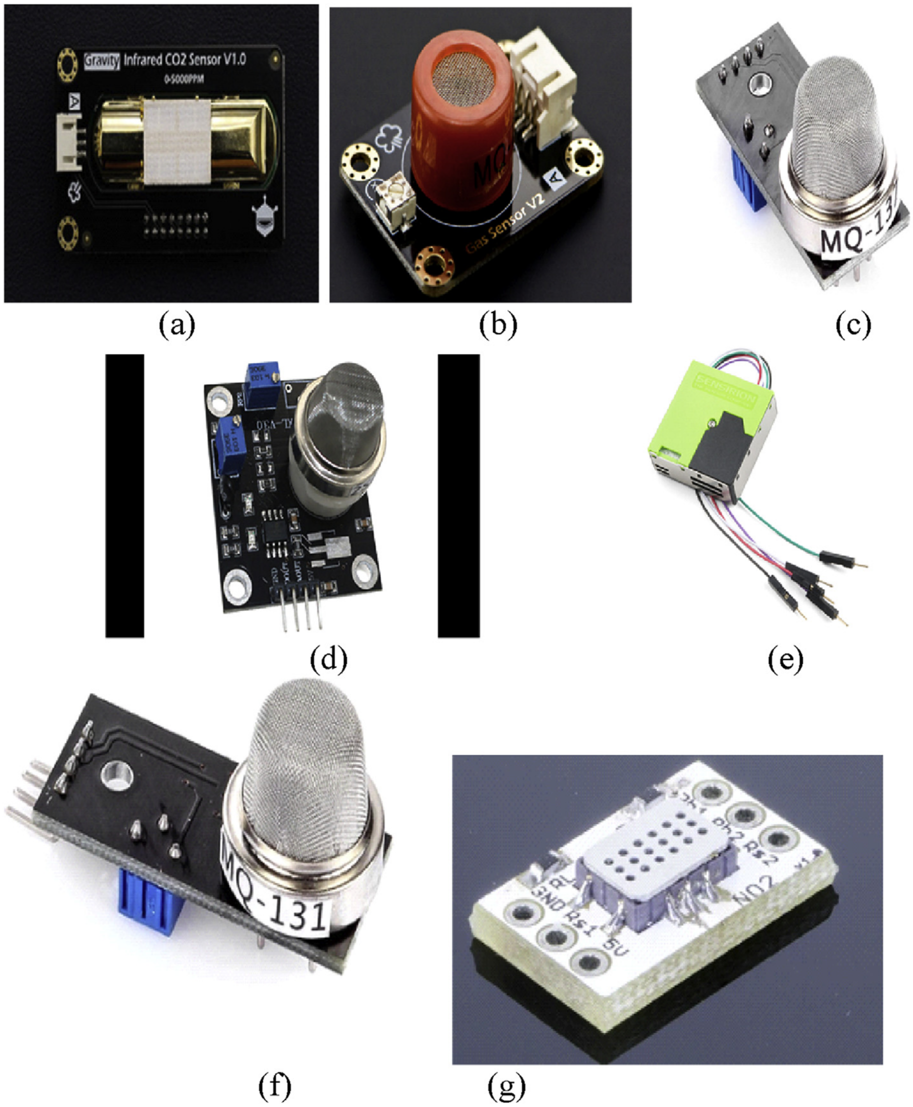

Figure 3. Gas Sensors used in the E-Drone System. (a) CO 2 Sensor. (b) CO Sensor. (c) NH3 sensor. (d) SO2 sensor. (e) PM sensor. (f) O3 sensor. (g) NO2 sensor.

- *Pollution Abatement*

There are several abatement options for NO_2. One method uses a scrubbing solution containing hydrogen peroxide (H_2O_2) and nitric acid (HNO_3). Another employs a scrubbing solution of sodium hydroxide (NaOH) and H_2O_2 (www.h2o2.com). The onboard abatement solution for NO_2 was a scrubbing solution comprising of H_2O_2 and HNO_3, with a Volume of 500 ml. The pollution abatement option for NO_2 on the E-drone was a scrubbing solution comprising of H_2O_2 and HNO_3. Onboard abatement solution tests have not yet been implemented for the other air pollutants. Future work includes the integration of on-board pollution abatement solutions for O_3, C O, CO_2, SO_2, NH_3, and PM.

A 500 ml capacity tank was used to hold the abatement solution for NO_2. A motor coupled with pump was used to pressurize solution solution and then to discharge it in a spray of droplets by means of a nozzle. This technique has been used by Yallapa (Yallappa et al., 2017) and Hoffmann (Hoffmann et al., 2009). In its simplest application, H_2O_2 and HNO_3 are used to scrub both nitric oxide (NO) and nitrogen dioxide (NO_2) The reactions are rapid at moderate temperatures (30–80 °C), with about 1.7 and 0.37 lbs hydrogen peroxide required per lb NO and NO_2, respectively (www.h2o2.com). The chemistry controlling the process is outlined below:

$$3NO_2 + H_2O \Leftrightarrow 2HNO_3 + NO \tag{1}$$

$$2NO + HNO_3 + H_2O \rightarrow 3HNO_2 \tag{2}$$

$$HNO_2 + H_2O_2 \rightarrow HNO_3 + H_2O \tag{3}$$

The health risk involved in spraying this abatement solution is the resulting increase in acid-forming compounds in the air, which would in turn increase the acidity of rain in that region. When rainwater becomes too acidic, it could kill freshwater fish in riverine areas and damage crops in farmland regions. It could also erode buildings and monuments. The net weight of the on-board 500 ml NO_2 abatement solution was approximately 1 pound or 0.45 kg. At this stage, the design of the E-drone system allows for the drone to be able to carry 500 m l of abatement solutions for each of the seven air pollutants being measured by the system. Assuming 500 ml abatement solutions for for O_3, CO, CO_2, SO_2, NH_3, and PM each were to be carried aboard the E-drone this would result in an additional payload of 6 pounds or 2.73 kg. While this additional payload can be accommodated by the current E-drone system, it would limit the $E_{altitude}$ height at which the environmental data can be measured.

