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# Using a Micro Sampler on a Drone to Extract Organic Vapors—A Case Study of Monitoring Industrial Pollution

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## ABSTRACT

Kaohsiung city located in the southern Taiwan is an industrial town and air pollutants were emitted from factories in the adjacent industrial zones. In order to track the pollution emission sources, a needle trap sampler (NTS), which is a micro solid phase microextraction (SPME) sampling device, was carried by a quadrotor drone to extract organic vapors from industries. The NTS was fabricated by packing divinylbenzene (DVB) particles of 60–80 mesh diameters into a 7 cm-long, 22-gauge stainless steel needle. The telescoping sampling device was carried by a DJI Mavic Pro quadrotor drone, and its effectiveness for extracting organic vapors from industrial processing air exhausts from chimneys was studied. The total weight of sampling device, including a NTS, a telescoping shaft, a Li-battery, a mini-air pump and the ABS (acrylonitrile butadiene styrene) loading frame, was less than 200 g. The mainly emitted compounds, including aromatic hydrocarbons (toluene of 1,450 ± 650 ppb, ethylbenzene of 34 ± 12 ppb and xylenes of 51 ± 25 ppb), formaldehyde (50 ± 12 ppb), alkanes (propane of 30 ± 10 ppb), triacetin (7,620 ± 1600 ppb) and terephthalic acid (20 ± 5 ppb) were collected and then identified by the off-line gas chromatography (GC)-mass spectroscopy (MS) system in the laboratory. The quadrotor drone successfully monitored air pollution and tracked their emission sources from waste incineration, petroleum refinement, chemical processing and electronic part production.

**Keywords:** Drone, Air sampling, Needle trap sampler, Monitoring, Air pollution



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## 1 INTRODUCTION

Technology for monitoring the atmospheric environment using unmanned aircraft systems (UAS) has recently been developed. The effectiveness of UAS depends on mission objectives, and different types of aircraft and sensors have been used. Drones are VTOL (vertical take-off & landing) UAS, which require no takeoff or landing run, and are commonly used in situations where access to terrain is limited (Watts *et al.*, 2012). The other advantage of drones is their high mobility. A drone can fly near the sources of air pollution, and thus detects emitted compounds using micro detectors or takes air samples for analysis.

Optical and electrochemical micro detectors have been used on a drone to detect the gaseous compounds and particle matter (PM). Greenhouse gases, such as carbon dioxide ($CO_2$), carbon monoxide (CO), nitric oxide (NO), nitrogen dioxide ($NO_2$), ozone ($O_3$) and methane ($CH_4$), are the main monitored gaseous compounds (Huang, 2013; Villa *et al.*, 2016; Schuyler and Guzman, 2017; Gu *et al.*, 2018; Chiba *et al.*, 2019; Guimarães *et al.*, 2019). $PM_{2.5}$ (diameter < 2.5 µm) and $PM_{10}$ (diameter < 10 µm) are the main PM measurement targets (Gu *et al.*, 2018; Zhou *et al.*, 2018). Micro detectors are suitable for use on a drone for detecting gaseous compounds and PM owing to their light weight and real-time monitoring ability. However, volatile organic compounds (VOCs) are generally detected as TVOCs (total VOCs) and individual compounds cannot be identified using micro detectors.

To collect gas samples and identify the organic compounds, stainless steel canisters have been installed on drones for sampling. Chang *et al.* (2016, 2018) collected air samples using 2-L stainless steel canisters on an octo-rotor multicopter to study 106 VOC emissions from a traffic tunnel, and the seasonal distributions of VOCs in the sky, following their transportation from Mainland China, Southern Korea and Japan to northeastern Taiwan. Vo *et al.* (2018) installed a 0.5-L stainless steel canisters on a quadcopter to collect the ambient gas samples from hundreds of meters to 1 km above several industrial parks in southern Taiwan. VOCs, ketones and alkanes were identified as fingerprints of sources of industrial pollution based on instrumental analysis in the laboratories (Vo *et al.*, 2018). McKinney *et al.* (2019) used a DJI Matrice 600 professional grade hexacopter, which carried 5 VOC sorbent cartridges (0.90 kg and dimensions of 19 cm × 20 cm × 5 cm) to collect biological VOCs, which were emitted from Amazonia forests, for the off-line analysis by the gas chromatography. Such laboratory analysis depends on the use of large canisters and sorbent cartridge devices, which must be carried by a large drone.

