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Development of Drone Real-time Air Pollution Monitoring for Mobile Smart Sensing in Areas with Poor Accessibility

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The topic of air pollution, especially in terms of particulate matter (PM), is a very serious problem in current society. This problem is caused by such factors as forest fires, construction, industrialization, and the ever-increasing number of motor vehicles. Thus, $PM_{2.5}$ has become an important risk factor for citizens in Thailand as well as globally, not only in terms of the problems associated with health risks, but also the negative impact on the image of the country. Measuring pollution for air quality monitoring is a challenging task, especially when considering areas that have poor accessibility. The aim of this work is to develop a drone equipped with sensors to monitor and collect air quality data in real time from such areas of potential pollution. The proposed drone is called the drone for real-time air pollution monitoring (Dr-TAPM) and is equipped with the ability to measure the concentration of carbon monoxide (CO), ozone (O_3), nitrogen dioxide (NO_2), PM, and sulfur dioxide (SO_2). Additionally, the collected data is transmitted to a cloud server every second over a wireless internet connection. In this study, the measurement was conducted in the experiment area, which is considered to be in the pollutant model scenario. The experimental results are shown as graphs of quantitative pollutant levels and air quality index (AQI) values obtained from real-time monitoring on a mobile application.

1. Introduction

Drones, also called unmanned aerial vehicles (UAVs), have been developed since World War I. The Curtiss N2C-2 drone was developed in 1937 by the US Navy. In 1941, the radio-controlled plane OQ-2 was launched by Reginald Denny as the first commercially produced drone to be used in the military. Since then, drones or UAVs have been implemented in a variety of military applications. Today, UAVs are being developed to deliver shipments, take aerial footage of sport matches, and for many other applications.(1)

Measuring air quality is important to ensure that the general public, governmental agencies and any involved parties are conscious of the state of pollution. It is also important

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for prompting the required precautions to ensure the safety of the population. As indicated by a report from the World Health Organization (WHO), around 7 million individuals die per year from causes related to air contamination. Urban air pollution has become a salient environmental issue in many Asian countries owing to their rapid industrial development, urbanization, and motorization. Particulate matter (PM) pollution such as $PM_{2.5}$ is of concern owing to its impact on health and climate change. Bangkok is an example of a developing Asian megacity that has a PM pollution problem. Thailand's Pollution Control Department (PCD) has conducted routine monitoring for $PM_{2.5}$ in Bangkok since 2010, after a standard was made effective. It is evident that a 10 μg/m change in daily PM_{10} concentration is associated with a 1–2% increase in natural mortality, 1–2% increase in cardiovascular mortality, and 3–6% increase in respiratory mortality.(2,3) In addition, the city has also faced the problem of acid rain. In fact, the acidity of rainwater has been reported to be increasing.

The aim of our work is to build a system that will help environmental researchers and other parties interested in the monitoring of air quality. Additionally, it should provide researchers with the necessary tools to visualize and analyze the gathered data via user-friendly interfaces. The system will gather and transmit real-time air quality data and provide live streaming to the control center. The objective of this study is to develop a "quadcopter" drone equipped with air quality sensors that will enable it to collect data and transmit the collected data, as well as to provide an easy and user-friendly platform to observe and visualize all the collected measurements. In this paper, we propose the new mobile smart sensing technology in the form of a drone for real-time air pollution monitoring (Dr-TAPM). Figure 1 shows the Dr-TAPM prototype.