- *AQHI Maps*

The AQHI maps were generated using a custom designed software owned by CANADA INC, New Brunswick Canada, and RACETT NIGERIA

LTD., Zone 8, Abuja, Nigeria. AQHI data measured by the E-drone was sent to a computer at the monitoring station on the ground. The map of the region to be environmentally monitored was divided into the sub-regions by the software, based on the number of E-drones available to perform regional data acquisition and the physical location of each E-drone. In this experiment, the region monitored was New Brunswick, Canada, and software map of New Brunswick was divided into 5 sub-regions, as the input to the software indicated that there were five (5) E-drones available to monitor the region. Once the measured AQHI data was sent to the computer in the monitoring station, the software extracted the data from the computer and using a scale based on the received values, plotted the AQHI values of the various pollutants over the map of New Brunswick. AQI maps for O_3, NO_2, SO_2, CO, and HCHO, are available online (http://db.eurad.uni-koeln.de/de/vorhersage/eurad-im.php), but these maps are restricted to the largest cities in the region of Europe only, and do not discuss the method used in obtaining the daily AQI data.

- *Solar Panel Base Charger*

The E-drone was powered by an 11.1 V 3200 mAh Lithium Polymer battery. This provided a flight time of approximately 15 min and was sufficient to power for the drone to acquire environmental data at the test $E_{altitude}$ height of 100 m. In order to recharge the battery and ensure continuous environmental monitoring, a solar base panel charger was designed for the E-drone. It consisted of a stationary solar power pack at the base location of the E-drone. In between environmental data acquisition, the 11.1 V 3200 mAh Lithium Polymer battery was recharged by the Solar Panel This ensures that full power is available for the drone to take off for another round of environmental data acquisition. In this manner, the E-drone has a self-charging system capable of continuous monitoring. The solar panel has an output power of 8W, an output voltage of over 18V, and an output current of 450 mA.

A sample of the aerial robotic system developed for the E-drone is shown in Figure 4.

2.2. Methods

The operation of a single E-drone is shown in Figure 5. The E-drone operates every hour (depending on the pollutant being measured). At the start of each hour, the drone checks it current battery charge level to determine if it has sufficient power for take-off. Each E-drone is equipped with a stationary solar power pack at the base for battery charging, in addition to an in-built battery supply to assist during night-time charging. These two batteries are contained within the Solar Panel Power Base Charger. Once the E-drone lands on the ground, it automatically connects to this base charger for automatic recharging of its batteries.

Figure 4. Sample aerial robotic system for the E-drone.

If the battery level is less than a predetermined threshold, the drone does not take off. Instead, it sends a text or an e-mail message to the monitoring station that environmental data cannot be acquired at that time.

If the battery level is above the predetermined threshold, power is supplied to the motors of the drone using the ESCs, causing the drone to lift up into the air. Using the altimeter, the drone flies up until it achieves the desired height, $E_{altitude}$, at which the environmental data can be measured. The $E_{altitude}$ selected is such that when pollution abatement options are implemented by the E-drone, the affected air and time of exposure to the abatement option is maximized. Once the drone reaches the $E_{altitude,}$ it hovers at this particular height while the environmental data is acquired using the onboard sensors. These data include the following: date and time of data acquisition, barometric pressure, temperature, humidity, wind speed and direction, precipitation, AQHI for O_3, PM, NO_2, CO_2, SO_2, CO, NH_3 and the maximum AQHI. The sensors are programmed to automatically recalibrate once a week in between weather data acquisition. For the E-drone, measured data from the O_3, PM, NO_2, CO_2, SO_2, CO, and NH_3 pollutant sensors were transmitted as a single data stream to the computer in the monitoring station on the ground through the Xbee. The E-drone system is a centralized system, with the computer at the monitoring station on the ground collecting the measured environmental data. However, each E-drone makes its own decision autonomously, as they are programmed to operate individually to cover specific geographic regions and areas.

After measuring and acquiring the environmental data mentioned above, the system conducts automated analysis on the data. The degree of pollution for each pollutant is classified using a customized automated algorithm, and the air pollutants that are above the recommended threshold set by Health Canada and Environment Canada are identified (www.ec.gc.ca). For those pollutants above the recommended threshold onboard pollution abatement solutions are implemented. When the Environmental Drone detects a pollutant concentration above its recommended level, it automatically implements and releases an on-board pollution abatement solution for that specific pollutant. The volume of pollution abatement solution released depends on the level of pollutants detected. This will ensure that the pollution concentration level is brought down to acceptable levels. These on-board abatement options will be used to alter measured high AQHI of pollutants and will be carried out at the $E_{altitude}$ to maximize the effective area and the length of time for AQHI correction.

The onboard pollution abatement options used by the E-drone will mainly be chemical processes to convert the pollutants at that altitude into harmless gasses and liquids. Presently, the E-drone is equipped with the on-board pollution abatement for NO_2 only. Future models will also be equipped with the on-board pollution abatements for O_3, PM, CO_2, SO_2, CO, and NH_3. The length of time the E-drone implements an abatement option will be determined by the measured AQHI for that particular pollutant. If there are no pollutants with AQHI above the predetermined threshold, the drone will descend back to the ground. If there are pollutants with AQHI above the predetermined threshold, the drone will descend back to the ground after implementing the appropriate solutions.