Different types of micro active sampling systems have been used on a drone to extract atmospheric gaseous compounds. Aurell *et al.* (2017) designed a VOC sampler for use in a hexacopter (DJI Innovations Matrice 600). They used a Carbotrap 300 stainless steel thermal desorption tube and a micro air pump to take gas samples in the thermal desorption tube to evaluate factors that affect air emission from open-area combustion sources. Cheng *et al.* (2019) used a quadrotor drone (Mavic Pro, DJI) to carry a needle trap sampler (NTS) that was packed with adsorbent to collect toluene, ethylbenzene and xylene exhausted from chimneys by the active sampling mode. Li *et al.* (2020) also developed and tested the similar active sampling pump, which was connected to an air bag on a hexacopter drone, to collect carbon dioxide, $PM_{2.5}$ and $PM_{10}$ above a corn field for examining.

In this work, a quadrotor drone (Mavic Pro, DJI), that was equipped with a NTS, was used to extract air compounds from industrial sources around Kaohsiung City, southern Taiwan. Additionally, two sampling sites were sampled using different types of sampling devices, NTS devices and Tedlar sampling bags on the drone, respectively, to compare the performances of sampling air compounds. Based on the gas chromatography (GC)-mass spectroscopy (MS) analysis, the emitting factories were further identified.

## 2 METHODS

### 2.1 Sampling Sites

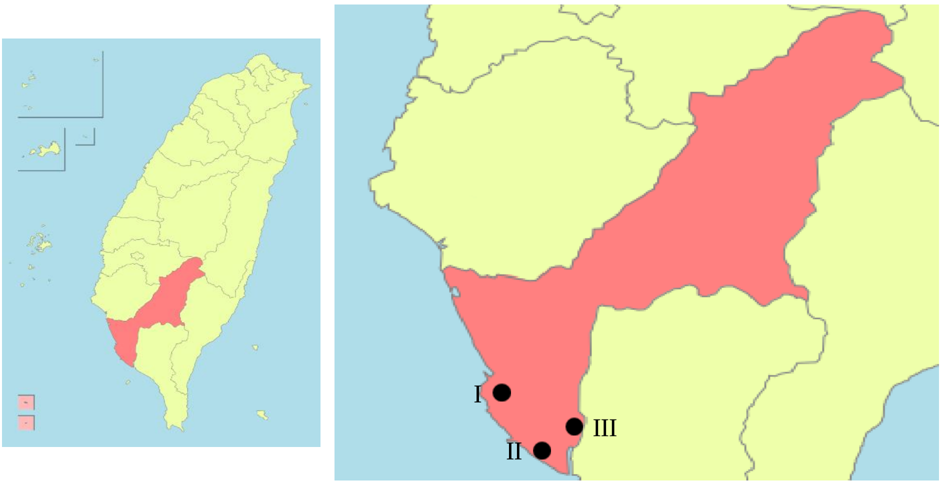
Air samplings were performed at seven sites (Fig. 1) using a NTS on a Mavic Pro quadrotor drone (DJI, China) from June to November, 2019. Table 1 presents the sampled air pollution sources. Sampling A targeted stationary industrial exhaust outlets. Sampling B was in response to public chemical emission complaints. Sampling C was performed using the NTS on a drone for comparing the analysis data from a stationary Fourier Transform Infrared (FTIR) spectrometer, or the micro sensors. The FTIR and micro sensors have been installed at the specific hot zones around target industrial parks.

