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Viability and Application of Mounting Personal PID VOC Sensors to Small Unmanned Aircraft Systems

Cheryl Lynn Marcham
Embry-Riddle Aeronautical University

James P. Solti
Embry-Riddle Aeronautical University

Scott S. Burgess
Embry-Riddle Aeronautical University

Brandon Breault
Embry-Riddle Aeronautical University

Joseph Cerreta
Embry-Riddle Aeronautical University

Joshua G. Marcham
Embry-Riddle Aeronautical University

Patti J. Clark
Embry-Riddle Aeronautical University

Using a UAS-mounted sensor to allow for a rapid response to areas that may be difficult to reach or potentially dangerous to human health can increase the situational awareness of first responders of an aircraft crash site through the remote detection, identification, and quantification of airborne hazardous materials. The primary purpose of this research was to evaluate the remote sensing viability and application of integrating existing commercial-off-the-shelf (COTS) sensors with small unmanned aircraft system (UAS) technology to detect potentially hazardous airborne contaminants in emergency leak or spill response situations. By mounting the personal photoionization detector (PID) with volatile organic compound VOC sensor technology on UAS platforms, the needed information may be obtained at an optimum range and resolution without needlessly exposing a human to possible adverse conditions.

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Small Unmanned Aircraft Systems (sUAS) less than 55 pounds have demonstrated tremendous usefulness in emergency and disaster response, mapping, inspection, and other analytic functions (Nex & Remondino, 2014; Remondino, Barazzetti, Nex, Scaioni, & Sarazzi, 2011). UAS are useful because they can fly over contaminated or inaccessible areas to mitigate some risks to first responders of having to do these tasks themselves (Nex & Remondino, 2014), and they fast data acquisition and mapping during emergency response actions (Remondino et al., 2011). UAS are currently used in emergency response for search and rescue, thermal imaging locating hotspots in fires, and evaluating structural stability (Calams, 2018). For example, the Millstone Valley, New Jersey Fire Department reportedly uses four different DJI models in various techniques for search and rescue (Petrillo, 2018). Since these devices can provide a live video feed, they can also “provide a real-time overview on the spread of wildland fires and the potential harm to firefighters, the public and the surrounding communities” (Werner, 2015, para. 4). The New York Fire Department (FDNY) has been using HoverFly tethered sUAS equipped with video and infrared cameras at incident scenes since March 2017 to provide real-time situational and operational awareness, particularly in seeing where a fire may be traveling, but they can be also be used for fire surveillance, identifying hot spots, search and rescue, hazardous materials reconnaissance, and accident reconstruction (Petrillo, 2018). The Los Angeles Fire Department (LAFD) uses DJI Matrice 200 Series, Matrice 600 Series, and Phantom 4 Pro sUASs equipped with electro-optic and thermal imaging cameras to identify hot-spots, perform aerial mapping, search and rescue, and for water rescues (Lillian, 2019).

In aviation, first responder localization and recovery of aircraft crash site survivors are often challenged by induced environmental hazards, such as pending fire hot spots and potential exposures to hazardous compounds such as residual fuels and combustion byproducts, some of which are known to cause a variety of adverse cardiovascular, respiratory, and neoplastic diseases (Brandt-Rauf, Fallon, Tarantini, Idema, & Andrews, 1988). The National Transportation Safety Board (NTSB) is currently using to capture images at accident sites as well as search for aircraft components for recovery and reconstruction (Bauer, English, & Richards, 2018). Using high-quality photos and photogrammetry, orthomosaic maps and 3-D models of crash sites can be created and viewed expeditiously, providing information from hard-to-access areas and keeping investigators safe (English, 2017).

Companies are incorporating the use of sUAS to perform a plethora of dangerous jobs, including inspection of confined spaces and towers, and entering tunnels and smokestacks (Pitcher, 2019). Shell (Oil Company) is using sUAS to inspect gas flares, eliminating the need to take the system offline to make it safe enough for humans to perform the work (Pitcher, 2019). The West Memphis Fire Department proposed the use of its DJI Phantom 4 sUAS after personnel had issues trying to get close to, and gather information about, a chemical spill. The use of the sUAS would allow viewing and approaching spills without putting responders in danger (Heard, 2017).

When encountering a crash site or a chemical spill, emergency responders must consider both physical hazards and chemical hazards that may be present and must protect themselves accordingly. When potential chemical exposure is present, the U.S. Department of Labor Occupational Safety and Health Administration (OSHA) requires that emergency responders be adequately protected from the hazards. In the absence of information regarding what chemicals are present, and/or what airborne concentrations are present, OSHA (2005) requires that maximum protection be provided to responders until the potential exposures can be characterized. This protective gear generally includes the use of a self-contained breathing apparatus and appropriate full suit protective clothing (OSHA, 2005). In addition to delaying the response, this personal protective equipment (PPE) provides a significant physiological burden for the responders (United States Department of Homeland Security/Federal Emergency Management Agency, 2004). Wearing this protective gear, workers must enter the potentially contaminated area and use direct-reading chemical sensor instruments to characterize potential chemical exposures (Kuiawa, 2003). Reassigning the task of evaluating potential exposures to a remotely operated UAS can protect workers, and reduce the cost and time associated with having and donning expensive and burdensome protective equipment.

In recent years adding sensors to sUAS for various uses has become more commonplace. Multispectral sensors currently in use on sUAS allow for the identification of problem areas, such as wilderness or urban fire hot spots and oil spills or leaks (Eismann, Stocker, & Nasrabadi, 2009; Campbell, Naik, Sowards, & Stone, 2002; Robinson, 1991). Chwaleba, Olejnik, Rapacki, and Tuśnio (2014) reviewed optical sensors that could be carried on-board an sUAS for atmospheric monitoring and determined that a Light Detecting and Ranging (LIDAR) sensor might be useful to measure ozone and nitrogen dioxide. Rossi and Brunelli (2016) evaluated the ability of metal oxide semiconductor gas sensors mounted on sUAS to determine whether containers of chemicals could be appropriately located. The researchers found that the long reaction and recovery time of these sensors caused a delay in the instrument response relative to the actual location of the chemical source. UAS have been used to measure airborne methane (Berman, Fladeland, Liem, Kolyer, & Gupta, 2012; Golston et al., 2017; Schuyler & Guzman, 2017) and carbon dioxide (Berman et al., 2012; Schuyler & Guzman, 2017). Bullock and Nath (2016) performed a proof of concept study using a UAS to carry air monitoring equipment to evaluate air quality during a fire. A hexa-copter sUAS was equipped with a monitor equipped to measure particulate matter and a four-gas monitor capable of detecting oxygen, carbon monoxide (CO), hydrogen sulfide, and lower explosive limit (LEL) concentrations and compared to readings obtained using identical hand-held real-time air monitoring devices on an elevated platform over the fire plume (Bullock & Nath, 2016). The comparison between the sUAS and elevated platform data was not broadly conclusive, especially in regards to the particulate measurements, which showed significant variability between the two monitoring methods (Bullock & Nath, 2016).

At least one fire department has placed hazmat detector kits on sUAS (in this case on the nose of a DJI Matrice 210 for the Daytona Beach, Florida Police Department) to determine the presence of contaminants in vapor or smoke from a fire. Such technology will only detect the presence or absence of chemicals, and will not provide any estimation of concentrations. At least one company has advertised that it has mounted a multi-gas detector and other sensors on an sUAS, but it appears that the sensors are mounted above the sUAS rotors (FLIR Systems, Inc., 2019). However, there is no information available on whether the placement of either of these detection devices is appropriate, given the potential interference of air movement from the sUAS. In addition, little information has been found addressing whether the use of sensors on sUAS can accurately quantify airborne concentrations of chemicals, such as fuel, from a crash or spill site.

A commonly used commercial off-the-shelf (COTS) sensing device used by emergency responders and safety and health professionals is the photoionization detector (PID). PIDs are sensing devices commonly used as an initial screening tool to monitor the ambient air for parts per million (ppm) concentrations of total hydrocarbons or volatile organic compounds (VOCs), such as those found in solvents, fuels, cleaning supplies, and paints. PIDs are used to determine both the potential hazard to, and to aid in the proper selection of PPE, for emergency responders (Kuiawa, 2003). A PID can also be used to evaluate whether a spilled fluid is a volatile organic compound, and if so, the migration pattern of airborne contaminants (Kuiawa, 2003).

