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Development of a multicopter-carried whole air sampling apparatus and its applications in environmental studies

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HIGHLIGHTS

- A sampling device was integrated with a multicopter drone to perform aerial sampling.
- The whole air sampling can be performed at desired positions aloft with ease.
- The leak- and contamination-free properties ensured the integrity of air samples.
- Subsequent in-lab analysis of whole air samples provided a large variety of species.
- Vertical profiles of gaseous species up to 1 km height can be easily obtained.

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ABSTRACT

To advance the capabilities of probing chemical composition aloft, we designed a lightweight remote-controlled whole air sampling component (WASC) and integrated it into a multicopter drone with agile maneuverability to perform aerial whole air sampling. A field mission hovering over an exhaust shaft of a roadway tunnel to collect air samples was performed to demonstrate the applicability of the multicopter-carried WASC apparatus. Ten aerial air samples surrounding the shaft vent were collected by the multicopter-carried WASC. Additional five samples were collected manually inside the shaft for comparison. These samples were then analyzed in the laboratory for the chemical composition of 109 volatile organic compounds (VOCs), CH_4, CO, CO_2, or CO_2 isotopologues. Most of the VOCs in the upwind samples (the least affected by shaft exhaust) were low in concentrations (5.9 ppbv for total 109 VOCs), posting a strong contrast to those in the shaft exhaust (235.8 ppbv for total 109 VOCs). By comparing the aerial samples with the in-shaft samples for chemical compositions, the influence of the shaft exhaust on the surrounding natural air was estimated. Through the aerial measurements, three major advantages of the multicopter-carried WASC were demonstrated: 1. The highly maneuverable multicopter-carried WASC can be readily deployed for three-dimensional environmental studies at a local scale (0–1.5 km); 2. Aerial sampling with superior sample integrity and preservation conditions can now be performed with ease; and 3. Data with spatial resolution for a large array of gaseous species with high precision can be easily obtained.

1. Introduction

The sources and fates of anthropogenic and biogenic compounds and their secondary products in the atmosphere are of interest to those studying anthropogenic–biogenic interaction mechanisms, air-sea interactions, and tropospheric chemistry of oxidants. In recent decades, light aircraft, and tethered balloons have offered a direct way of probing the lower troposphere (e.g., Toscano et al., 2011; Aurell and Gullet, 2010, 2013; Greenberg et al., 1999; Chen et al., 2002; Glaser et al., 2003; Tasi et al., 2012; Liu et al., 2013). While the advantages of light aircraft with engines include their large payloads and greater flight distances, their inability of vertical movement and hovering as well as their engine exhaust pose limits to aerial air sampling. Tethered balloons controlled by an electric capstan have proven useful when carrying

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sounding devices and Teflon bags for meteorological parameters and air pollutants without engine exhaust contamination; however, their greatest limitation is a lack of maneuverability and their short flight distances. To advance aerial investigations, a useful and novel technique using unmanned aerial vehicles (UAVs) has been developed as a flight platform in recent years and exploited in many fields, such as geological exploration, agricultural applications, military surveillance, and studies of atmosphere and climate, and early warning or subsequent monitoring before and after disasters (e.g., Patterson et al., 2006; Mak et al., 2013; Watai et al., 2006; Lin, 2006; McGonigle et al., 2008; Ramanathan et al., 2007; Gerhardt et al., 2014).

There are two types of UAVs that are most widely investigated and developed. Fixed-wing UAVs have been popular and commonly used for a variety of applications, particularly for long distance tasks (Corrigan et al., 2008; Mak et al., 2013). Rotary-wing UAVs have other unique abilities: hovering, vertical takeoff, agile movement and landing on small or limited spaces, such as on board ships or on the roofs of buildings (McGonigle et al., 2008; Saggiani and Teodorani, 2004). Rotary-wing UAVs include conventional helicopters with a single primary rotor and multi-rotor helicopters (i.e., multicopters) with multi-horizontal rotors (e.g., 4, 6, and 8). As a platform for aerial investigations, multicopters have more advantages than conventional single-rotor helicopters due to their omission of a vertical tail rotor and complex mechanical components that adjust the pitch of the fast-spinning primary blade. Additionally, the placement of rotors on the periphery of multicopters allows more room for probing devices in the center of the craft. Their simpler structure and the characteristics of stable flight make multicopters easier to operate and maintain and possibly less costly to acquire and modify. The inherent advantages associated with multicopters combined with measuring capabilities make them potentially useful for a variety of observation of different natures.