### 2.2 Drone and Sampling Device

The DJI Mavic Pro quadrotor drone is small and it can be flown above industrial manufacturing areas (Fig. 2). The launching weight of the Mavic Pro quadrotor drone was 734 g (DJI, 2020) and the total weight of the sampling device equipped on the drone was 200 g. Therefore, the maximum flight period of the drone continued for 15 min. The detailed specifications of sampling device are the same as those in the earlier work (Cheng *et al.*, 2019). The optimal location around the drone to sample VOCs for avoiding the downward air flows resulted from the rotating propellers was simulated by the SoildWorks software (2018), and then examined using a pilot emission plan test. The location of the inlet of the NTS to extract VOCs was below the head of the drone, exactly a vertical distance of 75 mm, and a horizontal distance of 173 mm from the center of the propeller, as shown in Fig. 2.

### 2.3 Preparation of Needle Trap Samplers

The NTS extracted gaseous chemical compounds through a needle by air diffusion. A linear




Taiwan and Kaohsiung City

Kaohsiung City adjacent industrial zones:
I. Nanzih Export Processing Zone (Plant A1)
II. Linhai Industrial Park (Plants A2, B2, C2 and C3)
III. Dafa Industrial Park (Plants B1 and C1)

**Fig. 1.** Sampling sites: Kaohsiung City adjacent industrial zones (Wikipedia, 2020).

**Table 1.** Descriptions of air pollution sampling sites.

| Sampling/Monitoring types | Numbers of sampling sites | Descriptions of air pollution and sampling location |
|---|---|---|
| A. Plant chimney exhaust | 2 | Plant A1: Sampling at chimneys from the capacitor processing.<br>Plant A2: Sampling at chimneys from the WWTB[(a)] collecting chemical manufacturing[(b)]. |
| B. Plant emission | 2 | Plant B1: Emission tracking around an incinerator of biomedical waste.<br>Plant B2: Emission tracking from an industrial park for electronic component processing. |
| C. Industry park monitoring | 3 | Air monitoring C1: NTS sampling simultaneously with a stationary FTIR[(c)] spectrometer for monitoring gaseous compounds around a complex industrial park.<br>Air monitoring C2: NTS sampling organic compounds simultaneously with stationary $PM_{2.5}$ micro sensors for monitoring around a petrochemical industrial park.<br>Air monitoring C3: NTS sampling organic compounds simultaneously with stationary $PM_{2.5}$ micro sensors for monitoring around a complex industrial park. |

Note:
a. WWTB indicates a wastewater treatment basin in Plant A2.
b. Plant A2 manufactures several chemicals, including formaldehyde, paraformaldehyde, hexamethylenetetramine, dipentaerythritol and sodium carbonate.
c. FTIR indicates the Fourier transform infrared spectrometer.

gaseous concentration profile ($C(Z)$ in Fig. 3) was obtained along the diffusion path ($Z$), and the extraction of the analyte was characterized by the area ($A$) of the opening of the needle and its length of the diffusion path. The total mass ($n$) of analyte that was adsorbed in a time interval ($t$) is given by using Eq. (1) (Lord *et al.*, 2010).

$$n = D_m \frac{A}{Z} \int C(t) dt \tag{1}$$

where $D_m$ is the diffusion coefficient of the compound that is adsorbed from the air by the NTS.

**Fig. 2.** The quadrotor drone with a needle trap sampler (red circle) on the telescoping shaft.

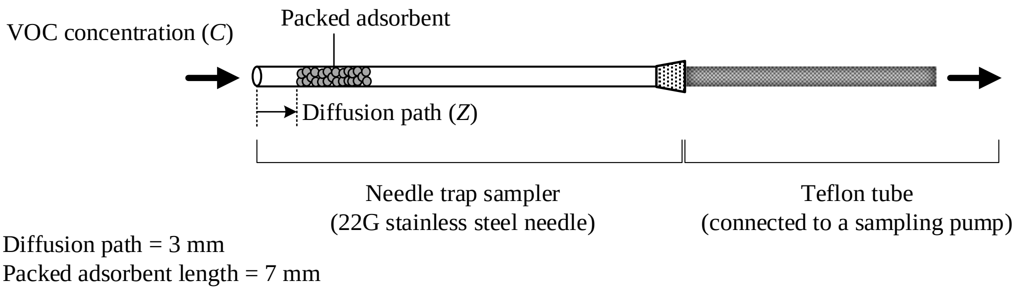



**Fig. 3.** Schematic needle trap sampler.

Accordingly, the quantity ($n$) of the extracted analyte is assumed to be proportional to the mean sample concentration over a time interval, $C(t)$.