The PID consists of a short-wavelength ultraviolet (UV) light that ionizes trace organic and some inorganic compounds (RAE Systems, 2013). The charged ions are collected on an electrode where the detector measures electrical current in proportion to the concentration of VOCs present (Crimmins, 2016). The amount of energy required to ionize a gas is called the ionization potential (IP), which is measured in electron volts (eV) (Crimmins, 2016). As a general rule, the PID will only detect chemicals with an IP less than the UV light's eV (Crimmins, 2016). While it does not measure all VOCs, the most commonly used lamp is a 10.6 eV lamp for general-purpose VOC screening, which will detect organic compounds such as painting and printing solvents; fuels such as gasoline, diesel, jet fuel, or kerosene; degreasers such as perchloroethylene; and refrigeration gases such as freons and ammonia (Crimmins, 2016; RAE Systems, 2013), typically in the range of 0.01 to 10,000 ppm (RAE Systems, 2013).

Purpose

The purpose of this pilot study was to evaluate the viability and application of integrating existing COTS sensors with sUAS technology to detect potentially hazardous airborne contaminants.

Research Questions

The research questions to be answered were:

1. Could sUAS-collected data compare to hand-held device collected data to establish sUAS as a future tool for remote exposure assessment?
2. Is it possible to collect airborne VOC information to characterize potential exposures for first responders using the sUAS? If so, can a 3D graphical representation of concentration surrounding the spill be created by mapping concentration to location using GPS data points?
3. Does the sUAS dispersion of air (at various altitudes) influence the VOC instrument readings?

Methodology

In order to evaluate whether sUAS-collected data would compare to data collected from hand-held devices to be able to ascertain whether sUASs may show promise in the future development of remote exposure assessment methods, the researchers simulated a spill scenario and performed subsequent monitoring using both traditional (hand-held) and sUAS-mounted direct reading PID instruments. To closely emulate conditions expected in an actual fuel contamination event, the research team utilized a static location (low ground near the top of a draw) in order to limit varying weather conditions. The goal was to maximize this first proof of concept collection by reducing as many external elements that might dilute test results, to maximize the collection of usable data.

Test equipment. To conduct this research, equipment included a DJI Inspire 1 and DJI Mavic Pro (DJI, n.d.a; DJI, n.d.b), testing equipment, flight operations support equipment, and safety gear and these are further explained below. Specifications for each aircraft are provided in Table 1.

Table 1
Descriptive Specifications for the DJI Inspire 1 and DJI Mavic Pro (DJI, 2019).

	DJI Inspire 1 with X3 camera	DJI Mavic Pro
Dimensions	438x451x301 mm.	88x83x198 mm. (folded)
Weight	6.75 lbs.	1.62 lbs.
Max Speed	49.1 mph.	40.4 mph.
Endurance	18 min.	27 min.
Range	3.1 mi.	9.3 mi.
Operating Frequency	2.4-2.483 GHz; 5.725-5.825 GHz.	2.4-2.4835 GHz; 5.150-5.25GHz.
Sensor	1/23" CMOS 12.3 Megapixels	1/23" CMOS 12.3 Megapixels
Image Size	4000 x 3000 pixels	4000 x 3000 pixels

Source: Adapted from DJI (n.d.-a) and DJI (n.d.-b)

Collection containment vessel. Potential fuel spill scenarios were staged using several gallons of either jet fuel (Jet-A) or gasoline placed in an open-top 32-inch diameter galvanized steel pan in an open field (Figure 1). The steel pan was used to prevent contamination of the fuel, and the pan was placed on a protective non-porous sheet to prevent contamination of the ground.

Figure 1. View of testing area with steel pan on a protective non-porous sheet.

Aircraft. The University's Department of Flight (DOF) performed an analysis of alternatives to select the best-fit sUAS, taking into account the payload sensor weight (2.91 ounces) and size (2.4in x 2.6in x 2.3in). Also, the analysis included a selection of sUAS that could be generalized to common systems selected by public safety agencies. The best fit sUAS included the DJI Inspire 1 and the DJI Mavic Pro (Figure 2). These aircraft performed the following tasks: test aircraft, observation platform, image collection for building orthomosaics from Pix4Dmapper photogrammetry software (Pix4D, 2019).

Figure 2. DJI Inspire 1 with the Ion Cub PID attached with a short tether (left) and DJI Mavic Pro with the Ion Cub PID attached directly below the UAS (right).

Flight operations support equipment. Weather data for wind direction and velocity, temperature, wet bulb, dew point, pressure, and relative humidity were continuously collected using a Kestrel 5500 weather meter. To protect the aircraft and PID during takeoff and landing, a 5-foot diameter helipad was used (Figure 3).

Figure 3. Helipad for takeoff and landing.

Continuous charging of the sUAS Li-Po batteries was needed, thus power was provided by a Honda EU2200i generator. The two days of data collection required enduring high temperatures and humidities, and the flight location included a 30 ftx30 ftx8 ft covered work area to house the team with work areas (bench, tables, chairs, etc.), separating humans from data collection area for safety, and protecting researchers from the elements. Fire extinguishers were also staged in the data collection site.

PID collection devices. Conducting this research required an ability to collect volatile organic compounds, and the ION Science Cub 10.6 eV PID was identified as an initial collection device (testing equipment). This particular device was selected because of its size and weight (only 2.91 ounces), compared to larger, traditional hand-held PIDs that can weigh around 30 ounces or more. The PID is equipped with a datalogger that can record total VOC readings at predefined time intervals that were being mapped to the known location and altitude of the UAS and matched to readings collected on the PID for total VOC. In this way, it was anticipated that a 3D graphical representation of VOC concentration both above and around a staged spill of the known solvent, gasoline, and jet fuel could be created. Two of these ION Science Cub PIDs were utilized for static and mobile collection.

The PIDs had been factory calibrated approximately 6-7 months prior to use, and the devices were field calibrated the day before sampling with a 100 ppm calibration gas. Both PIDs were bump tested prior to use each day to confirm that the instrument's alarms were functional (OSHA, 2013).

Flight profiles. The procedures used for collection included the use of several UAS

(DJI Inspire 1, and DJI Mavic Pro) flying various profiles. One 10.6 eV PID was hung at 24 inches directly over the pan (Figure 4).

Figure 4. PID hung 24 inches directly over pan with a second hung from a tether (close and distant views).

A second 10.6 eV PID was attached both directly to the sUAS via a Velcro™ type strap and on 15, 30, and 45-foot tethers hanging beneath the UAS so that side by side readings could be collected (Figure 4). The 45 foot length was determined through preliminary studies of the sUASs, which showed that rotorwash from the sUAS was visibly observed to disturb the surface of the Jet-A or gasoline in the pan at lower heights, and it was not until the sUAS was at 45 feet above the surface that no visible air disturbance was detected.

Additionally, one PID was directly attached to the Inspire 1 and the Mavic Pro using a Velcro™ type harness (Figure 5).

Figure 5. PID with a velcro harness to the DJI Mavic Pro (left) and the DJI Inspire 1 (right).

For each sUAS, the VOC sensor was first attached directly to the device, and then hung on a 15-, 30-, and 45-foot tether and flown over the pan such that the sensor was also at the height of 2 feet over the pan. Hovering time for each location was a minimum of 2 minutes, with actual hover times recorded in one second intervals. Data were also collected at altitudes of 3-, 5- and 10 feet in circular patterns around the fuel vessel. Data collected by each device were then compared and evaluated.

Because sUAS platforms are not completely intrinsically safe in design (Tompkinson, 2017), it was important to ensure that the sUAS were not operated in a zone in which the airborne concentration could provide an explosive atmosphere. To further explain, the lower explosive limit (LEL) of a flammable gas or vapor is the airborne concentration below which the concentrations are too lean to ignite (Asfahl & Rieske, 2010). OSHA's permit-required confined spaces regulation considers 10% or more of any LEL to be a *hazardous atmosphere* (OSHA, 2011), giving an extra protection factor for workers. An alarm was set on the PID to alert at 50 ppm, well below 1% of the LEL for either gasoline or Jet-A aviation fuel (Table 2).

Table 2
Lower Explosive Limit Concentrations

	LEL	10% LEL	1% LEL
Gasoline	1.4%	0.14% (1,400 ppm)	0.014% (140 ppm)
Jet-A Aviation Fuel	0.6%	0.06% (600 ppm)	0.006% (60 ppm)

Source: Adapted from Centers for Disease Control and Prevention National Institute for Occupational Safety and Health (2019) and Chevron Phillips Chemical Company (2019).

