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Applications of Drones for Air Pollutant Sensing in Industrial and Urban Environments

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Abstract: **Unmanned aerial vehicles (UAVs) have recently introduced simple methods for assessing and monitoring above-ground-level (AGL) air quality. This is possible due to their vertical accuracy and geo-special data collection capability. An extensive review of vertical profiling is necessary because various elements of the atmosphere, such as wind speed, Temperature, Rh (Relative Humidity) and wind direction are crucial in controlling atmospheric processes. Many applications of drone-aided systems are upcoming to monitor the natural (i.e. forest, wildlife, wildfires, volcanic eruptions) and anthropogenic (i.e., urban life, industrial processes, mineral extraction, transport, and energy sector, waste management and wastewater treatment; agriculture) activities.**

This paper deals with the significant literature on the drone economy, drone-aided AQ (Air Quality) monitoring and its applications for various AQ parameters. The review work focused on the type of UAVs used for the experiments, flight time and scope to improve battery life, available sensors, monitoring AGL height and application of ambient AQ monitoring. The scope for fusion with AI and the challenges of this technology are also discussed. Finally, the review identified the research gaps in drone-aided air quality monitoring and future research directions in air quality monitoring and sampling.

***Keywords*:** **UAV, Vertical Profiling, Gas Sensing, AQ monitoring, drone applications**

I. Introduction

The monitoring of environmental pollutants in certain unreachable regions is always a crucial task. Environmental factors, including GHG (Green House Gas) and aerosol pollution, are becoming out of control, harming people. Therefore, it is essential to check the air's concentration regularly. Tethered sampling, real-time data monitoring, source-based sampling, etc., are all part of the monitoring methods for these metrics. The early 1990's tower method, was introduced for vertical profiling of metrological parameters. However, monitoring these parameters in some unreachable regions is a critical task using traditional methods. As a solution to this problem, some researchers came up with the idea of a UAV, an airborne system or aircraft without a human pilot aboard for the monitoring work as observed.

Aerial surveillance can track visual, heat, vegetation, and atmospheric changes, while aircraft transport can collect air, liquid, and solid samples for laboratory examination. Drones have great potential for urban environmental studies, however, safety, security, and privacy problems exist. Ground-Based Monitoring (Internet of Things) can reach many of these potentials with no safety risk and lower perceived privacy and security risk. Low-altitude drones may struggle to define geographic regions geographically and attitudinal. For air quality and atmospheric analysis, higher altitude drones should be approved.

Drone Industry: The drone economy is the fast-expanding market for UAVs, or drones. In recent years, drones have become increasingly popular due to their versatile applications and significant advancements in technology(Kim, 2017) (Sayler, 2015). Drones are used for a variety of purposes, including commercial delivery, photography and videography, surveying, agriculture, and search and rescue missions (Shi et al., 2018) (Dutta & Mitra, 2021). The rise of e-commerce and the demand for quick and efficient delivery methods have boosted the commercial use of drones, creating new drone delivery companies and a surge in investment in this sector (Rachmawati et al., 2021) (Wawrla et al.).

In agriculture, drones equipped with cameras and sensors are used to gather data on crops and livestock, helping farmers make informed decisions about planting, fertilization, and irrigation (Abualigah et al., 2021a) (Kwon et al., 2017) (Kwon et al., 2017). This has the potential to increase yields, reduce costs, and improve the efficiency of farming operations (Ayamga et al., 2021). The drone industry is expected to continue its rapid growth in the coming years, with market research firm IDC projecting that global spending on drones will reach $100 billion by 2025(Enemark, 2013) (Knoblauch et al., 2019). The increasing use of drones in a wide range of industries has created new job opportunities, including drone pilots, engineers, data analysts, and maintenance technicians (Moon et al., 2019) (Knoblauch et al., 2019).

However, the rapid growth of the drone industry has also raised concerns about safety, privacy, and security (Vallet, 2014). Governments around the world are grappling with how to regulate drone usage, with some countries implementing strict restrictions on where and when drones can be flown (Berkowitz, 2014a; Kyrkou et al., 2019a) (Custers, 2016a) (Balasingam, 2017a). In conclusion, the drone economy is a rapidly growing market with tremendous economic growth and job creation potential. As technology continues to advance, the drone industry is likely to play an increasingly important role in a variety of industries and applications (Javaid et al., 2021) (Kellermann et al., 2020). It will be crucial for governments to strike a balance between promoting the growth of the drone industry and protecting public safety, privacy, and security (Carrivick & Smith, 2019) (Jung Sup Um et al. 2019) (Ayamga et al., 2021).