NTS comprises of a 22-gauge stainless steel needle that is packed with DVB adsorbent with a 60–80 particle size. DVB particles were packed by aspiration to the desired length of 7 mm and a diffusion path length of 3 mm (Fig. 3). A very small amount of epoxy glue was applied to the exposed portion of the adsorbent layer to immobilize DVB particles. Finally, the DVB in the NTS was conditioned by heating at the injection port of the GC to 280°C for 30 min.

The uniformity of the packing phase in an NTS was evaluated by following the procedures which were establish in the earlier works (Cheng *et al.*, 2011, 2013). The desired air flow rate through the NTS was set by drawing air through the packing phase using an aspiration pump. When the relative standard deviations (RSD) of the flow rates across three duplicate tests did not exceed 5%, the packed materials inside the NTS were assumed to be uniformly immobilized. Standard gas samples, the mixture of benzene, toluene, ethylbenzene and p-xylene (BTEX, analytic grade, Merck, Germany), around 10 ppm, were prepared in a 500 mL Pyrex glass bulb, in which the NTS was inserted for 1–2 h to adsorb gaseous BTEX. When the RSD of the sampled mass in triplicate tests was less than 5%, the BTEX adsorption capacities of the tested NTS were qualified and the NTS was ready for use (Cheng *et al.*, 2011, 2013).

## 2.4 Chemicals, Instrumental Analysis and Calibration Procedures

Stainless steel needles (22 G, length 7 cm and ID 0.41 mm, Fig. 3) were purchased from a local company (Herling Co. Ltd., Pingtung, Taiwan) for use in preparing the NTS. Adsorbent DVB particles were purchased from Supelco (Bellefonte, PA, USA). The unknown compounds in the air collected in fields were identified using an Agilent (Wilmington, DE, USA) GC (6890N)-MS (5973) system. The GC capillary column was HP19091Z-413 HP-1 PDMS (30 m × 320 µm × 0.25 µm) (Agilent Technologies, Inc., Wilmington, DE, USA). All gases (Jing-De Gas Co., Ltd., Kaohsiung, Taiwan) that were used in GC-MS analysis were of ultra-high purity, and the standard chemicals (Merck, Darmstadt, Germany) in the quantification analysis were analytic grade.

Tedlar sample bags with a volume of 1 L (SKC, Blandford, UK) were used for sampling emissions from Plants A1 and A2 to evaluate the feasibility of using the drone with an NTS. After the sampling was finished and then the NTS was removed, a Tedlar sample bag was installed and connected to the sampling tube. After VOC sampling, the NTS and Tedlar sample bags were taken to the laboratory and then inserted into the injection ports of the GC for analysis. The desorption time and temperature at the injection port were 30 s and 250°C, respectively. The temperature of the GC was increased from 50°C in increments of 15°C $min^{-1}$ to 180°C, which was held for 2 min. The flow rate of the carrier gas, helium, was 1.8 mL $min^{-1}$. Notably, according to the verifications by the earlier examinations by Cheng *et al.* (2011, 2013) using the operation procedures of analysis, no carryovers were available when NTS samples were thermally desorbed at the GC inlet ports.