Results

The first phase of testing focused on RQ1 - Could sUAS-collected data compare to hand-held device collected data to establish sUAS as a future tool for remote exposure assessment? was supported as posited above. First, a static sensor mounted at 2ft over the pan containing Jet-A was allowed to collect measurements for a total of 11 minutes to establish a background concentration. Values did rise and fall, and these variations were compared to data on wind speed and direction, but no apparent connection between detectable wind speed changes and variations in the ambient concentration levels were determined from this information. The average background VOC concentration on the static sensor at 2ft above the pan for this time period was evaluated and calculated to be 0.15 ppm. Then a PID sensor was attached to the Mavic Pro and the Inspire 1, and the sUAS was flown to hover over the pan at heights of 2 ft and 3ft. Airborne concentrations detected on the sensor mounted directly onto the sUAS were then compared to the static sensor readings. As the sUAS hovered over the open pan, ripples were observed on the surface of the liquid, and this disruption was reflected in the sensor readings (Figure 6).

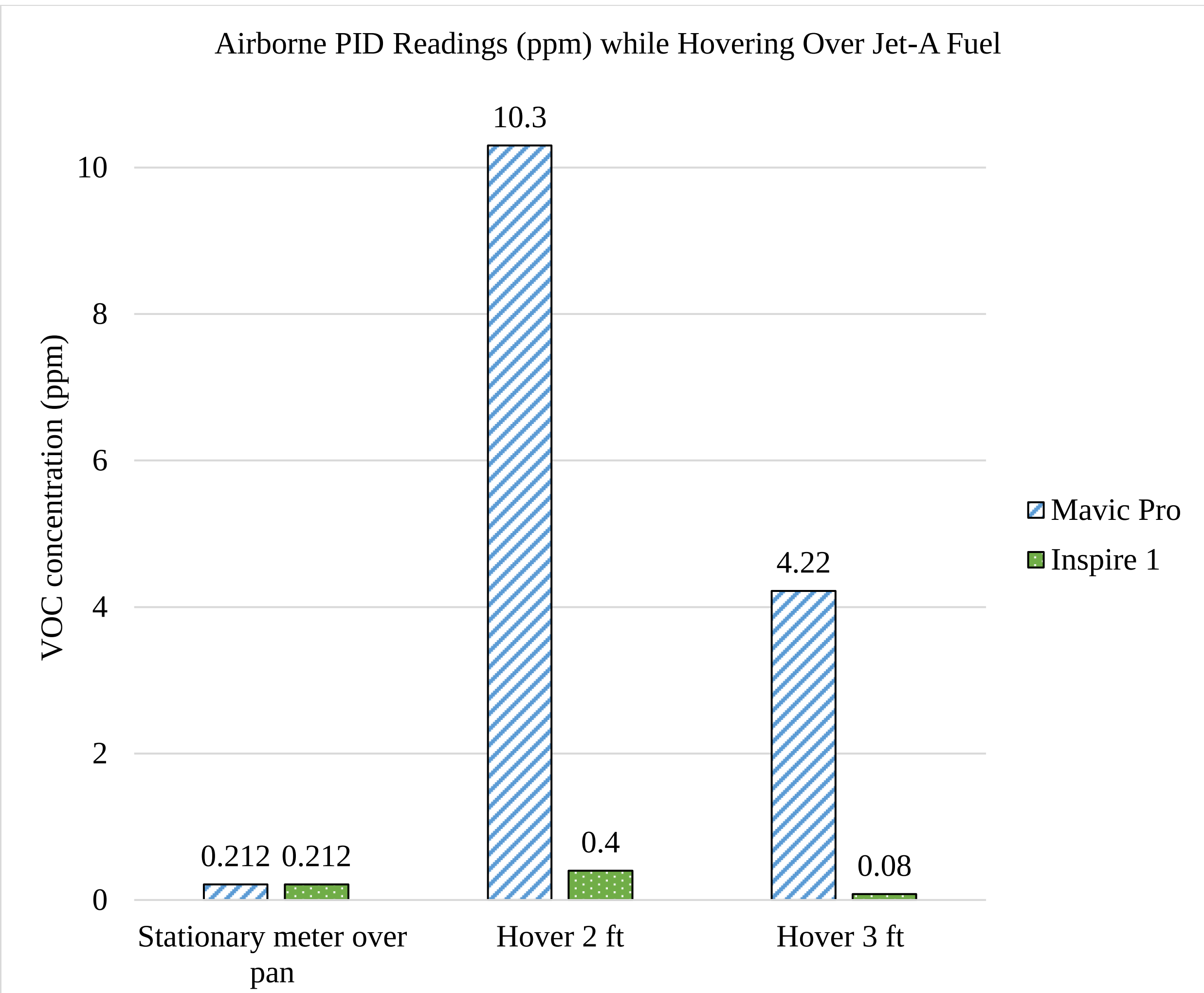

Figure 6. Average airborne VOC concentration readings with the PID sensor mounted directly on the Mavic Pro and Inspire 1 with no tether, hovering over a pan of Jet-A fuel at various heights compared to a static sensor.

Due to the increased volatility of gasoline over Jet-A fuel, similar measurements were collected using gasoline as the source of VOCs, which provided higher overall airborne concentrations. The average background VOC concentration on the static sensor at 2 ft above the pan for gasoline was evaluated and calculated to be 0.37 ppm. A PID sensor was then attached to the Mavic Pro and the Inspire 1, and the sUAS was flown to hover over the pan at heights of 3ft, 5 ft and 10 ft (see Figure 7).