After descent, the E-drone transmits all the acquired data to the monitoring station through text message, Xbee, and the internet. The E-drone also transmits the necessary abatement implementation utilized, including length of time of implementation, and names and volumes of compounds used for each abatement solution implemented. The E-drone then waits for an hour before proceeding to obtain the required environmental data again. Each E-Drone will be equipped with a GPS shield so the exact location at which the drone takes its measurement will be known. Multiple E-Drones can be used to obtain environmental data and AQHI for different pollutants in different locations. After transmission of environmental data to the monitoring station, custom-designed software will be used to generate AQHI maps. These are maps that show the measured AQHI for different locations within a specific region, and the

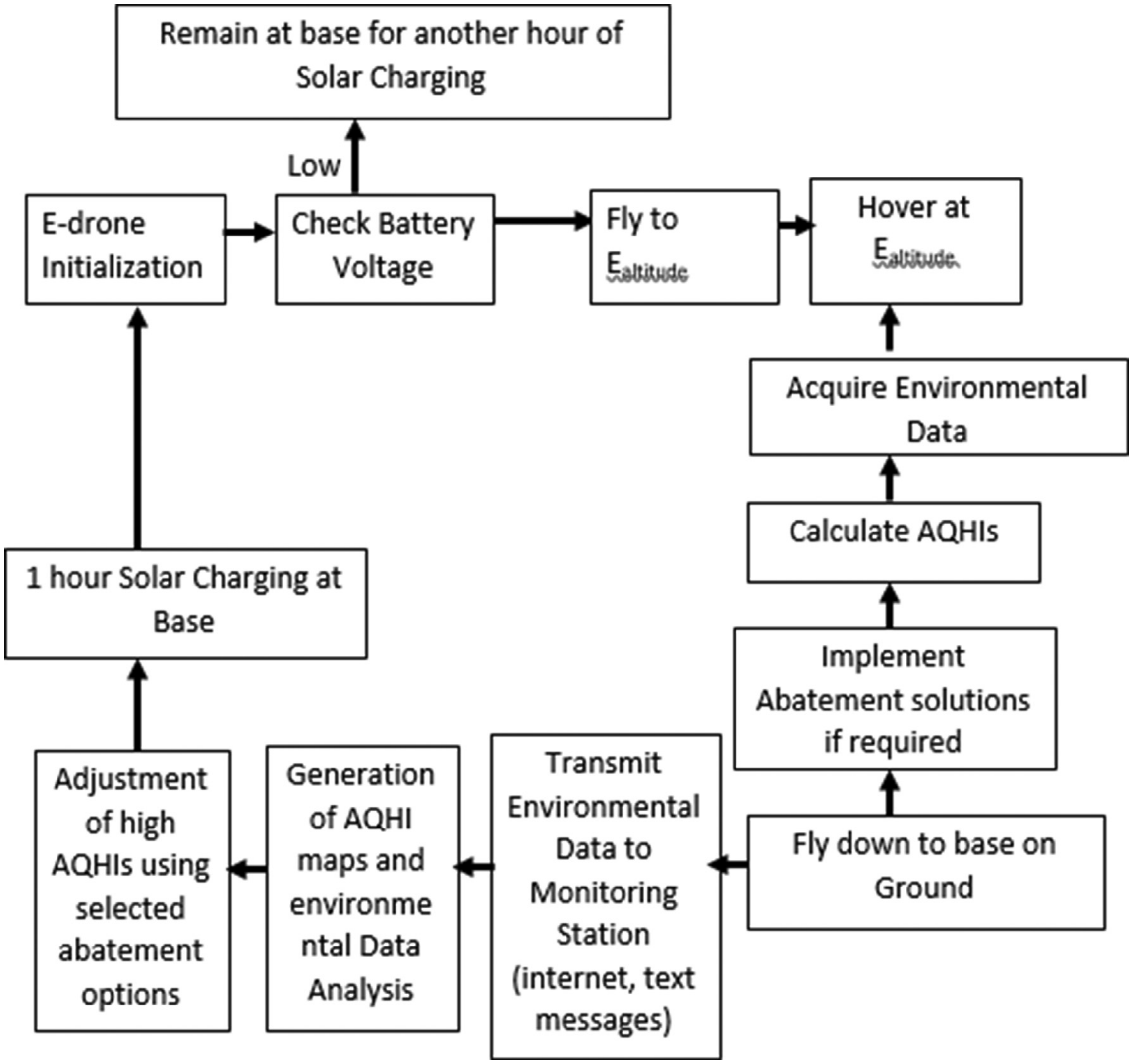

Figure 5. Schematic operation of a single E-drone.

measured AQHI for each location will be supplied by a single E-drone. For every air pollutant measured by the E-drones, a single AQHI map will be generated. Detailed environmental analysis (especially for air pollution) can then be conducted at the monitoring station using the generated AQHI maps.

3. Results

The E-drone's ability to measure the air pollutant concentrations of O_3, CO, CO_2, SO_2, NO_2, NH_3, and PM were tested and the sample data obtained is shown in Table 1.

The threshold value above which the implementation of the abatement solution for a particular pollutant will be triggered is already known and incorporated into the algorithm of the E-drone. The predetermined threshold was set to 8 μg/m^3. The E-drone was tested at five different locations to generate AQHI maps. The AQHI data acquired from the 5 locations are shown in Table 2. The data was obtained from test flights by the E-drone and have not been compared to any other data in published literature.

For this particular data acquired by the E-drone, the only air pollutant with a measured value above its predetermined threshold of 8 μg/m^3 was the NO_2, at Location 3. The onboard abatement solution for NO_2 was a 500 ml scrubbing solution comprising of H_2O_2 and HNO_3. The abatement

Table 1. Test Data from a single E-drone.

Date	April 30, 2017
Time	11:05 a.m.
Temperature	18 ± 2.2 °C
Humidity	82 ± 6%
Barometric Pressure	1006 ± 2 hPa
Precipitation	2 mm
Wind Speed	1.39 ± 0.4 m/s
Wind Direction	West
AQHI	
O_3	6.0 μg/m^3
PM (Smoke)	1.9 μg/m^3
NO_2	15 μg/m^3
NO_2(After Pollution Abatement)	14.2 μg/m^3
CO_2	5.5 μg/m^3
SO_2	2.2 μg/m^3
CO	0.9 μg/m^3
NH_3	0.1 μg/m^3
Maximum AQHI	15 μg/m^3

Table 2. Measured AQHI data by the E-drone.