The calibration analysis for organic compounds collected by NTS was carried out in the laboratory using a Tedlar bag of 1 L. The laboratory assistant used a micro syringe, injecting the liquid target chemical of 0.05 µL into the Tedlar bag, which is filled with 1-L zero air, and then put the bag in the oven under 40°C. After 1 hr, the compound is completely evaporated, and the concentration of the compound in the bag is $C_1$ (ppm). The calibration standard samples were of 0.5–10 ppm. Finally, the sampling pump of the same specifications as that was installed on the drone, was used to connect the NTS to the bag for an active sampling mode. Because the Tedlar bag is compressible, the volume of bag is reducing with the exhausting time; however, the concentration of the target compound in the Tedlar bag remains the same. When the sampling time is 1 min, and the GC-MS integral analysis area of the NTS is $A_1$, the concentration $C_2$ (ppm) of the target compound sampled by the NTS in the site is calculated as

$$C_2 = \left[\left(\frac{A_2}{A_1}\right) \times \frac{1}{t}\right] \times C_1 \quad (2)$$

where $A_2$ is the GC-MS integral analysis area of NTS taking a sample in the feild; and $t$ is the sampling time in the site. For example, triacetin was examined with an integral analysis of 605,424 by the GC-MS, and the sampling time in the field was 10 min. The standard concentration of gaseous triacetin prepared in the 1-L Tedler bag is 6.5 ppm and the analysis area by the GC-MS was 1,787,708. Substituting the data into the Eq. (2), the concentration of triacetin in the site was calculated as (605,424/1,787,708) × (1/10) × 6.5 = 0.220 ppm = 220 ppb.

For calibration analysis for the air sample, taken using a Tedlar bag in the fields, the laboratory assistant prepared chemicals of given concentrations in a 550-mL glass bulb, and then the 1 mL gastight syringe was used to draw a gas sample from the bulb for analysis using the GC-MS. The integral area was obtained for the given concentrations of target compounds. The concentration of gaseous compounds in the Tedlar bag, were also determined based on the proportional calculation, substituting the data of the calibration analysis into Eq. (2). According to the minimum analysis area which were examined by the GC-MS, the method detection limits for the standard chemical compounds by NTS sampling were: BTEX 1.0–2.2 ppb, triacetin 3.6 ppb, propane 4.0 ppb, terephthalic acid 3.0 ppb and aldehydes 2.0 ppb.

# 3 RESULTS AND DISCUSSION

## 3.1 The Feasibility of Using a Drone with an NTS for Industrial Pollution Sampling

Plant A1 is a capacitor manufacturing factory, in which toluene and ethanol are the main solvents that are used for cleaning. The drone sampling was performed around the chimney exhaust outlet. Plant A2 is a chemical manufacturing plant, in which formaldehyde is used as the main raw material. Table 2 summarizes the analysis of data that were obtained using the NTS sampling device on the drone.

Table 2 shows that the analyzed concentrations of compounds that were sampled using NTS and Tedlar sampling bags in Plants A1 and A2 are close to each other. Therefore, the novel sampling device, NTS, is an effective alternative to traditional sampling method, such as sampling

**Table 2.** Analysis data obtained by sampling of NTS on the drone at chimneys of Plants A1 and A2.

| Compounds exhausted from chimneys | Toluene @ Plant A1[a] | | Formaldehyde @Plant A2[a] | |
|---|---|---|---|---|
| Concentration (ppb)[d] | by NTS[b,c] | by sampling bag[b,c] | by NTS[b,c] | by sampling bag[b,c] |
| | 1,450 ± 650 | 1,590 ± 700 | 50 ± 12 | 60 ± 15 |

Notes:
a. Taking air samples at chimneys from Plant A1 for 6–9 min at a height of 8 m (standing on a 4-floor factory building) @29.5°C, cloudy; and at chimneys from the WWTB of Plant A2, ranged 10–12 min at a height of 7 m @30°C, clear.
b. Taking three NTS samples and two sampling bags at chimneys of Plants A1 and A2.
c. The detailed calculation procedures of concentrations are show in Appendix.
d. Main emitted compounds with concentrations > 10 ppb.

bags. Notably, the exhaust outlets of the respiration valves of large basins and pipeline fittings in the petrochemical factories were found to be the main VOC pollution sources. Considerable human effort should be made to conduct routine examinations of the VOC emission sources at height; however, an occupational accident always easily occurred when workers worked at height. The use of a drone that is equipped with a micro sampler is a safer means of sampling than standard sampling procedures that are legislated by governmental environmental protection departments. In particular, in highly industrialized urban areas, such as the Kaohsiung metropolitan area in Southern Taiwan, where more than 8,500 tons of VOCs were emitted by industry in 2018 and 2019, based on the report of Environmental Protection Bureau of Kaohsiung City Government (EPBK) (2020), drones with micro samplers should be used more frequently than now.