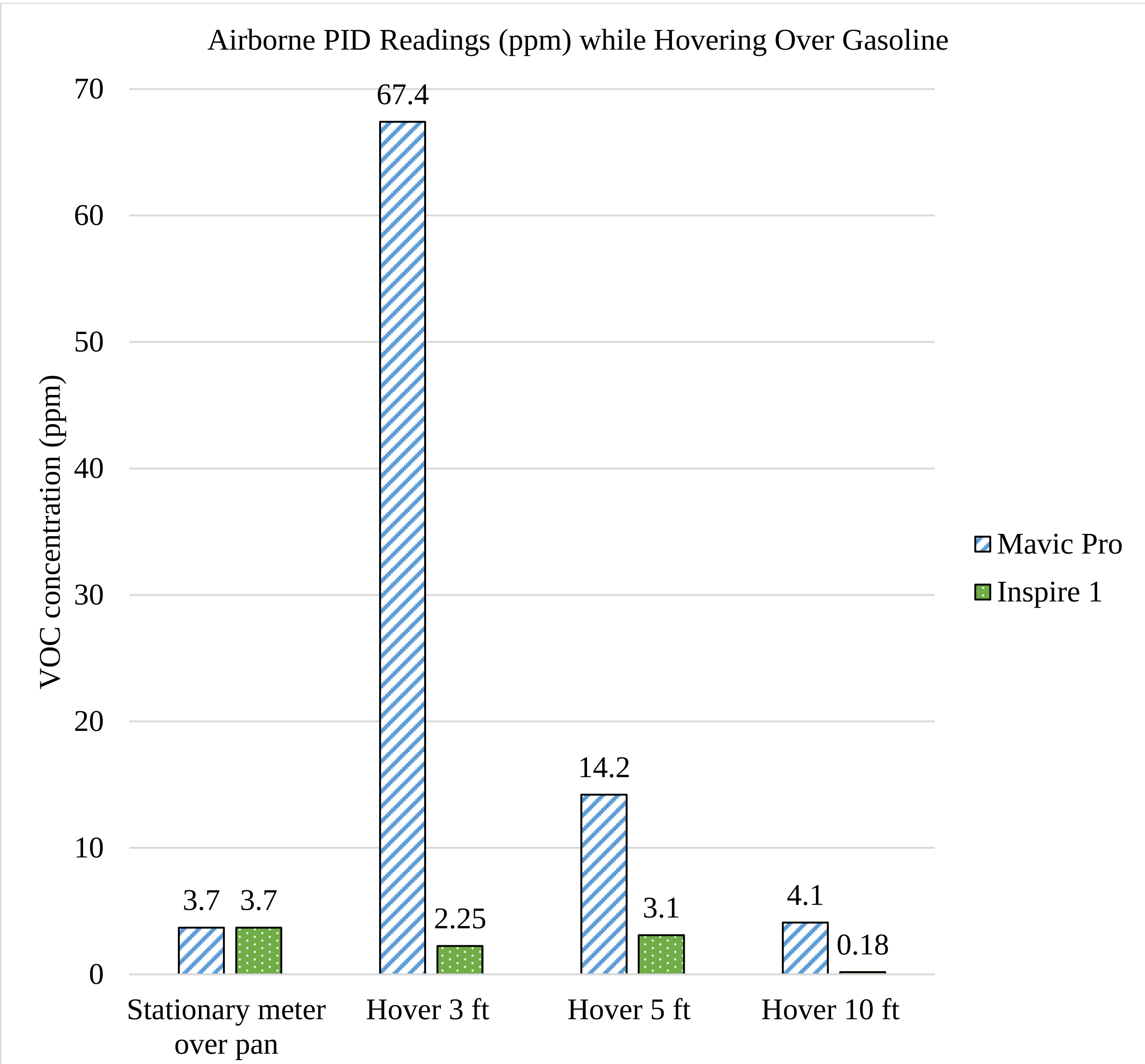

Figure 7. Airborne VOC concentration readings with the PID sensor mounted directly on the Mavic Pro and Inspire 1 with no tether, hovering over a pan of gasoline fuel at various heights compared to a static sensor.

When hovering directly over the pan, in all cases, the mean of the airborne concentration detected on the sensor attached directly to the Mavic Pro was statistically higher than both the mean of the airborne concentration above the pan without the influence of rotor wash, and higher than airborne concentrations detected with the sensor attached directly to the Inspire 1 (Figures 6 and 7). In the gasoline trials, with the sensor directly attached to the Inspire 1 hovering at 3 feet actually revealed a statistically lower average concentration (2.25 ppm) than background concentrations from the static sensor (3.7 ppm) ($P = .02$) (see Figure 6). One proposed basis for the differences in outcomes between the two sUAS is found in the operational aspects of the sUAS platforms. The Inspire 1 required continuous management of the hover altitude while in operation. Conversely, the Mavic Pro required very little adjustment of the vertical position of the aircraft (and sensor) while in operation. The Mavic Pro is also a smaller system and produces less thrust overall, resulting in less rotorwash than the Inspire 1, which is actually counterintuitive to the results. With higher concentrations detected with less rotor wash, one theory is that with greater rotor wash from the Inspire 1, the vapors may be pushed away from the sensor rather than drawing the vapors to the platform-mounted PID sensor.

The findings from the following phase of the research addressed RQ3: Does the sUAS dispersion of air (at various altitudes) influence the VOC instrument readings? Distancing the sensor from the rotor wash generated by the sUAS with a tether was then studied. Sensors mounted at various lengths on a tether hanging beneath the sUAS demonstrated a high similarity to the static sensor measurements, as depicted in Figure 8 and 9.

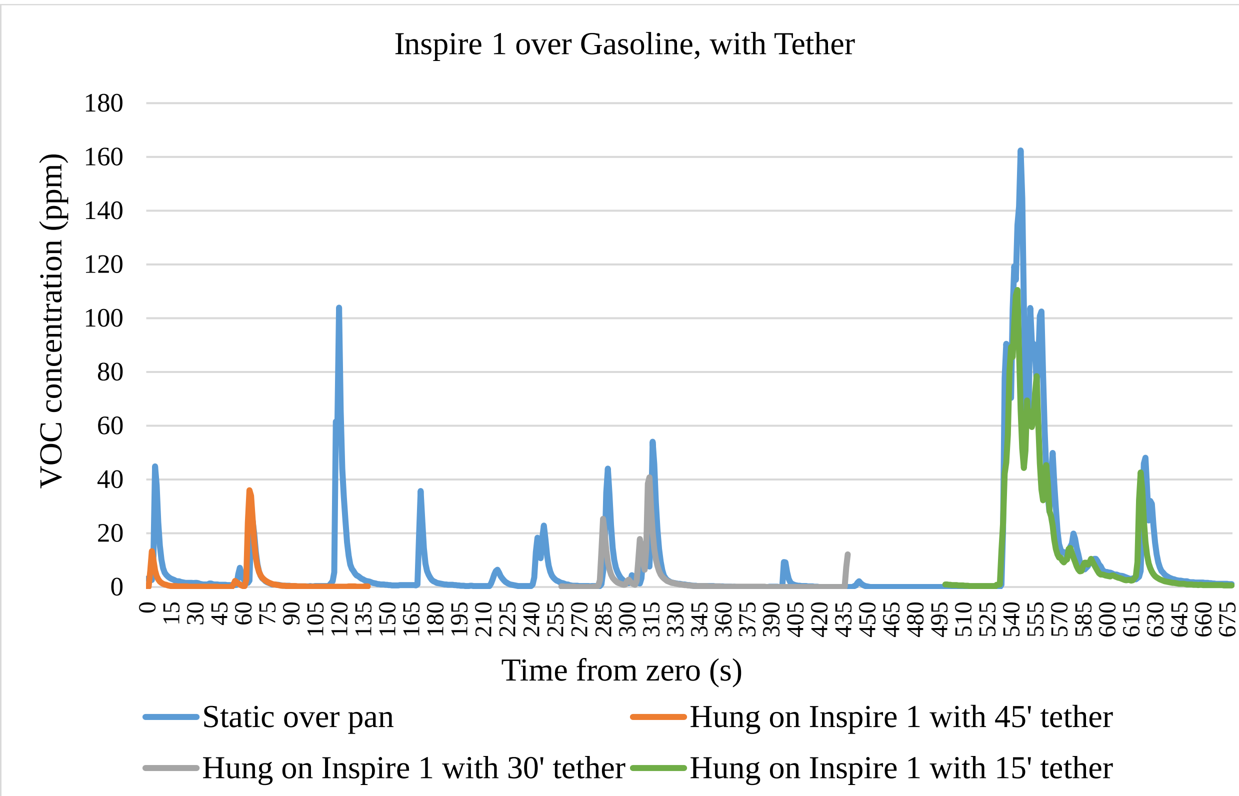

Figure 8. Static sensor over the pan compared to sensor hung by a tether at various lengths from the Inspire 1, gasoline.

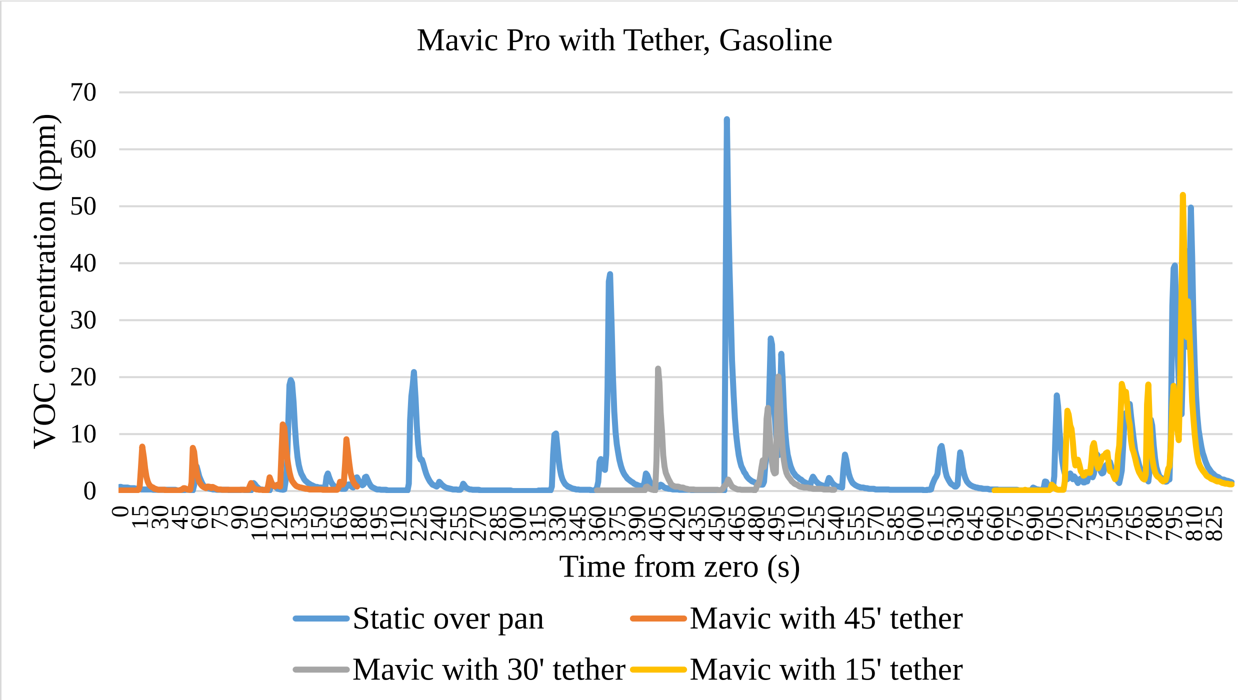

Figure 9. Static sensor over the pan compared to sensor hung by a tether at various lengths from the Mavic Pro, gasoline.