2. Related Work

The pioneer work on the design of a UAV capable of remote gas sensing was given by Rossi and Brunelli.(4) The aim of their research is to use UAVs as a tool to gather air quality parameters. The concept is a fixed wing UAV remotely controlled via a radio controller. A nondispersive infrared sensor was used to measure the gas concentrations and transmit the

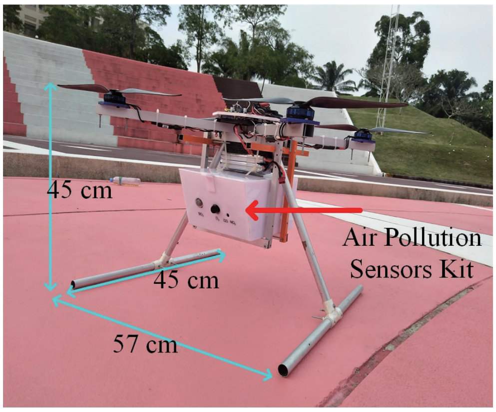


Fig. 1. (Color online) Dr-TAPM prototype.

data through a node network back to the base. The use of this node network increased the range of the UAV. The UAV used was a Green Falcon Kit, which had a wingspan of 2.52 m and a payload of 3 kg. A flight time of 1 h was achieved by mounting a high-capacity battery and integrating solar cells for increased power efficiency. The used sensors had an accuracy of ±0.26 ppm. Ardupilot Mega 2.5 autopilot software was installed in an autopilot mode (APM) flight controller. Ardupilot Mega supports flight paths set prior to take off and then it can track the route autonomously while enabling manual override for emergencies, whereby manual control can be enforced. In case of loss of communication with the ground station, the flight controller software will autonomously return the UAV to the point of take-off, after which it will wait for further commands. Data collection with a quadcopter was initially reported by Villa *et al.*(5) They utilized a user measurement system for monitoring air quality and air pollution. A quadcopter is the main core of their system and is equipped with sensors to detect gases, for example, O_2 and CO_2, vertically and horizontally, as well as pressure, temperature, and humidity. The total weight is 1.4 kg including the initial weight of the quadcopter. Using Arduino as a data acquisition device, they set the flight plan to navigate to specific coordinates using an on-board GPS system and record measurements in local memory to be retrieved upon landing. The ground station is operated by a human controller and the quadcopter communicates wirelessly via a 433 MHz link. The setup was driven by a 5 Ah 12 V battery that allows a flight time of 20 min and a maximum velocity of 8 m/s. Control was made autonomous with a backup RC controller in case of GPS signal loss. The setup was tested and data for CO_2 and O_2 were collected at different locations with various air pressures to identify the performance of the sensors relative to air pressure. This system is considered to be a fast, accurate, and affordable measurement system for monitoring and measuring the levels of CO_2 and O_2, and enables ecologists to quickly gather and analyze measured information. SCENTROID DR300(6) is a commercial quadcopter sold with a variety of sensors (30 to choose from), all for measuring air quality. Only two sensors can be equipped at any given time. The collected data, along with live video, are transmitted wirelessly via a 2.4 GHz link to an android application, the flight is controlled manually, and the flight time is approximately 25 min. This product is available commercially and does not require much time to set up. It is built on the Phantom quadcopter design sold by DJI Company. However, collecting larger amounts of data for all air quality parameters can be more difficult because only two sensors are supported at any given time and the flight time is limited to 20 min.

For smart cities, there is much research focused on environmental areas and Internet of Things (IoT) applications.(7–9) In our previous work,(10,11) we studied the development of air pollution sensors with both a narrowband IoT (NB-IoT) network and a low-power wide-area network (LPWAN) for the real-time monitoring of air quality in smart cities. The use of NB-IoT and LPWAN can help the sensor of pollutants to retain internet accessibility over long distances. In addition, the promotion of pollution-free routes in smart cities achieved by using air quality sensor networks was presented by Ramos *et al.*(12) The authors claim that the work revealed two limitations, the first being the number of active sensor stations in the sensor network, in this case, the Madrid network. It may affect the accuracy of spatial interpolation. The second limitation is the Environmental Systems Research Institute (ESRI) routing service, because the number of intersected streets with polygon barriers in routing is limited. The use of a UAV-based system to monitor air pollution in areas with poor accessibility was previously presented by Alvear *et al*.(13) Their experimental results showed that, when using pollution-driven UAV control (PdUC), an implicit priority guides the construction of pollution maps by focusing on areas where the pollutant concentration is higher. This way, accurate maps can be constructed faster than by other strategies. The PdUC scheme was compared with various standard mobility models through simulation, and it was found to achieve better performance. In particular, we were able to identify the most polluted areas with greater accuracy and provide higher coverage within the time bounds defined by the UAV flight time. However, a UAV is still more expensive. In this paper, we propose Dr-TAPM to implement mobile smart sensing for poorly accessible areas owing to, for example, fires in forests and gas leakage in industrial areas.

