VOC Sampler on a Drone Assisting in Tracing the Potential Sources by a Dispersion Model - Case Study of Industrial Emissions

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ABSTRACT

Volatile organic compound (VOC) related air pollution cause public concern and pose adverse effects on human health in the communities in most developed and developing countries. Our recent studies have applied a quadrotor drone (Mavic Pro, DJI) equipped with a micro needle trap sampler (NTS), and it could fast arrive at the polluted locations for immediately sampling and further tracking the suspended VOC sources. Notably, a remote-controlled telescoping sampling device was also equipped on the drone in order to extend the NTS outside the disturbed downward wind zone, which was resulted from the rotating propellers. Two plants which manufacture petrochemical products at an industrial complex in Kaohsiung City, southern Taiwan, were applied as the targets for VOCs sampling and further qualitative and quantitative analysis in the laboratory. Aromatic hydrocarbons, including toluene of 433 ppb, ethylbenzene and xylenes of 100–200 ppb and phenol of 111 ppb were identified. Additionally, an air mass backward trajectory model, FYTRAJ, was used to track the paths of VOC emitted from the potential sources and transported in the ambient air. According to the analyzed constituents of VOCs and the raw material data of the suspected plant, which was combined with the backward trajectory tracking simulation of VOC plumes, the NTS carried by a drone has been proven as a cost-effective air pollution monitoring apparatus for locating the VOC emission sources.

Keywords: Drone, Micro sampler, Backward trajectory simulation, Volatile organic compounds, Source tracking

1 INTRODUCTION

Atmospheric monitoring using unmanned aerial vehicles (UAV) began in 2007 (Ramanathan et al., 2007; Char, 2016). The research team of the University of California, San Diego, applied UAVs to the research of brown cloud on warming trends in Asia (Ramanathan et al., 2007). Thereafter, small and lightweight UAVs have gradually been developed. Technische Universität Braunschweig, Germany, also developed a light and small weather monitoring UAV with automatic navigation (Kroonenberg et al., 2008; Char, 2016). A drone is a kind of aircraft between the helicopter and the airplane, and the processes of flight for a drone and helicopter which is the most obvious are the rotor face of a helicopter tilts forward, and then the rotor of a drone tilts backward. Drones have unique advantages which have been unavailable either for typical UAVs or helicopters. During cruising, drones have strong resistance to wind, and good stability and relative safety. The vibration and noise produced by a drone is relatively low due to less power consumption. Drones can also take off and land vertically without using a runway, and fly at a fixed point in the air. Additionally, operators can perform basic flight tasks and maintenance of a drone after simple
training since a drone has the simplest mechanical structure among these three types of aircrafts (Ke et al., 2023; Dai et al., 2022; Chang et al., 2016, 2018; Feng, 2012; Quan, 2015).

However, due to the simple structure of a drone, its flight performance is limited, including low speed and poor endurance. The carrying capacity of a drone is also the lowest among the aircrafts. Pro Mavic (DJI) is a four-rotor miniaturized drone (Fig. 1) and its load of long distance is less than 1,500 g. Therefore, the rechargeable lithium battery which is installed in the drone can cruise for only about 15 min, especially due to the loading of additional acrylonitrile butadiene styrene (ABS) sampling rack on the ventral of the drone (Fig. 1). However, the needle trap sampler (NTS), developed by the authors’ research group for sampling volatile organic compounds (VOCs) in the air (Cheng et al., 2019; Cheng and Yuan, 2021, 2022), has a relatively light weight (much lighter than a stainless steel canister or the active sampling apparatus of Teflon bags as well as a sampling pump). It is most suitable to be used as a micro sampler which is installed on the DJI Pro Mavic for extracting VOCs in the atmosphere to take the advantages of being low-cost and easy to control using a drone.

Ambient VOCs are harmful to human health and the environment, and are the precursors of ozone (Dieu Hien et al., 2019; Juráň et al., 2021; Agyei et al., 2021; Zhang et al., 2020). VOCs enter the bodies through inhalation and skin absorption, and then hurt humans’ respiratory tract, kidneys, liver, lungs, nervous system, digestive system and hematopoietic system to cause diseases. Ozone irritates the mucous membranes of human eyes, nasal cavity and trachea. Long-term exposure to ozone will cause diseases such as allergic conjunctivitis and allergic rhinitis (Kent, 1998).