Conventional aerial observation primarily uses sensors or optical instruments. Sensors on a variety of aerial vehicles or remote sensing using optical instruments on satellites can provide valuable data with spatial resolution for some specific pollutants, such as ozone, formaldehyde, CO_2, NO_x, PM_{10}, glyoxal, etc. (Ligler et al., 1998; Chevallier et al., 2005; Emili et al., 2010; Liu et al., 2012). However, there are common limitations in precision, accuracy, and sensitivity for regular sensors and the often limited number of species that can be detected by remote sensing. For local-scale observations, air sampling accompanied by subsequent off-line analysis using more elaborate analytical instruments can be an alternative to acquire a large array of compounds with sufficiently high sensitivity. There are generally two methods for collecting air samples: one is to draw air with a pump through a tube filled with sorbents (Glaser et al., 2003; Greenberg et al., 1999; Ribes et al., 2007); the other is to collect air with an evacuated canister (e.g., electropolished stainless steel or fused silica-lined canister) or a sample bag (e.g., Teflon bag) with a sampling pump. Whole air sampling with an evacuated canister is well suited for the analysis of CH_4, CO, CO_2, N_2O, VOCs, permanent gases, and their isotopic ratios due to better preservation of the air sample.

Coupling the advantages of multicopters with their agile maneuverability as an aerial vehicle and the canister sampling technique can open up a new dimension to perform atmospheric measurements at a local scale from aloft over locations of interest. Their swift "arrive-and-return" aerial ability permits the rapid "load-and-launch" of canisters and thus a reasonably fast sampling coverage of a target space. The whole air samples can then be brought back to laboratory for analysis with an array of elaborate analytical instruments for detailed chemical composition or isotopic information. In this study, we integrated a multicopter and the canister sampling technique into a multicopter-carried whole air sampling apparatus. The technical details of the construction and operation of the aerial whole air sampling apparatus will be presented, accompanied by a set of test results of flight maneuverability, positioning, sampling actions and sample integrity. To demonstrate field applicability, real flights of aerial sampling above a vertical exhaust shaft of a long roadway tunnel in a mountainous area were conducted. Through these test results, three major advantages will be demonstrated: 1. Air sampling over hardly accessible locations can be performed with ease; 2. Vertical profiles of numerous gaseous species can be easily obtained to complement conventional ground-based measurements; and 3. Aerial sampling by multicopters can be easily deployed and readily performed to open up many possibilities in environmental studies or accident investigations.

2. Materials and methods

2.1. Configuration of aerial whole air sampling apparatus

The aerial whole air sampling apparatus (Fig. 1) integrates a multicopter drone with advanced UAV control techniques, the whole air sampling component (WASC) and sensors (e.g., temperature, humidity, pressure, black carbon, and CO_2). The multicopter has a deck with a surface area of 900 cm^2 on which lightweight probing sensors can be installed. The heavier WASC is mounted underneath the multicopter to enhance the center of gravity and thus maintain flight stability.

2.1.1. Multicopter driven by electricity

The multicopter used in the study is an octo-rotor multicopter (Spreading Wings S-1000, DJI Innovations) with a 1045 mm diagonal wheelbase and a 337.5 mm center frame diameter. The aircraft weighs 4.2 kg without payload, and its maximum takeoff mass is 11.0 kg. The octocopter is run on battery power (22.2 V, 10,000–20,000 mAh lithium polymer (Li–Po) battery) to avoid the use of a fueled engine and therefore self-contamination. With a 15,000 mAh Li–Po battery, it has a hovering time of approximately 15 min at a 2-m height for a takeoff mass of 9.5 kg. It is permissible to operate at ambient temperatures between −10 and 40 °C.

The multicopter is equipped with UAV control modules for easy flying and safety concerns. The integrated flight controllers with a high precision global positioning system (GPS) and an inertial measurement unit (IMU) can perform stable hovering at desired positions. The on-board video camera and on-screen display can provide real-time images and flight data (e.g., latitude, longitude, altitude, power voltage, and flight velocity). The multicopter can be controlled by a transmitter or set in autonomous flight mode by editing flight routes with a ground station program. In case of one-motor failure, loss of signal, or a low battery, the aircraft was equipped with an automatic return algorithm to ensure its automatic safe return.

2.1.2. Whole air sampling component (WASC)

Depending on the needs and purposes of flight studies, the multicopter drone is versatile in terms of the possible devices and sensors that can be carried. In this study, the key component of the multicopter drone was the remote-controlled WASC (Fig. 1), which consisted of a stainless steel (s.s.) sampling canister (either electropolished or fused silica-lined), a flow restrictor and a lightweight s.s. valve with a remote control circuit. A deactivated s.s. tube (1.6 mm O.D., 0.025 mm I.D.) serving as the flow restrictor was attached to the inlet of the canister to collect an integrated air sample for a duration of 1–15 min based on its length (0.5–10 cm). To remotely open and close a canister, an electric s.s. valve (TM1050S, Enteck) was used. The requirements for the electric valve used for aerial sampling should have the following