However, the Tedlar sample bag is not recommended as a general sampling device to be carried by the small drone like Mavic Pro quadrotor used in this study, because the bag is large, reducing the operational control and safety of the drone in flight. More important, a sampling pump with a flowrate of 600 mL $min^{-1}$ yields a collection period of less than 2 min for a 1-L sample bag, which results in the collection time using a drone for air sampling is limited. A NTS can perform a time-weighted-average (TWA) sampling of air pollutants during the flight of a drone at least 12–15 min, and its very small size makes it the preferred sampling device.

The affinity of DVB adsorbent to alcohols is low because of the high polarity of ethanol, so the DVB-NTS extracted low amount of ethanol from Plant A1. The final section of this work presents an alternative method for sampling chemical compounds with low affinities to DVB.

## 3.2 Using a Drone with a Micro Sampler for Monitoring and Tracing of Emission Sources

The public has frequently complained about chemical emissions around the southeast of Dafa Industrial Park. In June, 2019, an early morning, which was the time of the day when complaints were most frequent, a drone flight was used to collect air samples upwind and downwind Plant B1, which incinerates medical wastes. Table 3 presents at the upwind, triacetin had a concentration of 40–220 ppb, whereas downwind, triacetin had a much higher concentration of 9,200 ppb. Triacetin is widely used as a mobile-phase solvent in biomedical manufacturing. Based on air sampling using a drone, EPBK carried out an audit at Plant B1 in January, 2020, fining the manager for incinerating wasted organic solvent and illegally exhausting air pollutants.

Other public complaints of chemical emissions have been made in a neighborhood community near the south western corner of the Nanzih Export Processing Zone. A drone made several sampling flights in an afternoon at the end of September, 2019. Table 3 shows that the main detected air pollutants downwind were ethylbenzene, o-xylene and m-xylene, which are solvents that are used by suspected factories at upwind. Formaldehyde and acetaldehyde (around 20 ppb) were also collected by the NTS at downwind samplings. These aldehydes were probably emitted from the suspected resin synthesis factories at upwind.

Since 2016, EPBK has been installing FTIR spectrometers and micro sensors inside industrial parks and nearby neighborhood communities to monitor chemical emissions as an early warning system for air pollution events. Table 4 presents the results of air sampling and monitoring at industrial parks.

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**Table 3.** Analysis of air samples from the organic compound emissions by the drone with NTS.

| Number of plant | Compounds | Concentration (ppb) | |
|---|---|---|---|
| | | Upwind | Downwind |
| Plant B1 | Triacetin[(a)] | 130 ± 90 | 7,620 ± 1,600 |
| Plant B2 | Formaldehyde[(b)] | 12 ± 2 | 22 ± 2 |
| | Acetaldehyde[(b)] | ND | 20 ± 2 |
| | Ethylbenzene[(b)] | 34 ± 12 | 120 ± 10 |
| | o-Xylene[(b)] | 25 ± 10 | 87 ± 7 |
| | m-Xylene[(b)] | 20 ± 10 | 84 ± 5 |

Note:
a. Triacetin is the main compound and the concentration exceeds 50 ppb. Sampling periods ranged 9–12 min at a height of 20–30 m @27°C, partly cloudy.
b. These five compounds are the main compounds and the concentrations exceed 2 ppb. Sampling periods ranged 11–12 min at a height of 7–8 m @31°C, clear.