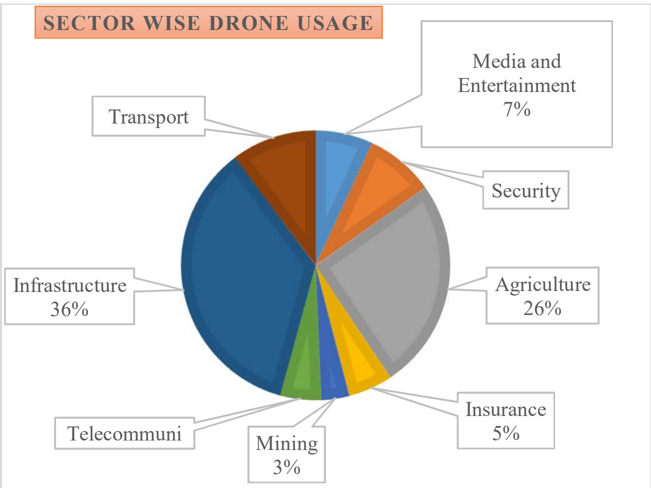

Fig. 1 Drone Economy

Air Quality sensors: Air Quality sensors are transducers used to assess a number of air pollutants, including PM, CO, NOx, and SOx organic substances that evaporate VOCs. These sensors are crucial in monitoring air quality in homes, buildings, cities, and industrial settings (DUNN, 2013) (Balasingam, 2017a) (*Hacking Drones on JSTOR*, n.d.) (Kreps, 2016). The advanced lightweight sensors are very useful to mount on multirotor drones.

The basic Types of Air Quality Sensors are electrochemical Sensors: These sensors use an electrochemical reaction to detect specific pollutants in the air. They are typically used for carbon monoxide and nitrogen oxide detection (Culver, 2014) (Kyrkou et al., 2019a) (Custers, 2016a). Optical Sensors: Optical sensors use light scattering or absorption to measure particulate matter and VOCs in the air (Bollard et al., 2022) (Ayamga et al., 2021) (Ayamga et al., 2021) (Campi et al., 2016a) (Hussein et al., 2020). They can be either laser-based or LED-based. Metal Oxide Semiconductor (MOS) Sensors: MOS sensors use metal oxides to detect pollutants such as VOCs, NOx, and O_3 (Campi et al., 2016a) (Burgués & Marco, 2020) (Campi et al., 2016a) (*Key Technologies for Safe and Autonomous Drones - ScienceDirect*, n.d.).

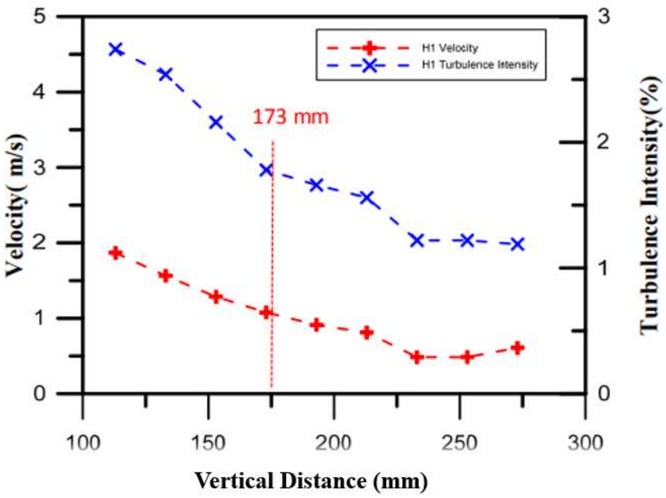

Fig. 2 Changes in velocity and turbulence Intensity on top of the quadcopter frame

Benefits of Air Quality Sensors: Improved Indoor Air Quality: Air quality sensors can help identify sources of pollution in homes and buildings, allowing for effective remediation measures Enhanced environmental monitoring: By monitoring air quality in real-time, governments and pollution control boards can better understand the impact of pollution on local communities and the environment. Improved Public Health: Exposure to air pollution has been linked to various health problems, such as respiratory issues, heart disease, and stroke. By monitoring air quality, individuals can reduce their exposure to pollutants.