	Location 1	Location 2	Location 3	Location 4	Location 5
	μg/m^3	μg/m^3	μg/m^3	μg/m^3	μg/m^3
O_3	2.8	0.7	6.0	2.5	1.2
PM (Smoke)	0.6	3.2	1.9	0.8	2.3
NO_2	7.2	1.5	15.0	3.8	0.4
NO_2 (After Abatement)	-	-	14.2	-	-
CO_2	7.7	6.2	5.5	3.4	4.4
SO_2	6.7	6.4	2.2	1.7	2.6
CO	0.3	1.1	0.9	1.4	1.2
NH_3	0.8	0.5	0.1	0.3	0.5

time was set to 15 min, as it was not yet known the volume of the abatement solution required to lower the AQHI of NO_2. The entire 500 ml was discharged at an $E_{altitude}$ of 100 m. The AQHI of the NO_2 was measured 45 min after the implementation of the abatement solution at Location 3, and it was found to be 14.2 μg/m^3. This showed a reduction of 0.8 μg/m^3. The AQHI reduction observed at Location 3 was performed at an $E_{altitude}$ of 100 m.

The AQHI maps were generated using a custom designed software owned, developed and patented by RACETT CANADA INC, New Brunswick, Canada, and RACETT NIGERIA LTD., Zone 8, FCT, Abuja, Nigeria (see Figure 6). The software automatically receives the environmental data from the drones within the specified region (in this case, New Brunswick, Canada) and then generates AQHI maps for each air pollutant. Human intervention is not required to generate these maps as the environmental drone sends its data to the computer with the software using its in-built GPS/GSM/GPRS shield, as well as the Xbee Pro Modules.

4. Discussion

Previous published work has demonstrated that drones can be used to acquire air pollution concentrations (Altstadter et al., 2015; Alvear et al., 2017; Babaan et al., 2018; Berman et al., 2012; Brady et al., 2016; Chang et al., 2018; Chilinski et al., 2018; Corrigan et al., 2008; Fladeland et al., 2011; Gu et al., 2018; Illingworth et al., 2014; Lawrence and Balsley, 2013; Mayer et al., 2012; Ramana et al., 2007; Ramanathan, 2006; Ruiz-Jimenez et al., 2019; Reuder et al., 2012; Smidi and Hofman, 2013; www.scmp.com; Villa et al., 2016; Vo et al., 2018; Watai et al., 2006). However, the ability of a drone to automatically detect when the concentration of a pollutant has exceeded the recommended threshold has not been reported. Furthermore, there are no previous studies demonstrating pollution abatement using drones for the data presented in the results section to be compared to. To our knowledge, this is the first attempt to utilize drones for automated pollution abatement.

For the data presented in Section 3, the threshold to commence the abatement solution for each pollutant was set to 8 μg/m^3. It should be noted that for practical application of the E-drone, the threshold for each pollutant will be different. For the data acquired by the E-drone, the only pollutant with a measured AQHI value above this threshold at 11:05 a.m. on April 30, 2017 is NO_2. Therefore, the only abatement solution implemented at 11:05 a.m. on April 30, 2017 was the scrubber solution of H_2O_2 and HNO_3. The authors are currently testing automated air suction and custom filters to reduce PM dust. Onboard abatement solution tests have not yet been tested for the other air pollutants. Future work includes the integration of on-board pollution abatement solutions for O_3, CO, CO_2, SO_2, NH_3, and PM.

The amount of time the abatement solution is implemented depends on the magnitude of the measured AQHI for that particular pollutant. The higher the value of the measured AQHI, the more time the solution will be implemented. For this particular instance, a measured AQHI of 15 μg/m^3 for NO_2 resulted in the abatement solution being applied for 15 min and 500 ml of the on-board pollution abatement solution for NO_2 was released at an $E_{altitude}$ of 100 m. Based on AQHI measurement acquired before and after abatement implementation, a reduction of 0.8 μg/m^3 was observed. This shows the possibility of using the E-drone for aerial pollution abatement and reduction. Based on our data, 500 ml of H_2O_2 and HNO_3 scrubber solution applied at 100 m resulted in an AQHI reduction of 0.8 μg/m^3 for NO_2. More tests will need to be conducted to determine how much volume of the NO_2 abatement solution is required to reduce the NO_2 AQHI per μg/m^3, and to determine the effective coverage area of such a reduction. Although the pollution abatement conducted in this paper was performed at 100 m, the effect of the $E_{altitude}$ on the AQHI reduction will need to be explored to find the optimum height at which abatement should be implemented. The health effects of the pollution abatement solution will also need to be quantified and characterized. The increase in acidity of rain as a result of the application of the pollution abatement solution will need to be investigated.

More work will need to be done to determine the optimum $E_{altitude}$, the effective coverage area, how much scrubber solution is required per μg/m^3 AQHI reduction, and the health risks of utilizing this abatement method. The $E_{altitude}$ at which the E-drone implements abatement solutions for pollutants is also very critical, because this altitude will have an impact on the effective area and the length of time for the AQHI adjustment and correction. Currently, the current range under consideration for the effective $E_{altitude}$ is between 500 m and 1,000 m above sea level.

The data obtained by the E-drone is used to generate the AQHI maps for each pollutant. In this particular case, we assumed 5 E-drones were operating in 5 different locations in New Brunswick (Location 1, Location 2, Location 3, Location 4, and Location 5). Each location covered a certain geographical area within the New Brunswick. The exact position of the E-drone is shown within each location in the AQHI map. Each AQHI map shows the concentration of the pollutant for the 5 locations. Table 1 shows the data acquired by the E-drone in Location 3, and Table 2 shows the data acquired by the E-drone in the five locations. In Figure 6a, the following AQHI measurements of O_3 were acquired by the drones in the 5 locations: 2.8 μg/m^3, 0.7 μg/m^3, 6.0 μg/m^3, 2.5 μg/m^3, and 1.2 μg/m^3. None of these values were above the abatement solution threshold of 8 μg/m^3 and so the drone did not implement any abatement solution for O_3. In Figure 6b, the following AQHI measurements for PM were acquired for the 5 locations respectively: 0.6 μg/m^3, 3.2 μg/m^3, 1.9 μg/m^3, 0.8 μg/m^3, and 2.3 μg/m^3. None of these values were above the abatement solution threshold of 8 μg/m^3 and so the drone did not implement any abatement solution for O_3.