**Table 4.** Analysis comparisons of simultaneously air sampling and monitoring for industrial parks.

| Number of air monitoring | Compounds and concentrations (ppb) analyzed and monitored by different approaches | | | | | |
|---|---|---|---|---|---|---|
| | Sampling by NTS and analyzing by GC-MS | | Detecting by FTIR spectrometers | | Detecting by stationary micro sensors[(a)] | |
| Air Monitoring C1[(b)] | Acetaldehyde | 15 ± 5 | Ammonia | 10 ± 5 | – | |
| | Terephthalic acid | 20 ± 5 | Methanol | 10 ± 5 | | |
| Air Monitoring C2[(b)] | Propane | 30 ± 10 | – | | TVOC | 65 ± 24 |
| | Acetaldehyde | 15 ± 5 | | | | |
| Air Monitoring C3[(b)] | p-Xylene | 51 ± 25 | – | | TVOC | 95 ± 12 |

Notes:
a. Micro sensors measured organic compounds as TVOC.
b. The sampling conditions for three air monitoring:
C1: Drone sampling times ranged 12–15 min at a height of 10 m @33°C, clear; the FTIR monitored at 10 m.
C2: Drone sampling times ranged 10–12 min at a height of 8 m @26°C, cloudy; micro sensors were at the same heights.
C3: Drone sampling times ranged 10–12 min at a height of 8 m@32°C, clear; micro sensors were at the same heights.

Air Monitoring C1 was performed using a drone with a NTS at the southern corner of Dafa Industrial Park, simultaneously monitoring with FTIR spectrometers was performed. Acetaldehyde, terephthalic acid and methanol were consistent with emissions from factories in the industrial park. Ammonia, analyzed by FTIR spectrometers, was possibly as a result of neighboring agricultural activities. A NTS carrying by a drone can be used together with FTIR spectrometers to measure the concentrations of air pollutants. That is, an FTIR spectrometer is used to monitor emissions from the hot zone at a fixed height above the ground; however, the mobile drone with a NTS can fly for sampling at different altitudes.

Air Monitoring C2 was performed inside Linhai Industrial Park. Propane at a concentration of 30 ± 10 ppb and acetaldehyde at 15 ± 5 ppb were emitted as a result of the petroleum refining process, and TVOC at 65 ± 24 ppb was also detected by the micro sensors. Air Monitoring C3 was performed inside Dafa Industrial Park. p-Xylene at a concentration of 51 ± 25 ppb was emitted by the manufacture of flexible circuit boards at upwind, and TVOC at 95 ± 12 ppb was detected by the micro sensor.

## 3.3 Comparisons of Different Types of Samplers Carrying by a Drone to Extract Organic Pollutants from Emission Sources

Table 5 summarizes the results of different types of samplers on a drone to collect organic compounds from stationary sources. Typically, GC-MS is an essential instrument for analysing the unknown organic compounds in the ambient. Also, the medium to mini sized multicopters, manufactured by DJI, are the commonly-used carriers for installing the sampling devices recently due to their lower launching weights than governmental maximum limits (Villa *et al.*, 2016). Hexa-

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**Table 5.** Comparisons of organic gaseous compounds from stationary sources sampling via a drone in recent studies.

| Specifications of drones | Emission sources | Sampler[c]/Analysis | Chemicals and emitted concentrations[d] | References |
|---|---|---|---|---|
| DJI Innovations Spreading Wings S-1000 octo-rotor multicopter 1,045-mm diagonal, launching weight 11 kg[a] | Exhaust shafts of a vehicle tunnel (sampling at 10–200 m) | 1-L Stainless steel canister with a solenoid valve/GC-MS | Alkanes 2–20 ppb<br>Alkenes 1–24 ppb<br>Aromatic compounds 1–23 ppb<br>Ethyne 0.5–4 ppb<br>Oxygenated compounds 1–4 ppb | Chang *et al.*, 2016 |
| DJI Innovations M600 hexacopter 772-mm diagonal, launching weight 15.1 kg[a] | Open burning sites at two obsolete ordnance bases (sampling at 524–602 m) | Adsorptive tubes, Carbotrap 300 with a pump/GC-MS | PAHs 0.01–0.31 ppb[e][f]<br>Benzene 2 ppb[e] | Aurell *et al.*, 2017 |
| DJI octo-rotor multicopter[b] | Ambient air above two industrial parks (sampling at 100–1,000 m) | 400-mL Stainless steel canister with a solenoid valve/GC-MS | TVOCs 40–327 ppb[g] | Vo *et al.*, 2018 |
| DJI Mavic Pro quadrotor drone 335-mm diagonal, launching weight 0.734 kg[a] | VOC matrixes exhausted from a chimney (pilot plan test and sampling around 2 m) | Adsorptive needle trap sampler with a pump/GC-FID | Toluene 142 ± 20 ppm<br>Ethylbenzene 359 ± 23 ppm<br>p-Xylene 176 ± 19 ppm | Cheng *et al.*, 2019 |
| DJI Mavic Pro quadrotor drone 335-mm diagonal, launching weight 0.734 kg[a] | Industrial chimneys (sampling at 7–30 m) | Adsorptive needle trap sampler with a pump/GC-MS | Toluene 1,450 ± 650 ppb, Ethylbenzene 34 ± 12 ppb, Xylenes of 51 ± 25 ppb, Formaldehyde 50 ± 12 ppb, Propane 30 ± 10 ppb, Triacetin 7,620 ± 1600 ppb, Terephthalic acid 20 ± 5 ppb[h] | This study |