Challenges with Air Quality Sensors: Air quality sensors can be expensive, especially for high-end devices with multiple sensors. Calibration: Some sensors require regular calibration to ensure accurate readings. Interferences: Interferences from other sources, such as RH, T, and sunlight, can affect the accuracy of air quality readings. Air quality sensors are essential for monitoring and improving the air quality we breathe (Yazdinejad et al., 2021) (Campi et al., 2016a). Despite some challenges, their benefits to public health and the environment make them a necessary tool in the fight against air pollution. As technology advances, air quality sensors are becoming more affordable and accessible, allowing for greater air quality monitoring and protection in homes, buildings, cities, and beyond (Boucher, 2016) (Liu et al., 2020a) (Ltd, 2022).

1. Sensors in the drone

Drones are becoming increasingly popular for various purposes, including aerial photography, delivery, and surveying(Clarke, 2014b). One of the critical components of a drone is the sensor, which helps the drone navigate, avoid obstacles, and gather data. This article will discuss some of the most common types of drone sensors and how they work.

GPS Sensors: GPS sensors are used to determine the drone's position and navigate through the airspace(Clarke, 2014a) (Clarke, 2014b). These sensors use satellite signals to determine the drone's location, speed, and altitude, allowing it to fly autonomously.

Obstacle Avoidance Sensors: Obstacle avoidance sensors, such as ultrasonic sensors, infrared sensors, and stereo cameras, help the drone detect and avoid obstacles in its path (Nouacer et al., 2020) (Sandbrook, 2015) (Lv, 2019). These sensors are advantageous when the drone cannot rely solely on GPS signals.

Optical Flow Sensors: Flow sensors help the drone maintain a stable hover and control its position (Sandbrook, 2015) (Lv, 2019) (Clarke, 2014a) (Clarke, 2014a) (Boyle, 2015). These sensors detect changes in the drone's surroundings, such as ground features, and use this information to control the drone's movement.

Magnetometer Sensors: Magnetometer sensors are used to determine the drone's orientation and help it maintain stability(Emery, 2016) (Mahadevan, 2010) (Nayyar et al., 2020). These sensors detect the drone's heading and direction by measuring the earth's magnetic field.

Barometer Sensors: Barometer sensors are used to determine the drone's altitude (Hiebert et al., 2020). These sensors measure changes in air pressure to determine the drone's height above the ground.

Inertial Measurement Units (IMUs): IMUs combine accelerometers, gyroscopes, and magnetometers that help the drone determine its orientation, velocity, and acceleration (Raychowdhury & Pramanik, 2020) (Kumar et al., 2021) (Park et al., 2021) (Park et al., 2021). These sensors provide information about the drone's movement in all three dimensions, allowing it to fly and maneuver precisely.

In total, drone sensors play a crucial role in the operation and functionality of drones (Hawkins, 2014) (Hawkins, 2014) (Preethi Latha et al., 2019). All these sensors are operated at a 5V or 12 V power supply. From determining the drone's position and orientation to avoiding obstacles and collecting data, sensors are essential to a successful drone mission. With the continued advancement of drone technology, we can expect to see even more advanced sensors-based applications and data collection in 3D space.

2. Vertical profiling

Various types of UAVs are available for commercial applications. The Multirotor UAVs are categorized per the number of rotors and their thrust (*Drones: Innovative Technology for Use in Precision Pest Management \textbar Journal of Economic Entomology \textbar Oxford Academic*, n.d.) (*Science, Technology and the Future of Small Autonomous Drones \textbar Nature*, n.d.) (Kumarasuvamy & Rajendran, 2020a) (Dering et al., 2019a). (Quadcopters, Hex copters, Octocopters), fixed wings, single rotor helicopter, fixed wing hybrid VTOL. It is observed that fixed wings and multi-rotors are commonly used for monitoring purposes (Culver, 2014) (Skorup & Haaland, 2020a) (Kyrkou et al., 2019a). However, the fixed wings have some drawbacks when compared with the multi-rotors. Fixed wings have a more complex learning curve and larger datasets, whereas multi-rotors are more straightforward and have smaller data sets. Frozen wings take a more extensive and transparent area for take-off/landing, whereas the multi-rotors can take off in a minimal area (vertical) (Choi-Fitzpatrick, 2014) (Hussein et al., 2020) [17]. Although fixed-wing provides higher alt with more excellent coverage, they give fewer details, whereas this can be covered up by the more powered multi-rotors (Quadcopter, Hexa-copters, Octocopters), which can provide us with the previous features as well, giving us with greater details. Multi-rotors are commercially available and are more cost-efficient as compared with fixed wings (Javaid et al., 2021) (Hafeez et al., 2022) (*Full Article: Applications of Multirotor Drone Technologies in Construction Management*, n.d.) (Boukoberine et al., 2019a). As observed in the research works studied, researchers have combined the calibrated sensors used for air quality parameter measurement with the UAVs making it more feasible so that it provides us with real-time data by using wireless data transferring and even by combining it with onboard sensors for data storage and by making more changes in them to increase their autonomy (battery power) (Gharibi et al., 2016) (*Hacking Drones on JSTOR*, n.d.) (Park et al., 2021).