According to the report published by Kaohsiung City Environmental Protection Bureau (KEPB), Taiwan (KEPB, 2021), the annual emission amounts of VOCs in Kaohsiung City, which is the largest
Fig. 2. Locations of two sampling sites: Site A ★ and Site B ★. The shaded area of the inset on the right is the area of Linhai Special Industrial Complex (LSIC).

international harbour in Taiwan, were 11,150 tons in 2019. Among 38 administrative districts in Kaohsiung City, 25.7% of VOCs were emitted from Xiaogang District (KEPB, 2019a). KEPB has regulated twenty major plants, which emitted the largest amounts of VOCs, to continuously reduce the total annual emission of VOCs from 907.75 tons year$^-1$ in 2020 to 605.12 ton year$^-1$ in 2023. Notably, five of the twenty target plants are located in the Linhai special industrial complex (LSIC). LSIC is located in the Xiaogang District (Fig. 2) (Ministry of Economic Affairs (Taiwan), 2023a) and catalogued as a special industrial park under the environmental management of the municipal government, and is currently the largest-scale heavy industrial complex in Taiwan. In order to achieve the goal of VOC reduction year by year, it is an effective environmental management approach to use a drone equipped with a micro sampler to collect and identify VOCs from industries and then trace their emission sources.

2 METHODS

2.1 Theory and Preparation of Needle Trap Samplers

An NTS adsorbs gaseous VOCs through its needle by diffusion, and a newly fabricated NTS was tested using the passive sampling mode in the laboratory. During this process, a linear gaseous concentration profile $C(Z)$ in Fig. 1) is obtained along the diffusion path $Z$, and the extraction phase is characterized by an opening area $A$ and the diffusion path length $Z$. The total amount $n$ of analyte which is collected during a time interval $t$ can be estimated as (Lord et al., 2010)

\[ n = D_m \frac{A}{Z} \int C(t) dt \]  (1)
where $D_m$ is the diffusion coefficient of the VOC that is sampled by the adsorbent within the needle. The quantity of the extracted analyte is assumed to be proportional to the total sample concentration over time ($C(t)$) given a constant $D_m$, a uniform needle opening area ($A$), and a fixed diffusion path distance ($Z$). Eq. (1) applies only when the amount of analyte that is extracted onto a sorbent is a small fraction in equilibrium with the analyte in the air sample.

In this study, the NTS mainly consisted of a stainless steel needle that was packed with sulfated divinyl benzene (DVB) particles with 60–80 mesh. Notably, the DVB adsorbent had been sulfated in advance by authors’ laboratory assistants and the sulfated DVB was proven to have more affinity for alcohols and ketones (Huang et al., 2021). DVB particles filled in the needle were immobilized without bleeding. The detailed preparation procedures of an NTS are described as Cheng et al.’s procedures established since 2011 (Cheng et al., 2011). Notably, the uniformity of the packing phase in an NTS was examined to evaluate the sampling flow rate (mL min$^{-1}$) through an NTS when drawn by an aspirating pump through the packing phase. When the relative standard deviations (RSD) of the sampling flow rates across three duplication tests did not exceed 5%, the materials filled inside the NTS were assumed to be uniformly immobilized. BTEX standard gas samples (around 0.1–5 ppm) were prepared in a glass bulb, in which the NTS was inserted to extract BTEX for 1–2 h. When the RSD of the extracted mass in the triplicate tests did not exceed 5%, the adsorption capacities in the NTS were assumed to be constant. The tested NTS were ready for use for sampling VOCs in the field.

2.2 Sampling VOCs Using a Telescoping Sampling Device on a Drone

The Mavic Pro quadrotor drone (DJI, Fig. 1), was used as a sampling vehicle. It had a 335-mm diagonal wheelbase (excluding propellers) and a maximum horizontal voyage speed of 65 km h$^{-1}$. A telescoping sampling device, including an NTS, was connected to a Teflon sampling tube and a 6-V-DC air-extracting pump. The air-extracting pump was operated using an on-off switch via the remote drone controller by an operator. However, the rotation speed of the propeller of a drone is up to 5,700 rpm and the air turbulence resulted in the disturbance of VOC concentration in the atmosphere. According to the simulation using SolidWorks, the optimum VOC sampling zone, where the turbulence and wind speed resulting from the rotating propellers approached lowest, is located at a depression angle of 45° and a horizontal distance of 8 cm from the nose of the drone. The simulation result was used for designing the extension length of a telescoping shaft. Cheng et al.’s (2019) work showed that the telescoping device equipped on a drone effectively reduced the dilution of VOC concentrations due to air turbulence by rotors. The sampling time of a single flight usually cannot exceed 12 min.