The collective results demonstrate that the side-by-side sensors appear to provide similar results, however, the overall airborne concentration increased as the tether length decreased (see Figures 10 and 11). The higher concentration with shorter tether length was likely due to the rotorwash, increasing the evaporation rate of the solvent and causing more vapor to become airborne.

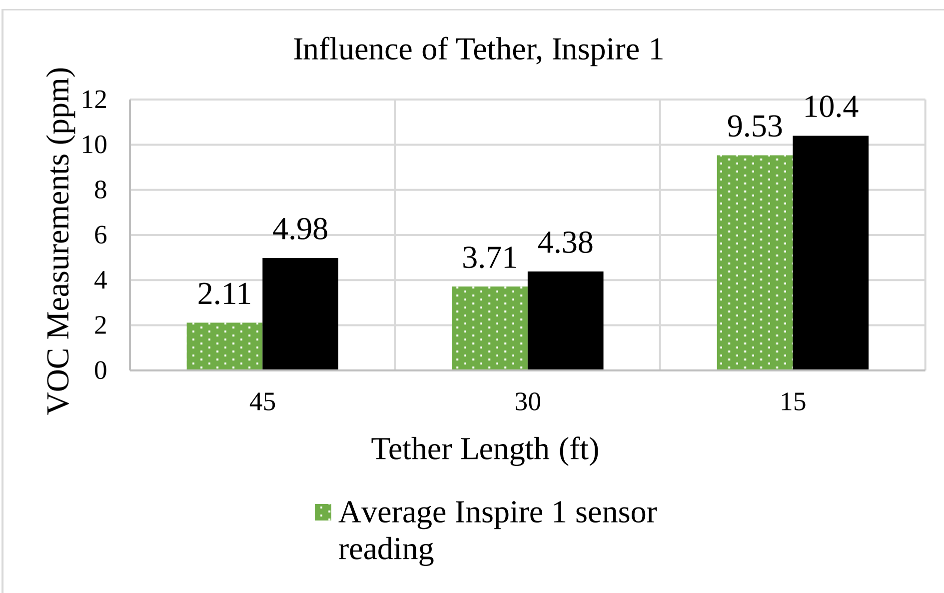

Figure 10. Average readings for static sensor over the pan compared to sensor hung by a tether at various lengths from the Inspire 1, gasoline.

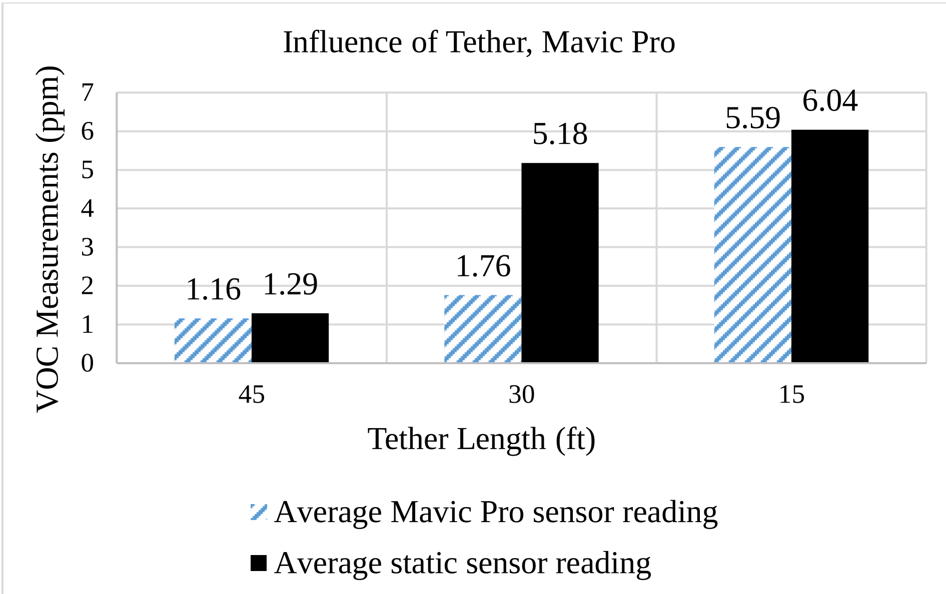

Figure 11. Average readings for static sensor over the pan compared to sensor hung by a tether at various lengths from the Mavic Pro, gasoline.

Additional testing was conducted determine whether the second research question (RQ2) could be supported that theorized: Is it possible to collect meaningful airborne VOC information to characterize potential exposures for first responders using the sUAS? To gather the needed data, the sUAS was flown in a circular pattern surrounding the pan at 3-, 5- and 10 feet altitude and at 5-foot radius and 10-foot radius in order to determine whether a measurable plume of vapor could be detected over the pan of evaporating fuel. The researchers discovered that while airborne vapor concentrations were detected directly above the pan on the static sensor, the sensor mounted on the sUAS did not consistently detect airborne VOC concentrations when not directly over the pan, even when measured as close as to within a 5-foot radius of the center of the pan and only 3 feet off the ground. Figure 12 displays examples of those results for the Inspire 1 and Figure 13 displays results for the Mavic Pro, in both cases using gasoline as the source of VOCs.

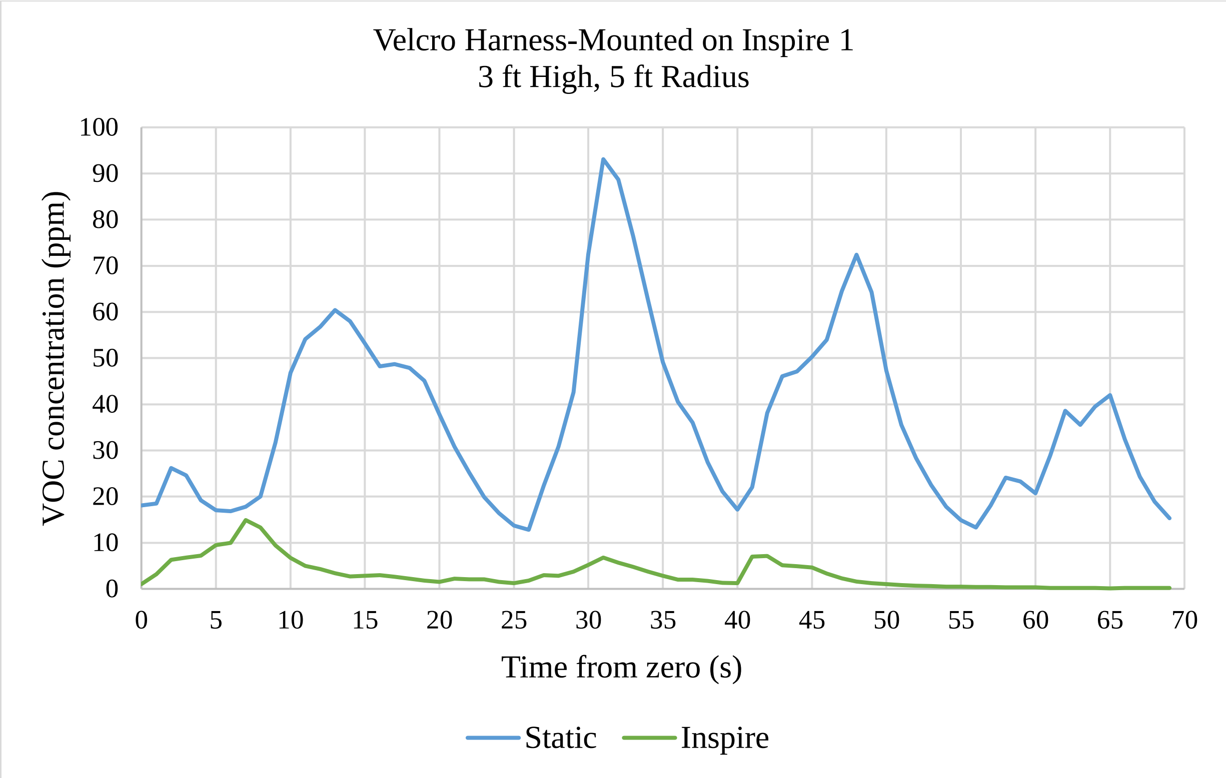

Figure 12. Static sensor over the pan compared to velcro harness-mounted on the Inspire 1, gasoline.