There are various types of UAVs available Multi-Rotors (Quadcopters), Fixed wing, Hexa-copters, Octocopters, Single rotor helicopters and Fixed Wing Hybrid VTOL. Because their lift is created by a set of rotors, which are vertically oriented propellers, Multi Rotor UAVs (quadcopters, hex copters, and octocopters) are the primary topic of this article. (DUNN, 2013) (Nasir et al., 2016a). These are viable solutions to a number of the recurrent issues that are associated with vertical flight. By utilizing counter rotation, torque-induced control concerns as well as efficiency problems caused by tail rotors can be resolved. Moreover, the construction of relatively small blades is made a great deal simpler. (Oertel, 1956a) (Radjawali & Pye, 2017a) (Carrivick & Smith, 2019). The best way to understand quadcopters is to think of them as helicopters with four propellers. Helicopters have rotors at their tails, which enables them to remain steady when they are flying. Quadcopters, on the other hand, do not have a pitch since their four independent rotors can easily keep them stable in the air while it is flying, which is the most crucial component that is required. It is fitted with cameras that can record aerial footage, and additional payloads can be attached to it while it is in flight. (Boukoberine et al., 2019a) (Nasir et al., 2016a) (Oertel, 1956a) (Kumarasuvamy & Rajendran, 2020b). In quadcopters, two propellers spin clockwise, and two spin anticlockwise this results in hovering as well as flying. Because the four rotors work together to lift the weight of the quadcopter airborne, it is able to carry more cargo than a helicopter of the same size. This is because the four rotors aid the craft in carrying high loads without any further engineering tweaks. (Boyle, 2015) (Radjawali & Pye, 2017a) (Carrivick & Smith, 2019). As a consequence of this, it is more capable while also maintaining its cost-effectiveness. They can move in a wide range of directions thanks to their capacity to fly and hover in any position. A hexacopter is a form of UAV that has six propellers that are positioned in a circular pattern above the primary body of the hex copter. (Yazdinejad et al., 2021) (Nasir et al., 2016a) (Azari et al., 2018) (Hawkins, 2014). Hex copters offer more lifting power and stability than quadcopters and can reach higher altitudes without stability issues. Six propellers increase uplift power and speed. Because it has more wings and rotors than a quadcopter, it costs more to produce but is more efficient than any fixed wing. Octocopters have eight propellers and are stronger than quadcopters and hex copters. It combines quadcopter and hex copter speed, maneuverability, and uplift power. As they have eight rotors and can fly higher, they are incredibly steady. The big device can carry heavy loads. Its eight rotors make it big and pricey compared to quadcopters and hex copters.

II. METHODOLOGY

This literature study was done by reviewing the work of reputed scientists, researchers, and subject experts in UAV and their analyzed work and research. The focus of this activity was on the UAV'S applications for air pollutant sampling and related environmental research activities. We selected original research papers from web of science, google scholar, IEEE explore and pub med databases related to UAV-based applications on ecological research and monitoring. The various reputed journals, conference papers, and reports work was considered for this review. The common related data and important related work have been taken into analysis to conclude. The publications from the year 2011 to the year 2022 were selected for this review paper. The data analysis has been done in a tabular format. AI toolbox was also applied to understand the significant focus of the research in the drone-related application development domain.