In Figure 6c, the following AQHI measurements for NO_2 were acquired for the 5 locations respectively: 7.2 μg/m^3, 1.5 μg/m^3, 15 μg/m^3, 3.8 μg/m^3, and 0.4 μg/m^3. In Location 3, the E-drone reported a measured value greater than the 8 μg/m^3 threshold for NO_2. Therefore, the E-drone in Location 3 remained at the $E_{altitude}$ for an extra 15 min to implement the abatement solution for NO_2, before it descended back to the ground. The time interval between data acquisition was set to 1 h for each drone. If an E-drone has to implement an abatement solution, then the time interval between data acquisition is reduced accordingly so that the drones will still commence data acquisition at the same time. So in this particular case, after the E-drone in Location 3 returned back to its base station, the time interval before it took off to perform another round of environmental data acquisition was reduced to 45 min.

In Figure 6d, the following AQHI measurements for CO_2 were acquired for the 5 locations respectively: 7.7 μg/m^3, 6.2 μg/m^3, 5.5 μg/m^3, 3.4 μg/m^3, and 4.4 μg/m^3. In Figure 6e, the following AQHI measurements for SO_2 were acquired for the 5 locations respectively: 6.7 μg/m^3, 6.4 μg/m^3, 2.2 μg/m^3, 1.7 μg/m^3, and 2.6 μg/m^3. In Figure 6f, the following AQHI measurements for CO were acquired for the 5 locations respectively: 0.3 μg/m^3, 1.1 μg/m^3, 0.9 μg/m^3, 1.4 μg/m^3, and 1.2 μg/m^3. In Figure 6g, the following AQHI measurements for NH_3 were acquired for the 5 locations respectively: 0.8 μg/m^3, 0.5 μg/m^3, 0.1 μg/m^3,

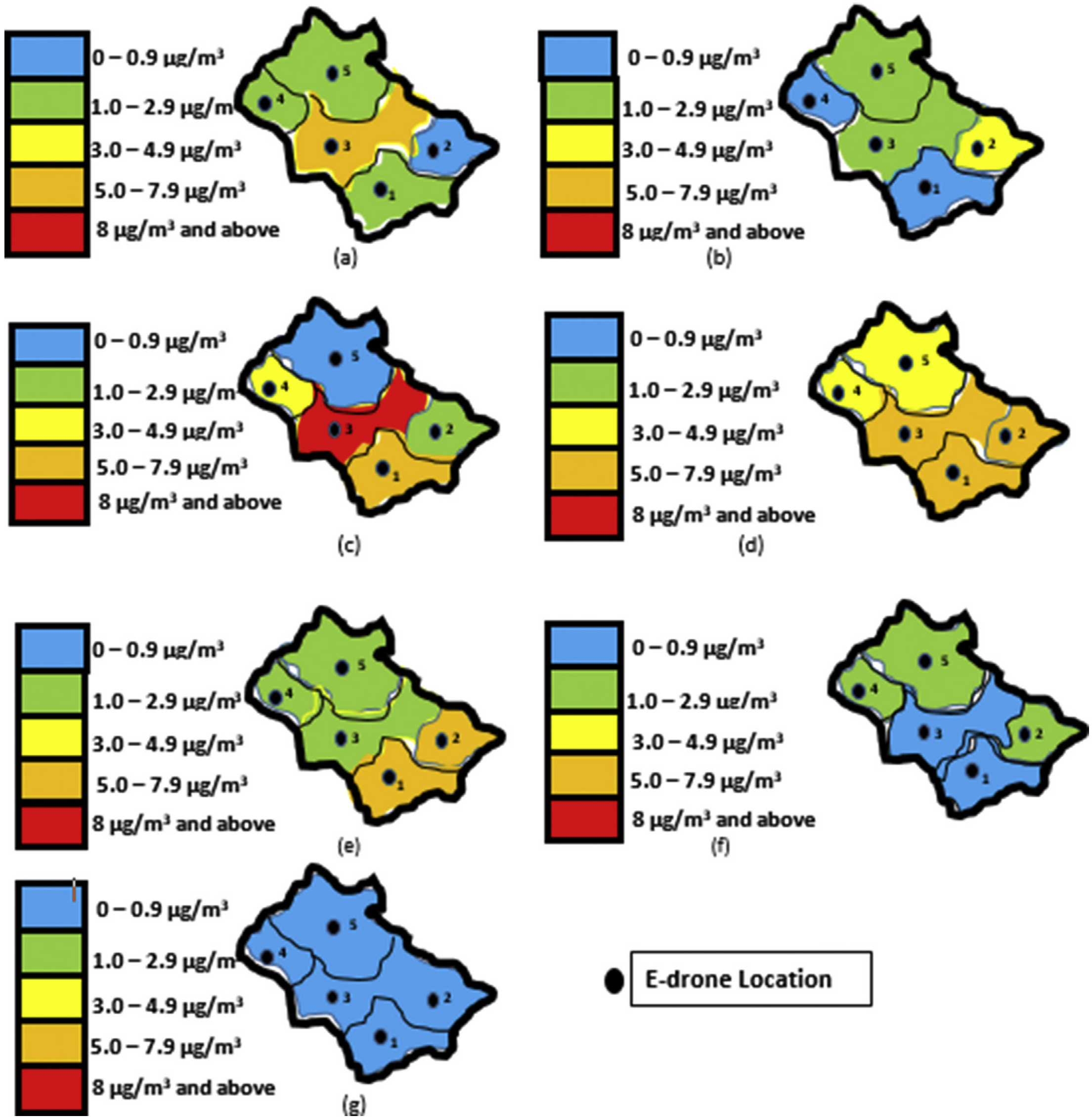

Figure 6. AQHI maps by E-drones in Ontario, New Brunswick at 11:05 p.m. April 30, 2017. (a) AQHI O_3. (b) AQHI PM. (c) AQHI NO_2. (d) AQHI CO_2. (e) AQHI SO_2. (f) AQHI CO. (g) AQHI NH_3.

0.3 μg/m^3, and 0.5 μg/m^3. None of these values were above the abatement solution threshold of 8 μg/m^3, and so the E-drone did not implement any abatement solutions for CO_2, SO_2, CO, and NH_3.