Notes:
a. Length excluding propellers and launching weight excluding sampling devices.
b. Detailed specification information is not available.
c. The samplers were equipped on the drones.
d. Listing the chemicals of the top five compounds or significant compounds in the reference and this work.
e. Calculated from the reported data which was originally presented in µg $m^{-3}$.
f. Main PAHs including naphthalene, fluorine, phenanthrene, fluoranthene and pyrene.
g. Main VOCs including C2-VOCs, ketones, and BTEXs.
h. Sampled from different industrial emission sources.

and octo-rotor multicopters, which has a launching weight higher than 11 kg, were suitable to convey heavy sampling devices, like stainless steel canisters and metal adsorptive tubes, to collect chemicals at high altitude (from hundreds to one thousand meters); however, mini drones (DJI Mavic Pro series) performed satisfyingly when it was used to cruise between industrial factories and collect air samples exhausted from chimneys below 30 m. DJI Mavic Pro quadrotor drone has a low launching weight 734 g, so the small-sized NTS with the telescoping shaft and ventilation system, which is less than 200 g, is adequately delivered by it. Notably, the cruising period of the quadrotor drone with the sampling device ranged from 10 to 15 min.

### 3.4 Limitation: Using DVB as NTS Adsorbent for Sampling Compounds of High Polarities

Based on the results of the sampling and analysis for Plants A1, A2, B1 and B2, and Air Monitorings C1–C3, the sampling of air using a drone with a NTS and GC-MS analysis are determined to be a satisfactory alternative to the use of traditional ambient sensors. The greater advantage of DVB-NTS sampling and GC-MS analysis is their ability to identify individual organic compounds. However, alcohols, which are widely used chemicals in industry, cannot be completely adsorbed by DVB.

Actually, Tedlar sample bags (1 L) were used for taking air samples from Plant A1, and ethanol at a concentration of around 1,050 ppb was thus collected from a chimney outlet, but NTS just adsorbed 805 ppb ethanol for the same exhaustion. Therefore, finding alternative adsorbents to replace DVB to sample more chemical compounds, or modifying the affinity of DVB to adsorb hydrophilic alcohols, is an important task.

## 4 CONCLUSIONS

In this work, an NTS, which is a micro sampler, was installed on a telescoping shaft and carried by a quadrotor drone for tracking the emission sources of organic compounds. The sampling device was investigated to determine its feasibility for sampling organic vapors from factories. It was successfully used to monitor air pollution and track sources of industrial emissions. The light weight and very small size of the NTS enable its installation as a sampler on the drone for cruising between the factories in the industrial zones, especially a highly industrialized town like Kaohsiung City. Notably, the NTS is an environmental friendly sampling technology because it is reusable and it uses no solvents when it is thermally desorbed in the injection port for the analysis using a gas chromatography. So a drone, which carries a NTS, is promoted to collect air samples for industrial emissions.

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