3. System Architecture

3.1 Air pollution sensors

In this section, the designs of all the off-the-shelf sensors for air pollution are described. Figure 2 shows the air pollution sensors kit, which can be characterized by four component parts: the microcontroller comprising Arduino MEGA2560 and Raspberry Pi 3, sensors for air pollutants including carbon monoxide (CO), ozone (O_3), nitrogen dioxide (NO_2), particular matter ($PM_{2.5}$), and sulfur dioxide (SO_2), and a NB-IoT module for wireless broadband internet access, and the power supply or power bank of 20000 mAh with an output of 5 V that powers all the sensors for longer than 5 h of operation. The size of the sensors kit box is about 15 cm wide × 23 cm long × 10 cm high and the weight is approximately 0.451 kg. A circuit diagram of the sensors is shown in Fig. 3, while descriptions of the sensors are listed in Table 1.

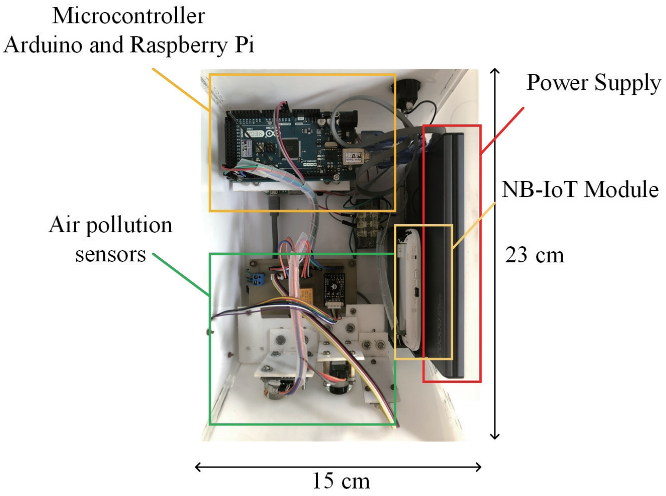


Fig. 2. (Color online) Off-the-shelf air pollution sensors kit used in Dr-TAPM prototype.