2.3 Analysis of VOCs and the Quality Assurance and Quality Control

The instrument for examining VOCs was a gas chromatograph connected with a mass spectrometer (GC-MS, 6890N and 5973, Agilent, Santa Clara, CA, USA). The capillary column is HP19091Z-413 HP-1 PDMS (30 m × 320 µm × 0.25 µm) (Agilent, Wilmington, DE, USA). All standard gases (Jing-De Gas Co., Ltd., Kaohsiung City, Taiwan) that were used for the chromatographic analysis were of ultra-high purity. After VOC sampling, NTS were delivered to the laboratory for analysis as soon as possible. An NTS was injected into the injection ports of GC used for VOC desorption and further analysis. The desorption time at the injection port of GC was set as 30 s. The temperature of the GC increased from 50°C at an increment of 15°C min$^{-1}$. The final temperature was held at 180°C for 2 min. The carrying gas flow rate was 1.8 mL min$^{-1}$ for helium, and the split-off operation mode was selected. Notably, after the operation and subsequent analysis, no carryover was available for the sample extracted by an NTS.

Quality assurance (QA) and quality control (QC) were implemented for the sampling and analysis of VOCs using an NTS in this study. One to three air samples were taken using NTS around a stationary pollution source by the drone, and at least one additional sample for the downwind was also taken. For each sampling site, a background sample was collected at the upwind area, and this sample was also regarded as a blank for delivery. Nine VOCs such as ethanol, methyl acetate, methyl ethyl ketone, benzene, toluene, ethylbenzene, m-xylene, o-xylene (BTEX) and phenol were analyzed by NTS for qualification and quantification. Additionally, seven replicate NTS analyses of nine VOCs by the GC-MS were conducted until the RSD values of analysis area were less than
10%. For each of the 9 VOCs, the calibration correlations must have at least four given analytical concentrations from 0 to 10 ppm, and the linear regression coefficient ($R^2$) should not be lower than 0.995. Two GC-MS blank analyses were performed before analyzing the VOC sampling samples, and the total concentration of the compounds to be tested should not exceed 10 ppb. Other VOCs sampled by the NTS, except the mentioned nine components, were also identified by the GC-MS for qualification. The detection limits of nine VOCs ranges from 2–18 ppb.

2.4 Target Sites A and B for Sampling at the Linhai Special Industrial Complex

The development of LSIC (Fig. 2), with a land area of 1,560 hectares, was completed in 1983, and is currently the largest comprehensive industrial zone developed in Taiwan. LSIC provides employment for 36,667 people and it has convenient transportation owing to being close to the highway, 0.5 km away from the Kaohsiung International Airport, and only 2 km away from the Fifth Container Terminal of the Kaohsiung International Port. In this study, VOC samplings and analysis were implemented for two main VOCs emission sources in the industrial zone. Plant A, which was selected as the target (Site A in Fig. 2) is an important chemical manufacturing plant in the industrial complex. Its main products include caprolactam, ammonium sulfate and sulfuric acid. Plant B, which was selected as the other target (Site B in Fig. 2), is a refinery plant and it is a manufacturing industry with the highest value of economic output in LSIC. It is also the main manufacturer of oil products, such as diesel, gasoline and aviation fuel in Taiwan (Ministry of Economic Affairs (Taiwan), 2023b).

2.5 Predicting Sampling Points and Tracing of Potential VOC Emission Sources

Before the sampling of a drone, according to the weather forecast of the sampling day as well as the emission data of the target chimney which were provided by KEPB, the atmospheric diffusion model (AERMOD) was used to analyze the influence area and vertical concentration profile distribution of the pollutants during the sampling period, and the sampling location and height was obtained in advance. The AERMOD used in this study is a steady-state Gaussian dispersion model (Industrial Source Complex Model, ISC), which is the 2005 version and used by the U.S. Environmental Protection Agency. The AERMOD model that involves pollutant dispersion is the same as that of the previous Gaussian ISC, and the atmospheric boundary layer and atmospheric dispersion theory have been further considered.