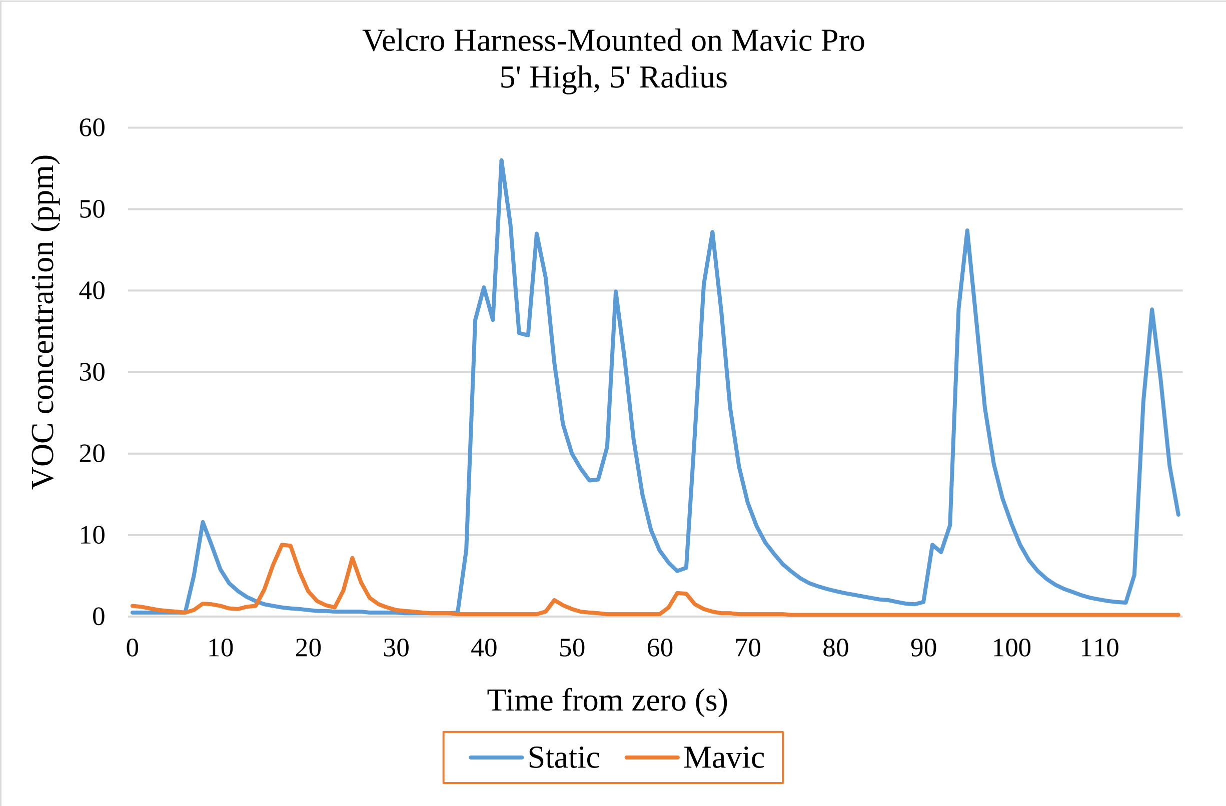

Figure 13. Static sensor over the pan compared to velcro harness-mounted on the Mavic Pro, gasoline.

The second part of RQ 2 theorized: If so, can a 3D graphical representation of concentration surrounding the spill be created by mapping concentration to location using GPS data points? The outcome of the collection and evaluation of the data demonstrated promise in the capability to develop a 3D image of mapping of airborne concentrations around the open container by applying GPS coordinates to the recorded sensor readings. By combining the time points of the PID data with concentrations, and the time points with GPS location on the sUAS, and considering that according to an Ion Science representative that there is no delay between exposure and sensor readings (B. Piritz, personal communication, December 6, 2019), the concentration and GPS data points (accounting for tether length) were plotted. An example of such a 3D plot is presented in Figure 14, using the Inspire 1 data with a 15-foot tether over gasoline.

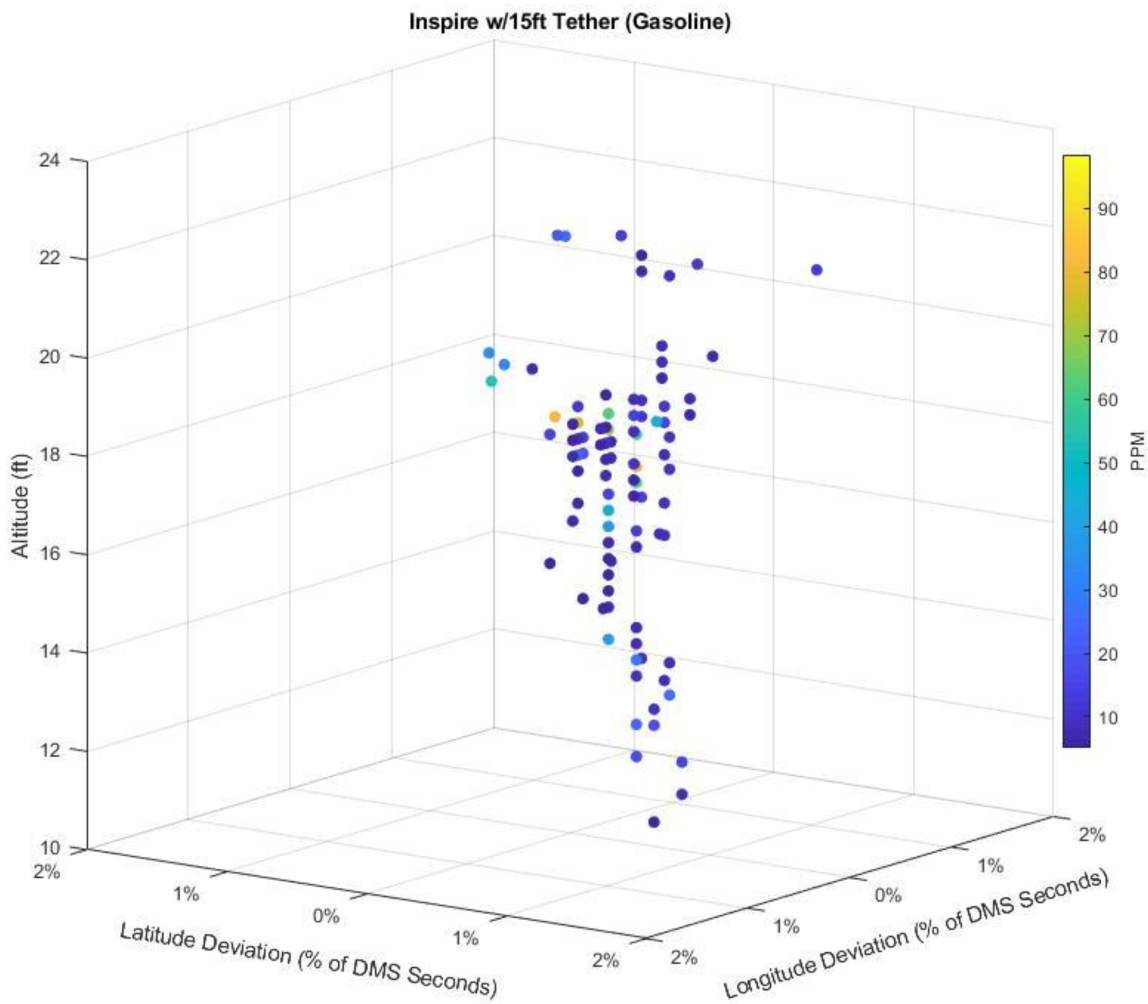

Figure 14. Airborne concentrations of VOCs (ppm) surrounding open pan of gasoline detected with the Inspire 1 using a 15-foot tether.