The Environmental Drone is equipped with 500 ml of pollution abatement solution for NO_2. Future work will include equipping the E-drone with six 500 ml pollution abatement solutions for each of the other six air pollutants for implementation in cases of excessive air pollution. Additional amounts of the pollution abatement solutions will also be incorporated into the ground solar panel base charger for the E-drone. Using this, the drone can conduct environmental pollution removal within a specific region, the range of which will be determined experimentally (e.g. 500 m^2 coverage area). By utilizing multiple drones for wider regions (e.g. 10 drones for 5,000 m^3 coverage area), effective removal can be done on a large scale and with great efficiency. 500 ml of pollution abatement solution for NO_2 resulted in an AQHI reduction of 0.8 μg/m^3. The effective coverage area of the AQHI reduction will need to be determined before it can be unequivocally stated that small and lightweight abatement methods on a drone can reduce air pollutants substantially. The results from this on-board pollution abatement implementation for NO_2 shows potential and is promising, and warrants further investigation. Once the effective coverage area for AQHI reduction is determined, multiple E-drones can be utilized to expand the coverage area for pollution monitoring, detection, and abatement. The work presented in this paper will be greatly improved upon by the incorporation of pollution abatement solutions for the other six pollutants measured by the E-drone (O_3, CO, CO_2, SO_2, NH_3, and PM). Then, if the E-drone detects the pollution concentration for any of the 7 pollutants exceeds their recommended thresholds, the pollution abatement solution for those pollutants will be implemented one after the other. The E-drone system also enables the ability to check the effect of implement air pollution abatement, as it is designed to monitor and report the air pollution concentrations at a particular location every hour. So, the effect of implementing an onboard pollution abatement solution can be monitored and characterized hours and days after its application. Work will also be done to study, measure, characterize, and resolve any adverse issues that may occur due to the application of each abatement solution implemented by the E-drones.

Path planning refers to planning an optimal flight track for a UAV from a starting point to a target point to guarantee successful completion of mission while avoiding static and dynamic obstacles. Path planning

(Filippis et al., 2012; Yanmaza et al., 2017) is essential for UAVs to avoid obstacle collision. The E-drone was programmed to fly upwards in a straight trajectory to the predetermined $E_{altitude}$, conduct environmental pollution detection and abatement, and then to fly downwards in a straight trajectory back to the earth surface. No obstacles were encountered during the testing of the E-drone conducted in this paper. Although the E-drone is a mobile node in a Wireless Sensor Network (WSN), data transmission to the monitoring station is not performed until the drone is back at its base station on the ground. Because of this, the WSN between the E-drone system and the monitoring station can be considered to be a collection of fixed nodes connected in a wireless communication technology, rendering the effect of altitude on data transmission non-existent (Robles et al., 2017).

The E-drone offers a unique method to acquire a comprehensive set of environmental parameters at altitudes other systems are unable to harness. The author is presently unaware of any system capable of generating AQHI maps for cities, provinces, and countries for a wide variety of air pollutants and the E-drone possesses this capability. Moreover, most systems that acquire environmental data do not integrate abatement solutions into their functionality. The E-drone is the first system that will be capable of not only acquiring and measuring a wide range of environmental parameters, but will also be able to perform environmental data analysis and take appropriate action to rectify and eliminate the excessive air pollutants within its region of operation using specific abatement solutions.

The E-drone is designed to be able to correct air pollution that already exists in an environment. In addition to this, the E-drone can also be used to detect and correct air pollution as soon as it is released into that environment. Therefore, immediately after the installation of an E-drone, if there is any excessive air pollutants in the E-drone's region of operation, it will implement the abatement solution for that particular pollutant until the measured AQHI is lowered to an acceptable level. In such a case, the E-drone will be functioning in correction mode until the measured AQHI for every identified pollutant is below the determined threshold. Once this is achieved, then the E-drone will switch into the monitoring mode since the air pollution in its region of operation is now within acceptable limits. Once this occurs, then if a specific activity in that region generates additional pollution that causes the measured AQHI of any of those pollutants to exceed the threshold, it will be detected by the system quickly, and the source of that pollution can be readily identified.

The E-drone offers an effective means to autonomously measure and acquire environmental data, especially for air pollution, at altitudes that are inaccessible by other systems. Environmental data analysis is performed onboard and pollution abatement solutions can be implemented by the E-drone wherever the system detects the concentration of a pollutant is above a predetermined threshold. The generated AQHI maps for the various pollutants will be extremely useful for long-term environmental planning, maintenance, and conservation.

5. Conclusion

E-drones offer a new approach to large scale air pollution elimination that will be able to autonomously monitor and remove pollutants that are already in existence in the environment. This novel approach involves the use of drones to autonomously monitor the air quality at a specific location, detect the presence of any of these pollutants, and implement a suitable abatement option at a specific altitude to ensure these pollutants in the environmental are eliminated. The E-drone has been used to measure the pollution concentrations of O_3, CO, NO_2, CO_2, SO_2, NH_3, and PM. On-board pollution abatement was performed for NO_2, resulting in an AQHI reduction of 0.8 $\mu g/m^3$ for NO_2, Future work includes the integration and testing of on-board pollution abatement solutions for O_3, C O, CO_2, SO_2, NH_3, and PM. The conclusion of our experiment is that E-drones can be used to perform automated aerial pollution detection and abatement, although further tests need to be carried out to optimize the system.

Declarations

Author contribution statement

Godall Rohi, O'tega Ejofodomi & Godswill Ofualagba: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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References

Abelsohn, A., Sanborn, M.D., Jessiman, B.J., Weir, E., 2002. Identifying and managing adverse environmental health effects: 6. Carbon monoxide poisoning. CMAJ 166 (13), 1685–1690.

Alcarria, R., Bordel, B., Manso, M.A., Iturrioz, T., Pérez, M., 2018. Analyzing UAV-based remote sensing and WSN support for data fusion. In: International Conference on Information Theoretic Security, pp. 756–766.