The source tracing analysis model of atmospheric VOCs used in this work was the air mass backward trajectory model (hereinafter referred to as FYTRAJ) developed by one of the authors, Dr. Chin-Ho Lin, at Fooying University, Taiwan. He has used FYTRAJ to analyze the potential sources of domestic air pollution incidents (Lin and Chang, 2002; Lin and Wu, 2003), and has assisted the KEPB to immediately trace possible pollution sources and their dispersion paths (KEPB, 2019b). This model used meteorological observation data from a single or multiple station(s) as the input data. Since this model did not consider the influences of obvious elevation differences or buildings along the wind field, this model was limited to be applied solely for the area where the terrain is flat and the real-time weather data are available.

FYTRAJ model interpolates the wind field at the location of air mass based on the wind speed and wind direction of the target weather stations, and then calculates the position of the air mass at the next time step based on the following post-difference principle

$$\vec{x}_{t+1} = \vec{x}_t - \vec{u} \cdot \Delta t$$  \hspace{1cm} (2)

where $\vec{x}_t$ and $\vec{x}_{t+1}$ are the locations of air mass when time = t and $t - \Delta t$ (min), $\vec{u}$ is the wind velocity (m s$^{-1}$) when time = t, and $\Delta t$ is the time step (min) which is used for the backward trajectory calculation. The parameters including time (t), wind speed and wind direction at the location of air mass can be substituted into Eq. (2) for deriving the location of air mass when time = (t – $\Delta t$). In this way, the past trajectory of the polluted air mass is obtained sequentially, and the time resolution of pollution source tracking ranges from 1 to 10 min.

When simulating the backward trajectory by using the FYTRAJ model, the location of air masses within the radius of 5 km should be firstly searched for checking whether there are available
weather stations nearby. If there is no weather station within the searching range, the FYTRJ model will then expand the searching area until weather station(s) was(were) found. Afterwards, the FYTRJ model uses the principle of the inverse square of distance and applies the meteorological monitoring data to interpolate the wind field at the location of air mass to be the wind field which is required to push air masses to the next time step.

In addition, for mixed layers and turbulent flow, it is necessary to simulate the transport routes of pollutants at different elevations, which is calculated as Eq. (3)

\[
\frac{u_1}{u_0} = \left( \frac{z_1}{z_0} \right)^\rho
\]

where \(z_0\) and \(u_0\) represent the height and wind speed of a weather station, \(z_1\) and \(u_1\) represent the height to be simulated and the estimated wind speed; \(\rho\) is a parameter of wind speed, which is related to the stability of the atmosphere and is generally assumed as a default value of 0.143 when the atmosphere stability is under a neutral condition (Wark and Warner, 1981). The result of a simulation by the FYTRJ model is presented in Supplement 1 for reference.

3 RESULTS AND DISCUSSION

3.1. Analysis of Qualification and Quantification of VOCS at Sites A and B

Air samplings were implemented during the winter (form late November to December, 2022). Table 1 summaries the analysis concentrations of VOCs which were collected by the NTS. Table in Supplement 2 summarizes the sampling data for Sites A and B. Locations 1 and 2 were sampled for the chimney of Plant A (a chemical manufacturing plant). Close to the chimney and the downwind (Location 2 in Fig. 3), TEX (433 ppb toluene, and 100–200 ppb ethylbenzene and xylenes)

Table 1. Concentrations of VOCs sampled by NTS around the chimneys of Sites A and B.

<table>
<thead>
<tr>
<th>Volatile organic compounds</th>
<th>Sampling locations at Site A</th>
<th>Sampling locations at Site B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Far from the chimney but not at the downwind (Location 1 in Fig. 3)</td>
<td>Near to the chimney and at the downwind (Location 2 in Fig. 3)</td>
</tr>
<tr>
<td>Quantified Compounds(^{(a)})</td>
<td>Toluen</td>
<td>Ethylbenzene</td>
</tr>
<tr>
<td>Unquantified Compounds(^{(a)})</td>
<td>n-Butyl acetate</td>
<td>Nonanal</td>
</tr>
</tbody>
</table>

\(^{(a)}\) Quantified compounds are indicated as the concentrations ranges (ppb); Unquantified compounds are indicated as detected (✓).  
\(^{(b)}\) “n.d.” denotes “non-detective.”
and phenol (111 ppb) were identified. Far away from the chimney but not at the downwind (Location 1 in Fig. 3), the concentrations of TEX and phenol were significantly lower than those for Location 2. According to the raw material declaration information to Kaohsiung City Government, Plant A have used a large amount of toluene (57.7 ton year\(^{-1}\)) as a solvent in the manufacturing processes, which matches the VOC distribution characteristics that toluene is the compound with the highest concentration at Location 2. TEX, which were simultaneously detected for Locations 1 and 2, are related to the spillage of oil storage tanks in the Kaohsiung Port at the upwind (Yuan et al., 2022). Notably, nonanal and decanal were the common compounds for Locations 1 and 2, which matches phenomenon that aldehydes have commonly monitored in the air of LSIC (Yuan et al., 2022).