However, because the airborne concentration detected dropped significantly when the sensors were not directly over the pan (e.g., Figures 12 and 13), it is unclear whether this process can serve as a useful tool for emergency responders.

Discussion

Integrating a tether system impacted the operational aspects of the sUAS as launching and recovering the sUAS required a great deal of caution. The use of a tether also caused the system to be more susceptible to wind variances. During the research, the sensor locations were monitored and manually stabilized if needed. If this system were to be used in the field, manual stabilization would not be a viable option.

Data collected from a sensor hanging below the UAS produced a similarity with the static sensor data gathered for both the Inspire 1 and the Mavic Pro. What is noteworthy is that when using the 15-foot tether, rotorwash visibly agitated the fuel, whereas such observable disturbance was not detected with the 30- or 45-foot tether. This rotorwash may be helpful in stirring up and generating higher airborne concentrations so that a spill may be detected, but this outside or induced influence may also impact the accuracy that is needed to quantify potential occupational exposure for first responders.

Some consideration for potential GPS error of the used sUAS platforms may need to be addressed for accuracy of the 3D image of airborne VOC distribution. Global accuracy of a GPS is reflected in circular error probability (GPS World Staff, 1998), and the circular error probability for this research had an error that was consistent with consumer-grade GPS of up to 3 meters. However, the relative errors of positional information were consistent as the sUAS maneuvered across the measurement area. For this research, the global accuracy of the positional information was irrelevant because the position data focused on the relative position of the sUAS to the fuel source and wind, not the global position of the sUAS or source of fuel vapor. However, if in future research or application, one was attempting to locate a fuel source, or setting a boundary for the use of protective equipment, using an sUAS equipped with a real-time kinematic (RTK) GPS solution could improve the relative positional data further. Ground control points could also be used to enhance accuracy, but RTK GPS may provide a greater relative and global accuracy than using manual tie points.

An sUAS has electronic components that may be a hazard in an environment with highly volatile VOCs. For example if a component were to electrically short out and burn up as electronic speed controllers (ESC) may do or get too hot, there is potential for fumes to combust. One way to address this risk would be for the sUAS to descend onto the test site as opposed to moving into the area laterally using the altitude to buffer the combustion risk. With the nature of VOC vapor pressures, vapors tend to settle closer to the ground. Descending into a hazard area would allow for slower integration into the environment and offer a quick and safe method of evacuating the area if the concentration was too hazardous for sUAS operation. Lateral sUAS introduction to the hazard area is vulnerable to wind direction changes that could potentially create unanticipated concentration spikes that may influence the validity of the data and consequently complicate the risk assessment. Wind conditions should be closely monitored prior to sending a sUAS into the situation, but the drop in method described above may be utilized to enter/exit the hazard area in a more safe manner.

Second, the thrust from the sUAS may create conditions for hazard escalation. In a real-world scenario where more than one chemical may be present, and the potential for dangerous incompatibilities exist. The thrust from an sUAS may accelerate chemical reactions or cause other hazards such as spilling or tipping over containers as we observed during the field testing with the fuel pan. This particular scenario was developed for an industrial environment or an accident situation, but the potential for quicker evaporation and larger affected areas due to the faster removal of surface concentrations over the spill could be cause for concern. This precautionary information should be included in any risk assessment of the use of a sUAS for detection levels of chemicals in a hazardous environment.

Conclusions

In this exploratory research much was learned about the characteristics and influencing factors for the sUAS tested. However, the researchers only conducted a brief investigation and further examination and delineation is required. When the impact of rotor wash is fully characterized for each type of sUAS, and the placement of the VOC sensor can be appropriately optimized, sUAS mounted sensor technology may be able to be used to assist emergency responders when responding to accidents, disasters (such as tornados and earthquakes), or other such events to evaluate and gain rapid intelligence on the presence of released hazardous materials without having to put first responders in harm's way. Information may then be gathered more expeditiously and efficiently, especially in hard to reach locations, thus reducing labor costs, resources, equipment usage, and time to respond. However, in this research we discovered some limitations to the use of this technology including the following:

- If the sensor is mounted directly on the sUAS, and the sUAS hovers directly over the spill, the specific sUAS configuration will influence whether the detected vapor concentrations higher or lower than ambient levels without the sUAS present.
- If the sensor is mounted directly on the sUAS, and the sUAS is *not* directly over the spill, the vapors from the spill did not always reach the sensor and were not always detected.
- Sensor data from a hanging sensor at 15, 30, and 45 feet below the sUAS provided similar readings to the static sensor data. However, with the use of a 15 foot tether, rotor wash from the sUAS visibly stirred up the fuel and elevated measured exposure levels, thus interfering with the ability to accurately measure potential emergency responder exposure levels, and the impact of rotor wash varied depending on the type of sUAS platform used and the length of the tether.
- With the sUAS platforms employed for this particular experiment, a 45-foot tether appeared to provide an optimal length of separation from the rotors to be able to estimate exposures above the spill without noticeable influence from the rotorwash. However, using a tether that long is a potential limiting factor due of the potential interference by ground objects and the possible influence of wind speed and direction on the hanging sensor.
- Using a shorter tether between the sUAS and the COTS sensor may be useful if the intent is to only detect the presence of a spill, rather than to determine responder exposure.

Data logged airborne concentrations can be correlated with geospatial positioning information obtained by the sUAS to produce color-coded imagery based on detected airborne concentrations as noted in the Results section and depicted in Figure 11. This type of information could be particularly useful in accident situations as it is imperative to know the presence, boundaries, and dispersion of chemicals or compounds prior to responding to the situation. However, additional research should be performed with a larger volume of spilled material to better represent typical crash or spill conditions.

Recommendations

Relatively inexpensive COTS sensors are ideal for use in hazard assessment situations as described due to the availability, low cost, ease of use, and ability to obtain relatively immediate information to evaluate health and safety or environmental concerns. The potential commercial application of this technique is not only extensive in scope but also in potential risk mitigation. Emergency responders and municipalities can use sUAS mounted COTS sensor technology such as a PID to respond to accidents, disasters such as tornados and earthquakes, or other events involving hazardous materials to evaluate and gain rapid intelligence on the presence of released hazardous materials without having to put responders in harm's way. Employers will be able to gather information expeditiously and efficiently, especially in hard to reach locations, thus reducing labor and resource costs. By and large general industry is eager to use such technology to perform evaluations of chemical containers such as those found in tank farms or remote storage or operational locations of pipelines or wells, for example. The gain or mitigation factor is not having to put workers in harm's way and providing a means to evaluate whether and how much chemical release has occurred at the location. By incorporating the use of sUAS and COTS sensor technology into routine inspections of tank farms or other outside chemical storage locations, leaks, spills, or other emission sources may be located more rapidly and potentially reduce the impact on the environment. The tested technique could also be perfected over time for use when performing environmental site assessments for property transfer as specified by the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)/ Superfund Amendments and Reauthorization Act (SARA) (United States Environmental Protection Agency, n.d.) or other jurisdictional requirement that mandates the potential owner or seller perform due diligence in determining whether the property has any pre-existing environmental contamination.

The research performed in this study was exploratory in nature, and the potential uses of the technique are extensive. Nonetheless, there is much more to be learned in this area, in turn, augment the practicality of utilizing sUAS and COTS sensor technology in assessing hazardous environments. Two areas requiring additional testing and validation is a full characterization of the impact of rotorwash for each type of sUAS, and optimization of the placement of the VOC sensor.

Another area that warrants additional research is an understanding of any adverse effects on the platform material of an sUAS when operating in hazardous environments. Currently, most sUAS are designed and built for operations in normal flying environments. As well, most sUAS platforms have little to no actual maintenance requirements specified by the manufacturers. Therefore the need for special inspections and perhaps scheduled replacements of sUAS components may be prudent and are areas of concern for sUAS operating in hazardous conditions. More data are needed in this area over a period of time and gathered from a variety of environments.