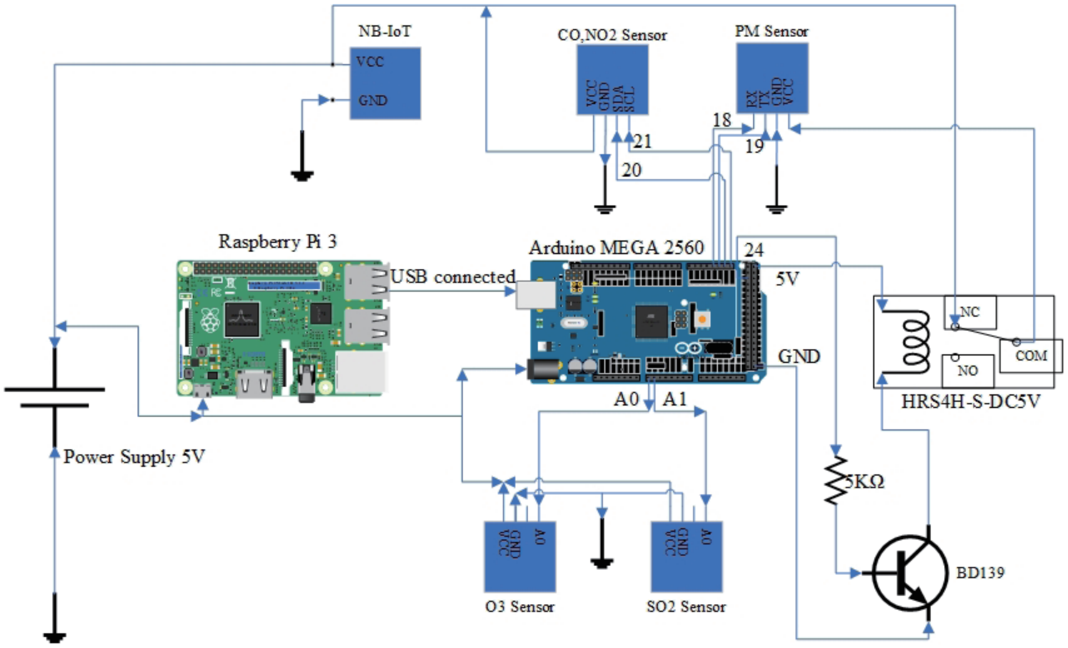


Fig. 3. (Color online) Circuit diagram of air pollution sensors kit.

Table 1
Description of sensors.

Sensor type	Model	Concentration	Voltage level	Interface
O_3 sensor	MQ-131	1–500 ppm	0–5 V	Analogue, A0
CO sensor	MiCS-6814	1–1000 ppm	0–5 V	I^2C
NO_2 sensor	MiCS-6814	0.05–10 ppm	0–5 V	I^2C
SO_2 sensor	2SH12	1–500 ppm	0–5 V	Analogue, A0
$PM_{10,2.5,1}$ sensor	PMS3003	0–1000 μg/m^3	0–5 V	RS232

The procedure is as follows. Turn on the power supply. All sensors send data to the Arduino MEGA2260 for data processing, and Raspberry Pi 3 transmits all data in the mobile application in real time via NB-IoT.

3.2 Dr-TAPM design

In this section, we describe the design of the Dr-TAPM framework. The dimensions and equipment are shown in Fig. 4. Dr-TAPM has a brushless DC 320 kV motor that runs on DC electric power supplied by a battery for converting the electrical energy into mechanical torque. The advantages of brushless DC motors are numerous, including very precise speed control, high efficiency, high reliability, low noise, and long lifetime. Dr-TAPM employs a 5300 mAh 6-cell lithium polymer (Li-Po) battery. Li-Po batteries have many advantages such as lighter weight, higher capacity, and higher discharge rates than other batteries.

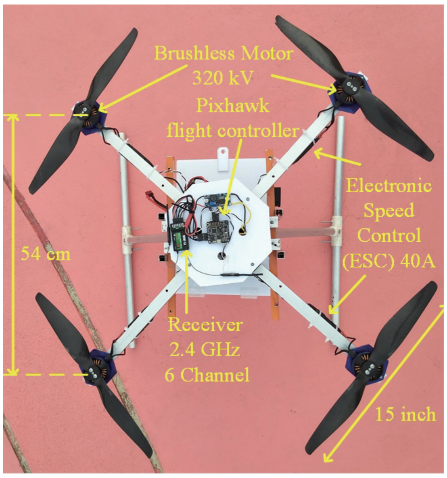


Fig. 4. (Color online) Dimensions and equipment of Dr-TAPM prototype.

Table 2
Component weights.