Locations 3, 4, 5 and 6 were sampled at Site B (an oil refinery plant). Close to a public wastewater treatment plant (WWTP) and at the downwind, TEX (800−1,000 ppb toluene and ethylbenzene, and 200−400 ppb xylenes) and phenol (1,653 ppb) were detected at Locations 3 and 4, and the VOC concentrations were higher than those at Locations 5 and 6. According to the photos taken by the drone, we found that the wastewater storage tanks and the aeration basins in the public WWTP were partially covered. Therefore, VOCs, especially aromatic compounds, were emitted and extracted by the NTS. Nonanal and decanal, which are the common VOCs in the air of LSIC (Yuan et al., 2022), were also detected at Sites A and B. Alkanes (octane and nonane) and naphthalene, which are characterized to the organic compounds in the air flumes emitted from refinery exhausts from the chimney of Plant B (IARC, 1989; Tsai, 2014) were also extracted by the NTS.

### 3.2 Simulation Analysis for VOC Source Tracing

Air mass backward trajectory simulation was carried out by the FYTRAJ model using the actual wind field data which were collected from the Dingcuo Air Quality Monitoring Station (AQMS) near LSIC from 00:00 to 23:59 on November 30, 2022. With a reverse time of 1 h and the resolution step of 1 min, the transport path of the sampled air mass was tracked as shown in Fig. 3. The simulations illustrated that the trajectories from Locations 1 and 2 were tracked to the pollution sources in the southwest, and polluted air was blown from the sea to the land by the southwestern wind, passing through the Kaohsiung Port to the LSIC and then to the sampling locations. The traceability path of Location 2 passed through the chimney of Plant A (as labelled in Fig. 3), indicating that the NTS on the drone could effectively collect VOCs emitted from the chimney at

![Fig. 3. Dispersion path prediction of sampling plumes using the FYTRAJ model for Site A.](image-url)
Location 2 (closer to the target chimney and at the downwind), and the analysis of VOCs was more representative than those at Location 1 (farther away from the chimney and not exactly at the downwind).

In these cases, same simulation procedures were followed up for the FYTRAJ model by substituting the actual wind field data of the AQMS at Zhongshan Junior High School from 00:00 to 23:59 on December 12, 2022. As illustrated in Fig. 4, all trajectories of air samples collected at Locations 3–6 showed that VOCs came from the north, and the dispersion routes of air plumes passed through LSIC from the Xiaogang residential area to the sampling locations. We thus concluded that the VOCs identified in these air samples fully represented the emission components from Plant B.

The approach for evaluating the effectiveness of on-site sampling by a drone flight at target Sites A and B was to apply the simulation of dispersion trajectories to examine whether the target sites are located on the dispersion paths. According to the air mass backward trajectory simulation after sampling, one of the two sampling points at Site A was less representative, that is, the sampling point is not located at the downwind of VOCs emission source. While, other four sampling points at Site B were relatively representative, that is, the sampling points were highly likely located at the downwind of the VOCs emission source. If the wind directions varied much during the sampling periods, it might cause significant deviations between the species and the concentrations of the emitted and the sampled VOCs by the NTS carried on a drone. To improve the correctness of traceability analysis, it can be overcome by properly increasing the number of NTS sampling flights.

In fact, we further adopted the weather forecast data of the Bureau of Meteorology during the sampling periods, plus the emission data of the indicator emission source, and used the atmospheric dispersion model (AERMOD) to facilitate the plan of suitable drone sampling locations and heights. Although the AERMOD model has been widely applied for predicting and evaluating the atmospheric dispersion of VOCs (Cimorelli et al., 2005; Perry et al., 2005; Kumar et al., 2006; Haq et al., 2019), significant deviations still exist between the forecasted and the actual wind direction during the sampling days. Additionally, in developing countries, the availability of surface and up-per air

![Fig. 4. Dispersion path prediction of sampling plumes using the FYTRAJ model for Site B.](image-url)
Table 2. Comparison of different atmospheric sampling and monitoring devices carried on a drone.