In summation, the research was successful in determining the initial value and application of mounting inexpensive COTS sensors like a PID on sUAS for use in hazard assessment situations. As an emerging technology, the obvious attributes are availability, low cost, ease of use, and ability to obtain relatively immediate information to evaluate health and safety or environmental concerns. But herein, the research team has only scratched the surface by developing and testing the initial technique. The commercial application potential of this technique is extensive, and based on the results, it is recommended that follow on research be conducted in the areas noted.

References

Asfahl, C.R. & Rieske, D.W. (2010). *Industrial safety and health management* (6th ed.). Upper Saddle River: Prentice Hall.

Bauer, M., English, W., & Richards, M. (2018). *Use of sUAS in developing photogrammetric model for wind simulation*. Retrieved from https://www.isasi.org/Documents/library/technical-papers/2018/Tues/Use%20of%20sUAS%20in%20Developing%20Photogrammetric%20Model%20for%20Wind%20Simulation%20-%20Bill%20English,%20Mike%20Bauer.pdf

Berman, E. S. F., Fladeland, M., Liem, J., Kolyer, R., & Gupta, M. (2012). Greenhouse gas analyzer for measurements of carbon dioxide, methane, and water vapor aboard an unmanned aerial vehicle. *Sensors & Actuators: B. Chemical, 169*, 128-135. doi:10.1016/j.snb.2012.04.036

Brandt-Rauf, P. W., Fallon, L. F., Tarantini, T., Idema, C., & Andrews, L. (1988). Health hazards of fire fighters: Exposure assessment. *British Journal of Industrial Medicine, 45*(9), 606-612. doi:10.1136/oem.45.9.606

Bullock, B. & Nath, R. K. (2016). *Air monitoring with UAVs during emergencies*. Poster presented at Railroad Environmental Conference, Urbana, IL.

Calams, S. (2018). 6 takeaways on how fire departments are using drones and the barriers preventing purchase. *FireRescue 1*. Retrieved from https://www.firerescue1.com/emergency-response-in-the-drone-age/articles/6-takeaways-on-how-fire-departments-are-using-drones-and-the-barriers-preventing-purchase-CDQozj7OMa49hjHd/

Campbell, A., Naik, R., Sowards, L., & Stone, M. (2002). Biological infrared imaging and sensing. *Micron, 33*(2), 211-225

Centers for Diease Control and Prevention National Institute for Occupational Safety and Health. (2019). Gasoline. Retrieved from https://www.cdc.gov/niosh/npg/npgd0299.html

Chevron Phillips Chemical Company. (2019). *Jet A aviation fuel*. Retrieved from http://www.cpchem.com/msds/100000014588_SDS_US_EN.PDF

Chwaleba, A., Olejnik, A., Rapacki, T., & Tuśnio, N. (2014). Analysis of capability of air pollution monitoring from an unmanned aircraft. *Aviation, 18*(1), 13-19. doi:10.3846/16487788.2014.865936

Crimmins, B. (2016). Understanding the photoionization detector. *Fire Engineering.* Retrieved from http://www.fireengineering.com/articles/print/volume-169/issue-11/features/understanding-the-photoionization-detector.html

DJI. (n.d.-a). DJI Inspire 1 product specifications. Retrieved from https://www.dji.com/inspire-1/info#specs

DJI. (n.d.-b). DJI Mavic Pro product specifications. Retrieved from https://www.dji.com/ mavic/info#specs

Eismann, M., Stocker, A., & Nasrabadi, N. (2009). Automated hyperspectral cueing for civilian search and rescue. *Proceedings of the IEEE, 97*(6)

English, B. (2017). Tools of the trade: Drones for the 21st century investigator. *NTSB Safety Compass*. Retrieved from https://safetycompass.wordpress.com/2017/02/ 16/tools-of-the-trade-drones-for-the-21st-century-investigator/

FLIR Systems, Inc. (2019). FLIR announces industry's first multi-gas detector for unmanned aerial systems. Retrieved from https://www.flir.com/news-center/public-safety/flir-announces-industrys-first-multi-gas-detector-for-unmanned-aerial-systems/

Golston, L. M., Tao, L., Brosy, C., Schäfer, K., Wolf, B., McSpiritt, J., . . . McGregor, M. (2017). Lightweight mid-infrared methane sensor for unmanned aerial systems. *Applied Physics. B, Lasers and Optics, 123*(6), 1-9. doi:10.1007/s00340-017-6735-6

GPS World Staff. (1998, January 1). GPS accuracy: Lies, damn lies, and statistics. *GPS World*. Retrieved from https://www.gpsworld.com/gps-accuracy-lies-damn-lies-and-statistics/

Heard, K. (2017, May 11). West Memphis, AR, fire department to use drone in responses. *Firehouse*. Retrieved from https://www.firehouse.com/tech-comm/drones/article/ 12326292/west-memphis-fire-department-to-use-drone-in-responses-firefighter-technology

Kuiawa, D. (2003). The PIDs role in first response. *EHS Today*. Retrieved from http://www.ehstoday.com/fire_emergencyresponse/ehs_imp_12348

Lillian, B. (2019). DJI links up with LAFD to advance drones for public safety. *Unmanned Aerial Online*. Retrieved from https://unmanned-aerial.com/dji-links-up-with-lafd-to-advance-drones-for-public-safety

Nex, F., & Remondino, F. (2014). UAV for 3D mapping applications: A review. *Applied Geomatics, 6*(1), 1-15

Petrillo, A.M. (2018). Fire department drones serve a variety of needs on incident scenes. *Fire Apparatus & Emergency Equipment.* Retrieved from https://www.fireapparatusmagazine.com/articles/print/volume-23/issue-10/features/fire-department-drones-serve-a-variety-of-needs-on-incident-scenes.html

Pitcher, J. (2019). Drones do deadly work so you don't have to. *Bloomberg*. Retrieved from https://www.bloomberg.com/news/articles/2019-07-26/drones-do-deadly-work-so-you-don-t-have-to?srnd=premium

Pix4D. (2019). PixDmapper [Computer software]. Retrieved from https://www.pix4d.com/product/pix4dmapper-photogrammetry-software

RAE Systems. (2013). *The PID handbook: Theory and applications of direct-reading photoionization detectors.* Retrieved from http://www.raesystems.com/sites/default/files/content/resources/pid_handbook_1002-02.pdf

Remondino, F., Barazzetti, L., Nex, F., Scaiono, M., & Sarazzi, D. (2011). UAV photogrammetry for mapping and 3D modeling: current status and future perspectives. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XXXVIII-1/C22* (pp. 25-31). ISPRS Zurich 2011 Workshop, 14-16 September 2011, Zurich, Switzerland

Robinson, J. (1991). Fire from space: Global fire evaluation using infrared remote sensing. *International Journal of Remote Sensing, 12*(1). doi: 10.1080/01431169108929628

Rossi, M., & Brunelli, D. (2016). Autonomous gas detection and mapping with unmanned aerial vehicles. *IEEE Transactions on Instrumentation and Measurement, 65*(4), 765-775. doi:10.1109/TIM.2015.2506319

Schuyler, T., & Guzman, M. (2017). Unmanned aerial systems for monitoring trace tropospheric gases. *Atmosphere, 8*(12), 206. doi:10.3390/atmos8100206

Tompkinson, W. (2017). Are drone inspections intrinsically safe? Retrieved from http://info.industrialskyworks.com/blog/are-drones-intrinsically-safe

United States Department of Homeland Security/Federal Emergency Management Agency. (2004). *Fact sheet: Personal protective equipment levels and risks*. Retrieved from https://www.cseppportal.net/csepp_portal_resources/ppe_factsheet.pdf

United States Department of Labor Occupational Safety and Health Administration. (2005). Chemical - biological - radiological - nuclear (CBRN) personal protective equipment selection matrix for emergency responders. Retrieved from https://www.osha.gov/SLTC/emergencypreparedness/cbrnmatrix/index.html

United States Department of Labor Occupational Safety and Health Administration. (2013). Calibrating and testing direct-reading portable gas monitors. Retrieved from https://www.osha.gov/dts/shib/shib093013.html

United States Department of Labor Occupational Safety and Health Administration. (2011). Permit-required confined spaces. Retrieved from https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.146

United States Environmental Protection Agency. (n.d.) Superfund: CERCLA overview. Retrieved from https://www.epa.gov/superfund/superfund-cercla-overview

Werner, C. (2015). Fire technology: Using drones in the fire service. *Firehouse*. Retrieved from https://www.firehouse.com/tech-comm/drones/article/12041104/drones-in-the-fire-service