Component of Dr-TAPM	Weight (kg)
Battery	0.834
Motors	0.592
Sensors	0.451
Frame and legs	0.523
Propellers	0.130
ESCs	0.113
Total	2.643

In the battery, the two main parameters are the battery voltage and the number of cells. The voltage provided by the battery must be at least equal to the voltage of the motor. On the other hand, the capacity of the battery is a measurement of how much power the battery can hold. In other words, it represents how much current a battery will discharge over a period of 1 h, where a higher capacity will lead to a greater weight of the battery. Moreover, electronic speed control (ESC) 40 A is an electronic circuit that controls the speed of the electric motor and its direction. The ESC has two main sets of wires. One lead plugs into the main battery. The second lead is connected to the brushless motor. In Fig. 4, Pixhawk is the main flight controller for Dr-TAPM. Pixhawk is a small flight controller based on a 32-bit processor running at 72 MHz. This flight controller is cooperative with the 2.4 GHz receiver of the 6-channel module to realize wireless control at a distance of up to 200 m. Propellers with a size of 15 inches carry the weight of Dr-TAPM (2.643 kg). The component weights are listed in Table 2.

4. Experimental Scheme

In this section, we present a schematic model and the experimental setup. A schematic model of the Dr-TAPM test for detecting air pollution in a situation with smoke is shown in Fig. 5. The Dr-TAPM flight test is carried out at heights of 5 and 10 m. In addition, Dr-TAPM moves in steps of 1 m up to 10 m. Note that this schematic model is a model for sensing air pollutants in a fire burning situation.

Figure 6 shows the experimental setup, where Fig. 6(a) is for the Dr-TAPM test at the height of 5 m, while the height is 10 m in Fig. 6(b). The measurement location is in the field of King Mongkut's Institute of Technology Ladkrabang Prince of Chumphon Campus. In the measurement of each point, Dr-TAPM is directed to collect data at each point approximately every 10 s. As a result, graphs of all pollutant levels and air quality index (AQI) values can be presented.

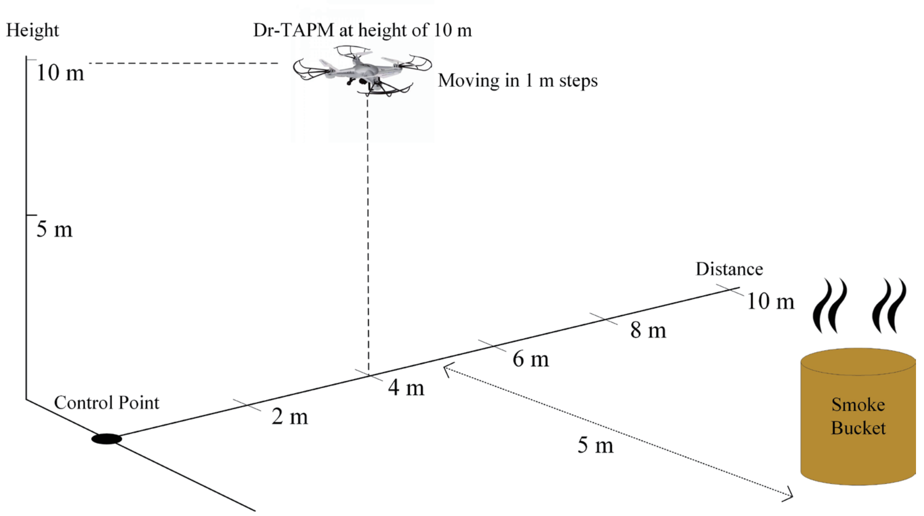
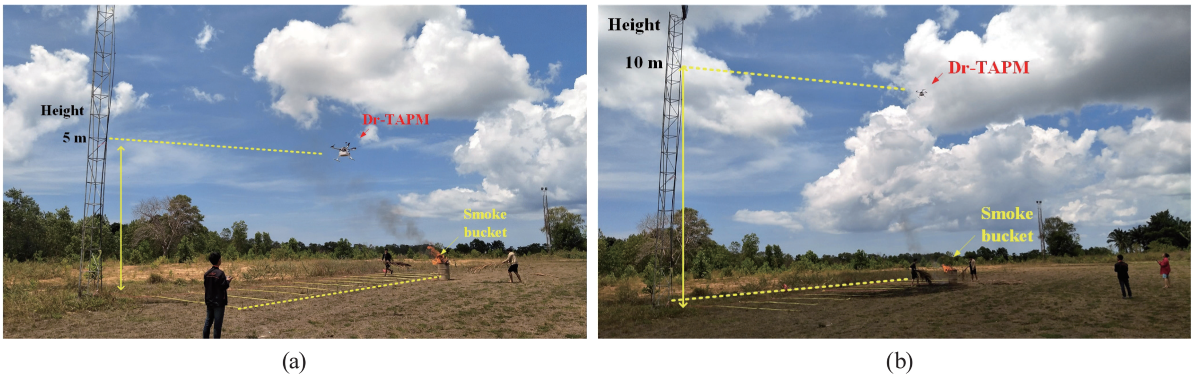