Altstadter, B., Platis, A., Wehner, B., Scholtz, A., Wildmann, N., Hermann, M., Kathner, R., Baars, H., Bange, J., Lampert, A., 2015. ALADINA—an unmanned research aircraft for observing vertical and horizontal distributions of ultrafine particles within the atmospheric boundary layer. Atmos. Meas. Tech. 8, 1627–1639.

Alvear, O., Zema, N.R., Natalizio, E., Calafate, C.T., 2017. Using UAV-based systems to monitor air pollution in areas with poor accessibility. J. Adv. Transp. 1–14. Article ID 8204353, 2017.

Anderson, J.O., Thundiyil, J.G., Stolbach, A., 2012. Clearing the air: a review of the effects of particulate matter air pollution on human health A. J. Med. Toxicol. 8 (2), 166–175.

Anenberg, S.C., Horowitz, L.W., Tong, D.Q., 2010. An estimate of the global burden of anthropogenic ozone and fine particulate matter on premature human mortality using atmospheric modeling. Environ. Health Perspect. 118 (9), 1189–1195.

Babaan, J.B., Ballori, J.P., Tamondong, A.M., Ramos, R.V., Ostrea, P.M., 2018. Estimation of PM 2.5 vertical distribution using customized UAV and mobile sensors in BRGY, UP campus, Dilman, Quezon city. The international archives of the photogrammetry, remote sensing and spatial information sciences, volume XLII-4/W9, 2018. In: International Conference on Geomatics and Geospatial Technology,Kuala Lumpur, Malaysia, pp. 89–103.

Baysal, O., Zhou, G., 2012. UAV-based multi-sensor data fusion for time-critical disaster response.

Berman, E.S.F., Fladeland, M.L.J., Kolyer, R., Gupta, M., 2012. Greenhouse gas analyzer for measurements of carbon dioxide, methane, and water vapor aboard an unmanned aerial vehicle. Sens. Actuators B Chem. 169, 128–135.

Bradshaw, K., 2007. Discovering the effects of CO_2 levels on marine life and global climate, sound waves. U.S. Geol. Surv. Mon. Newsl.

Brady, J.M., Stokes, M.D., Bonnardel, J., Bertram, T.H., 2016. Characterization of a quadrotor unmanned aircraft system for aerosol-particle-concentration measurements. Environ. Sci. Technol. 50, 1376–1383.

Chang, C., Chang, C., Wang, J., Lin, M., Ou-Yang, C., Pan, H., Chen, Y., 2018. A study of atmospheric mixing of trace gases by aerial sampling with a multi-rotor drone. Atmos. Environ. 184, 254–261.

Chilinski, M.T., Markowicz, K.M., Kubicki, M., 2018. UAS as a support for atmospheric aerosols research: case study. Pure Appl. Geophys. 175, 3325–3342.

Corrigan, C.E., Roberts, G.C., Ramana, M.V., Kim, D., Ramanathan, V., 2008. Capturing vertical profiles of aerosols and black carbon over the Indian Ocean using autonomous unmanned aerial vehicles. Atmos. Chem. Phys. 8, 737–747.

Filippis, L.D., Guglieri, G., Quagliotti, F., 2012. Path planning strategies for UAVS in 3D environment. J. Intell. Robot. Syst.

Fladeland, M., Sumich, M., Lobitz, B., Kolyer, R., Herlth, D., Berthold, R., McKinnon, D., Monforton, L., Brass, J., Bland, G., 2011. The nasa sierra science demonstration programme and the role of small-medium unmanned aircraft for earth science investigations. Geocarto Int. 26, 157–163.

Gryparis, A., Forsberg, B., Katsouyanni, K., Analitis, A., Touloumi, G., Schwartz, J., Samoli, E., Medina, S., Anderson, H.R., Niciu, E.M., Wichmann, H.E., Kriz, B., Kosnik, M., Skorkovsky, J., Vonk, J.M., Dörtbudak, Z., 2014. Acute effects of ozone on mortality from the "air pollution and health A European approach" project. Am. J. Respir. Crit. Care Med. 170 (10), 1080–1087, 15.

Gu, Q., Michanowicz, D.R., Jia, C., 2018. Developing a modular unmanned aerial vehicle (UAV) platform for air pollution profiling. Sensors 18 (4363), 1–14.

Hoffmann, W.C., Lan, Y., Wu, W., Fritz, B.K., 2009. Development of a spray system for an unmanned aerial vehicle platform. Appl. Eng. Agric. 25 (6), 803–809, 803-809.

http://db.eurad.uni-koeln.de/de/vorhersage/eurad-im.php.

Illingworth, S., Allen, G., Percival, C., Hollingsworth, P., Gallagher, M., Ricketts, H., Hayes, H., Ładosz, P., Crawley, D., Roberts, G., 2014. Measurement of boundary layer ozone concentrations on-board a skywalker unmanned aerial vehicle. Atmos. Sci. Lett. 15, 252–258.

Jian, Y., Messer, L.C., Jagai, J.S., Rappazzo, K.M., Gray, C.L., Grabich, S.C., Lobdell, D.T., 2016. Associations between environmental quality and mortality in the contiguous United States, 2000–2005. Environ. Health Perspect. 125 (3), 355–362. Published online 2016 Oct 7.

Krall, J.R., Anderson, G.B., Dominici, F., Bell, M.L., Peng, R.D., 2013. Short-term exposure to particulate matter constituents and mortality in a national study of U.S. urban communities. Environ. Health Perspect. 121, 1148–1153.

Latza, U., Gerdes, S., Baur, X., 2009. Effects of nitrogen dioxide on human health: systematic review of experimental and epidemiological studies conducted between 2002 and 2006. Int. J. Hyg Environ. Health 212 (3), 271–287.

Lawrence, D.A., Balsley, B.B., 2013. High-resolution atmospheric sensing of multiple atmospheric variables using the datahawk small airborne measurement system. J. Atmos. Ocean. Technol. 30, 2352–2366.

Lippmann, M., 1989. Health effects of ozone: a critical review. JAPCA 39 (5), 672–695.