<table>
<thead>
<tr>
<th>Sampling and monitoring devices</th>
<th>Teflon air bag</th>
<th>Stainless steel canister</th>
<th>Micro detector</th>
<th>Needle trap sampler</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of drone</td>
<td>Large hexacopter</td>
<td>Large hexacopter</td>
<td>Rotary wing</td>
<td>Small quadcopter</td>
</tr>
<tr>
<td>Aircraft load capacity</td>
<td>Heavy</td>
<td>Heavy</td>
<td>Middle</td>
<td>Small</td>
</tr>
<tr>
<td>Pollution sources</td>
<td>Large industrial area</td>
<td>Large industrial area</td>
<td>Specific source</td>
<td>Specific source</td>
</tr>
<tr>
<td>Analysis instrumentation</td>
<td>GC-MS</td>
<td>GC-MS</td>
<td>Lidar systems</td>
<td>GC-MS</td>
</tr>
<tr>
<td>Identification of individual gaseous compounds or not</td>
<td>Yes</td>
<td>Yes</td>
<td>Not</td>
<td>Yes</td>
</tr>
<tr>
<td>Analysis concentration of VOCs and detection limit</td>
<td>36–327 ppb; 0.03–0.95 ppb</td>
<td>8.4–46 ppb; no detection limit data</td>
<td>No data(a)</td>
<td>63–1653 ppb; 2–18 ppb</td>
</tr>
<tr>
<td>References</td>
<td>Vo et al., 2018</td>
<td>Yuan et al., 2021</td>
<td>Fumian et al., 2020</td>
<td>This study</td>
</tr>
</tbody>
</table>

(a) Authors did not provide the VOC concentrations and detection limits due to the Lidar system has been under development.

meteorological data is limited, which also results in the inaccuracy of model predictions (Haq et al., 2019; Kalhor and Bajoghli, 2017). Rzeszutek et al. (2017) and Rzeszutek and Szulecka (2021) particularly emphasized that the accuracy of AERMOD modelling results depends on the quality of the input data, including the representativeness of the meteorological data. In this work, the actual atmospheric dispersion of the forecast at Site A was better than the simulation using the AERMOD model, and the actual wind direction was 110° from the predicted azimuth. The actual atmospheric dispersion of VOCs at Site B was also better than the simulation, and the actual wind direction was 72° away from the estimated azimuth. Thus, the atmospheric dispersion of VOCs is not easy to be accurately forecasted by the AERMOD model, resulting in large difference of angles (72–110°) between the forecast and the actual directions of downwind. Therefore, we suggest that the optimum sampling location should be decided based on the direction of flume from the outlet of the target chimney.

A comparison of small-sized samplers or detectors that are equipped on a multirotor drone for monitoring organic compounds is shown in Table 2. Teflon air bag and stainless steel canister are commercial products, so they are easiest to be used. The micro detector is cheap and the signal transmission is fast. However, a large-scaled gas collection device is heavy and requires a heavy-duty aircraft to load it; the micro detectors are more suitable for monitoring total volatile organic compounds (TVOCs) and cannot specify individual VOCs.

4 CONCLUSIONS

A quadrotor drone equipped with a micro sampler was successfully applied to sample VOCs emitted from suspected chimneys in an industrial complex, and the results of qualitative and quantitative analysis of VOCs by a GC-MS, with the backward trajectory simulation of VOCs can effectively trace the sources. The analytical results provided a reference for subsequent air quality management. In this work, we used the AERMOD model to simulate the flume dispersion from a source for predicting the sampling point in advance, but the prediction was so different from the reality due to rapidly changing atmospheric conditions. If the UAV was equipped with a temperature telemetry device for detecting flume from a suspected chimney, and the data were transmitted to the ground personnel at the same time, even if the emitted flume is invisible, the operator can fly the vehicle immediately into the plume to take air samples. The representative samples and their concentration data were then obtained. This novel sampling method is recommended to be implemented in the future to improve the effectiveness of monitoring to VOCs.

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ADDITIONAL INFORMATION AND DECLARATIONS

Disclaimer
The authors declare no conflict of interest.

Supplementary Material
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