Fig. 5. (Color online) Schematic model of the pollutant area.



(a) (b)

Fig. 6. (Color online) Experimental setup for sensing air pollutants at different heights. Dr-TAPM flying at (a) 5 and (b) 10 m.

5. Results and Discussion

In this section, we present the results and discussion. For Dr-TAPM flying at 5 m, Fig. 7 shows the results for all pollutant sensors. In particular, Fig. 7(a) shows $PM_{2.5}$ concentrations at flight distances from 1 to 10 m. The $PM_{2.5}$ concentration is as high as the standard criterion of 112 to 118 μg/m^3, which was detected at distances of 9 and 10 m. In addition, the sensitivity of the CO sensor is higher than the standard criterion, as shown in Fig. 7(c). It can be observed that the CO concentration is increased by more than 20 ppb up to 44 ppb, which is unhealthy, at distances of 8 to 10 m. This is because the sensor at this distance is close to the smoke bucket. Therefore, the CO gas and $PM_{2.5}$ sensors can monitor the risk level of the pollutants in terms of air quality. Moreover, we can plot the AQI, as shown in Fig. 7(f), where the AQI represents the pollution caused by CO and $PM_{2.5}$ at these distances.

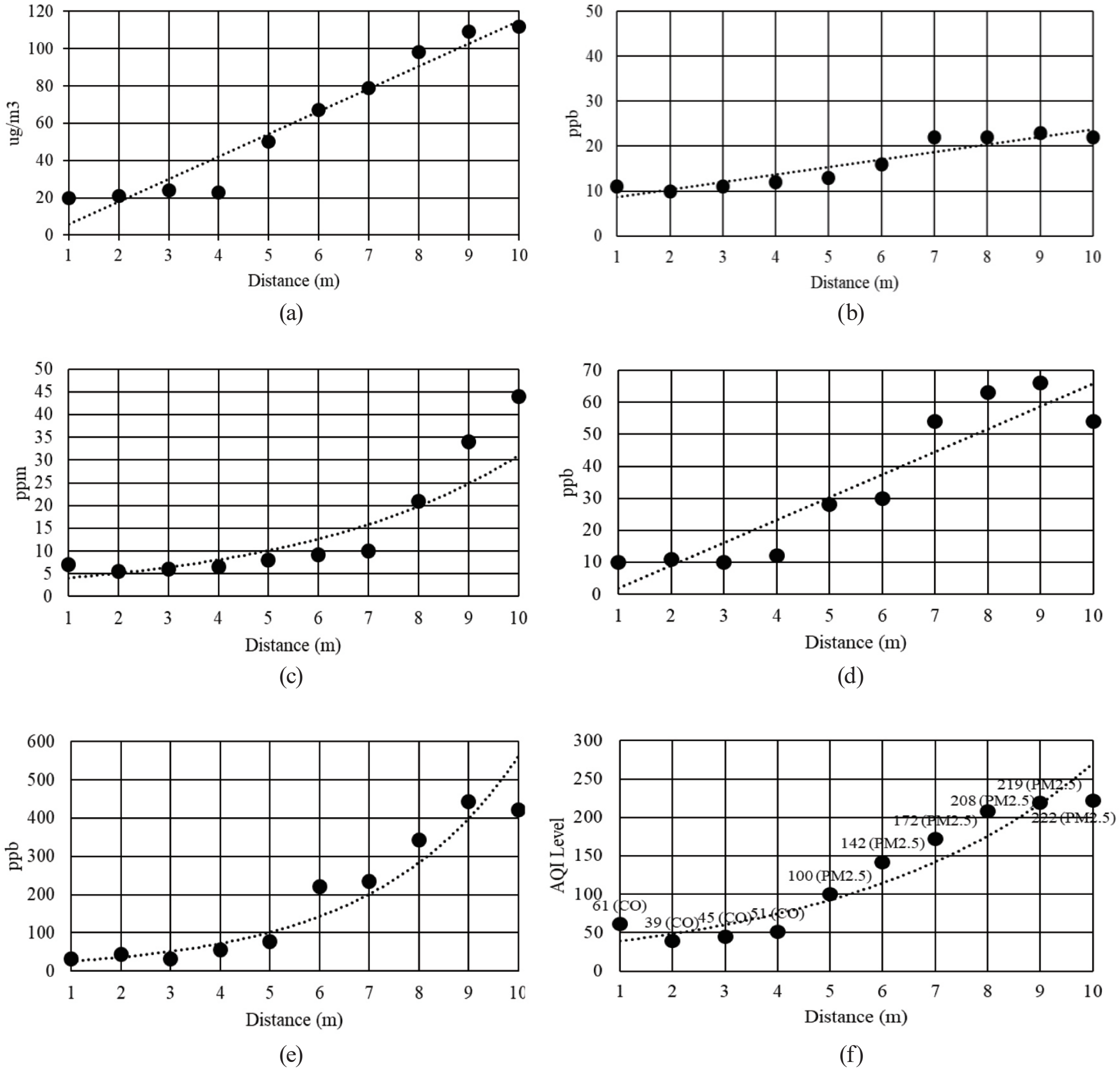
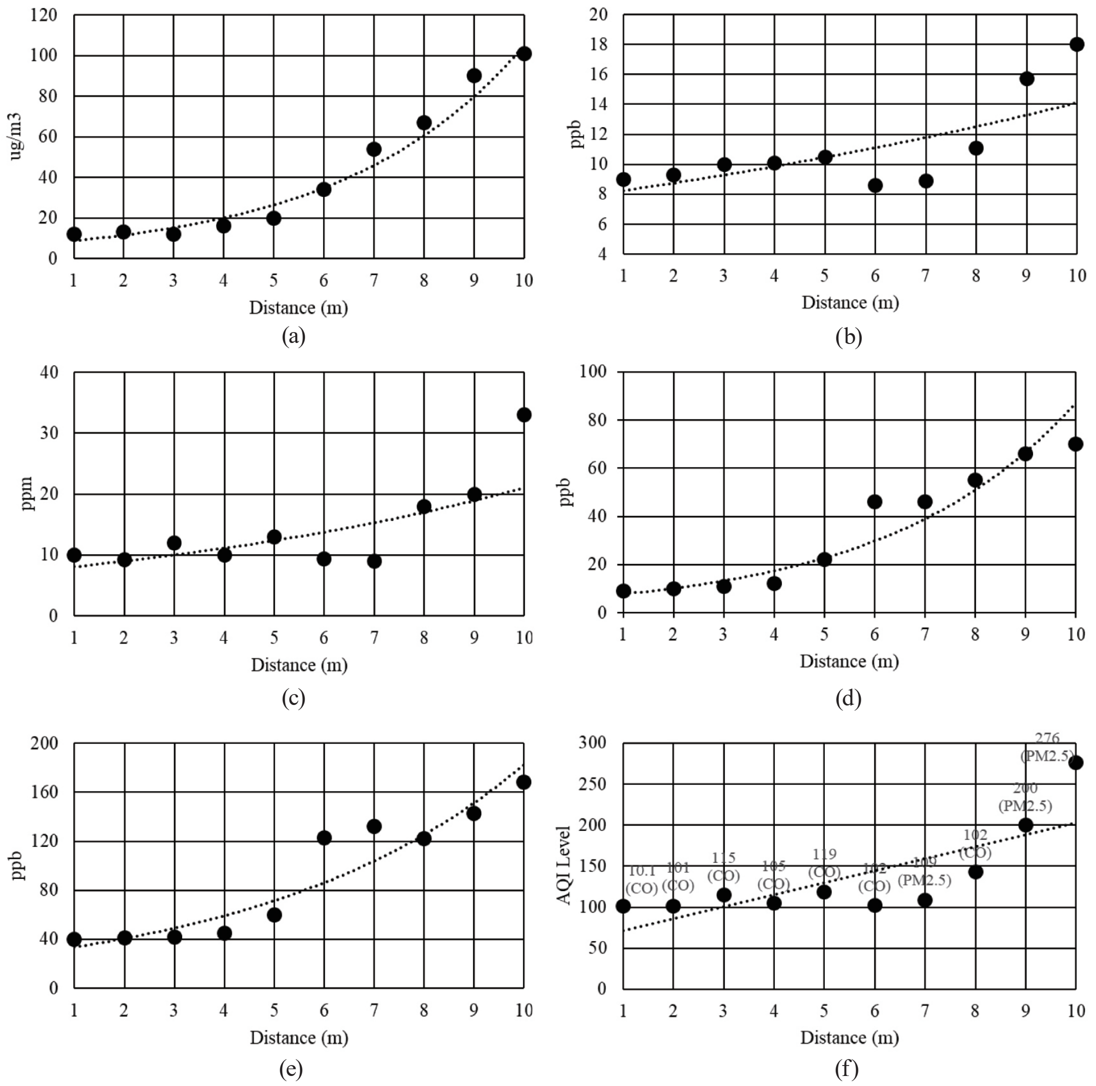