Malaver, R.J.A., Motta, N., Peter, C., John, B., Alessandro, D., 2011. Development of a gas nanosensor node powered by solar cells. In: Proceedings of the Solar2011, the 49th AuSES Annual Conference. Australian Technology Park, Sidney, Australia.

Malaver, A., Gonzalez, F., Depari, A., Corke, P., Motta, N., 2012. Towards the development of a gas sensor system for monitoring pollutant gases in the low troposphere using small unmanned aerial vehicles. In: Proceedings of Workshop on Robotics for Environmental Monitoring, Sydney, Australia, p. 118.

Malaver, A., Motta, N., Corke, P., Gonzalez, F., 2015. Development and integration of a solar powered unmanned aerial vehicle and a wireless sensor network to monitor greenhouse gases. Sensors 15, 4072–4096.

Malaver, R.J.A., Gonzalez, L.F., Motta, N., Villa, T.F., 2015b. Design and flight testing of an integrated solar powered UAV and WSN for remote gas sensing. In: Proceedings of the IEEE Aerospace Conference. Big Sky, MT, USA, pp. 7–14.

Mayer, S., Sandvik, A., Jonassen, M., Reuder, J., 2012. Atmospheric profiling with the UAS sumo: a new perspective for the evaluation of fine-scale atmospheric models. Meteorol. Atmos. Phys. 116, 15–26.

Ramana, M.V., Ramanathan, V., Kim, D., Roberts, G.C., Corrigan, C.E., 2007. Albedo, atmospheric solar absorption and heating rate measurements with stacked UAVs. Q. J. R. Meteorol. Soc. 133, 1913–1931.

Ramanathan, V., 2006. Maldives AUAV Campaign (MAC): Observing Aerosol-Cloud-Radiation-Climate Interactions Simultaneously from Three Stacked Autonomous Unmanned Aerial Vehicles (AUAVs), 5. National Science Foundation, Arlington, VA, USA. Report of the Field Campaign Held from March.

Reuder, J., Jonassen, M., Ólafsson, H., 2012. The small unmanned meteorological observer sumo: recent developments and applications of a micro-uas for atmospheric boundary layer research. Acta Geophys. 60, 1454–1473.

Rice, S.A., 2004. Human Health Risk Assessment of CO_2: Survivors of Acute High-Level Exposure and Populations Sensitive to Prolonged Low-Level Exposure. Third Annual Conference on Carbon Sequestration, Alexandria, Virginia, USA.

Robles, T., Bordel, B., Alcarria, R., Martín, D., 2017. Mobile wireless sensor networks: modeling and analysis of three-dimensional scenarios and neighbor discovery in mobile data collection. Ad Hoc Sens. Wirel. Netw. 35, 67–104.

Ruiz-Jimenez, J., Zanca, N., Lan, H., Jussila, M., Hartonen, K., 2019. Aerial drone as a carrier for miniaturized air sampling systems. J. Chromatogr. A 1597, 202–208.

Schwartz, J., Bind, M., Koutrakis, P., 2017. Estimating causal effects of local air pollution on daily deaths: effect of low levels. Environ. Health Perspect. 125 (1), 23–29. Published online 2016 May 20.

Settele, J., Scholes, R., Betts, R.A., Bunn, S., Leadley, P., Nepstad, D., Overpeck, J., Taboada, M.A., Fischlin, A., Moreno, J.M., Root, T., Musche, M., Winter, M., 2014. Section 4.3.2.1: Phenology, in: Chapter 4: Terrestrial and Inland Water Systems. In: IPCC AR5 WG2 A, p. 291.

Smidi, V., Hofman, R., 2013. Tracking of atmospheric release of pollution using unmanned aerial vehicles. Atmos. Environ. 67, 425–436.

Tao, Y., Huang, W., Huang, X., Zhong, L., Lu, S., Li, Y., Dai, L., Zhang, Y., Zhu, T., 2011. Estimated acute effects of ambient ozone and nitrogen dioxide on mortality in the pearl river delta of southern China. Environ. Health Perspect. 120 (3), 393–398. Published online 2011 Dec 8.

Techrepublic.com. How Drones Are Steadily Advancing Australia's Environmental Industry.

Villa, T.F., Gonzalez, F., Miljievic, B., Ristovski, Z.D., Morawska, L., 2016. International laboratory. An overview of small unmanned aerial vehicles for air quality measurements: present applications and future prospectives. Sensors 16 (1072), 1–29.

Vo, T.D.H., Lin, C.T., Weng, C.E., Yuan, C.S., Lee, C.W., Hung, C.H., Bui, X.T., Lo, K.C., Lin, J.X., 2018. Vertical stratification of volatile organic compounds and their photochemical product formation potential in an industrial urban area. J. Environ. Manag. 217, 327–336.

Watai, T., Machida, T., Ishizaki, N., Inoue, G.A., 2006. Lightweight observation system for atmospheric carbon dioxide concentration using a small unmanned aerial vehicle. J. Atmos. Ocean. Technol. 23, 700–710.

www.auav.com.au.

www.ec.gc.ca.

www.epa.gov.

www.h2o2.com/industrial/applications.aspx?pid=101.

www.nationaldrones.com.au.

www.scmp.com.

Yallappa, D., Veerangouda, M., Maski, D., Palled, V., Bheemanna, M., 2017. Development and evaluation of drone mounted sprayer for pesticide application to crops. In: IEEE Global Humanitarian Technology Conference (GHTC).

Yang, X., Luis, M., Garratt, M., 2011. Multi-sensor data fusion for UAV navigation during landing operations. In: Proceedings of the 2011 Australian Conference on Robotics and Automation. Australian Robotics and Automation Association Inc.,Monash University , Monash University, Melbourne, VIC, pp. 1–10.

Yang, Y., Hu, Z., Bian, K., Song, L., 2019. ImgSensingNet: UAV vision guided aerial-ground air quality sensing system IEEE INFOCOM 2019. In: IEEE Conference on Computer Communications, pp. 1207–1215.

Yanmaza, E., Yahyanejadb, S., Rinnerc, B., Hellwagnerd, H., Bettstettera, C., 2017. Drone networks: communications, coordination, and sensing. Ad Hoc Netw. 68, 1–15.