Fig. 7. Results of Dr-TAPM test at 5 m height: (a) $PM_{2.5}$, (b) O_3, (c) CO, (d) NO_2, (e) SO_2, and (f) AQI.

Figure 8 illustrates the results of the Dr-TAMP test at a hight of 10 m. It can be observed that, when Dr-TAPM flies at a height of 10 m, all the monitoring levels are slightly decreased from those at the height of 5 m. Obviously, the $PM_{2.5}$ values at 8 to 10 m in Fig. 8(a) are lower than those in Fig. 7(a). We observe that the SO_2 gas sensor results in Fig. 8(e) are also decreased from those in Fig. 7(e) at the same distances. This is because the flying height of Dr-TAPM is above the smoke from the source. However, in the AQI graph in Fig. 8(f), we can see that most pollutants originate from CO and $PM_{2.5}$. In particular, 8 to 10 m is a range in which AQI exhibits very unhealthy levels. We confirm that the performance of detecting air pollutants of Dr-TAPM can be monitored successfully with the pollutant area model.



(a) (b) (c) (d) (e) (f)

Fig. 8. Results of Dr-TAPM test at high of 10 m: (a) $PM_{2.5}$, (b) O_3, (c) CO, (d) NO_2, (e) SO_2, and (f) AQI.

6. Conclusions

In this paper, we presented the development of Dr-TAPM, which is a drone for real-time air pollution monitoring by mobile smart sensing in areas with poor accessibility such as those subjected to burning from forest fires or unsafe gas leakage in an industrial situation. This proposed device could be useful to users in relevant fields, such as inspectors of air pollution and environmentalists. Dr-TAPM can be used for monitoring $PM_{2.5}$, O_3, NO_2, CO, and SO_2. In addition, data monitoring is available as real-time information via a mobile application. In future work, a 3D air pollution model using Dr-TAPM will be considered to show the contours for different AQI levels.

Acknowledgments

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