Moreover, Artificial intelligence has power to process large volumes of data sets into equation form. These algorithms can process real-time AQ data sets also. As per the study of (Veeramanikandasamy & Khadar, 2020) AQ monitoring is required to make sure the workplace is safe and pollutant-free. The air quality in an industrial environment can be continuously monitored by the embedded IoT-based air quality monitoring and control system, which also shows the measured air quality index (AQI) and sudden spikes of poor AQI on the mobile app display and other IoT platforms such as Things Speak. It supports AI-driven algorithms for mapping hotspots and efficiently measures meteorological factors such as temperature and humidity in real-time. The CO, CO2, and ammonia gas concentrations, particulate matter PM2.5 and PM10 in the air, and other metrics can be monitored using a machine learning algorithm in a precise way. The data saved on the cloud server can also forward to the user in real-time.(Adela (Puscasiu) et al., 2022) The system has maintained the air quality index (AQI) in the workplace if the threshold values for gas concentrations and PM are exceeded. This will stop the gas leaks that might cause explosions and fire dangers. The application of AI ML algorithms is more popular in sensor calibrations and mapping. IoT devices are emerging as low-power-consuming devices and helping in reducing carbon footprints.

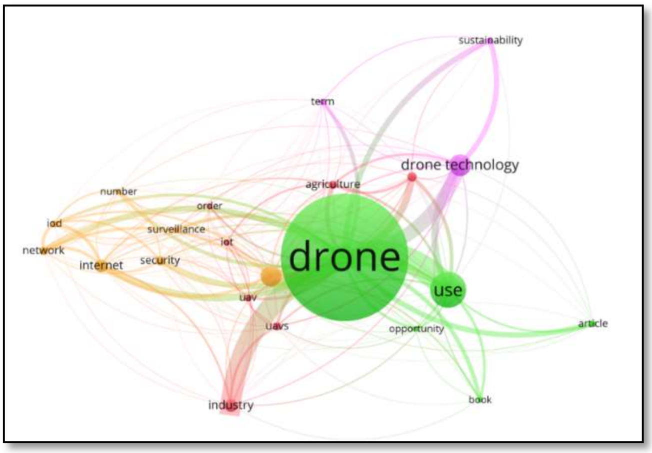

Fig. 3 Work going on with specified Keywords

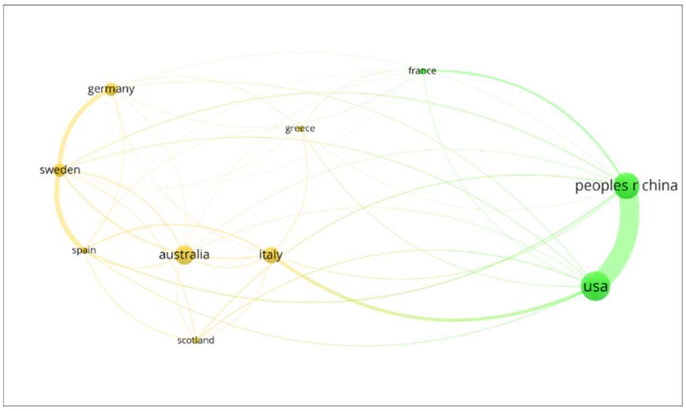

Fig. 4 Country-Wise Bibliography Coupling

III. RESULTS AND DISCUSSION

Validation and development of an autonomous gas-sensitive micro-drone capable of predicting the wind vector and performing real-time gas distribution mapping using just the micro-on-board drone's control unit. In this work, two distinct methods/approaches are proposed. The researcher has examined the target area using predetermined trajectories and implemented a sampling strategy based on adaptive techniques that would recommend the next sampling spots based on APF (Artificial Potential Field).

The preliminary results confirmed their proposed adaptive sampling technique for petrol distribution mapping and source localization. In their work, they performed periodical 16 runs for validation of adaptive sampling and distribution gas mapping methodology for accurate approximation of the sampling location. The conclusion is that combining micro-drones with various GHG gas sensors will reduce the potential risks of sampling and will not endanger people in the targeted field of the risk zone. Furthermore, the prototypes of gas-sensitive micro-drone were demonstrated at the actual site. It observed that micro-drone had limitations in payload capacity and flight time.

(Spiess et al., 2007) He measured vertical profiles of T, RH, and wind at 15000m above ground. M2AV (Meteorological Mini Aerial Vehicle). Five routine MOL-RAO measuring systems were employed to compare data with M2AV data. They took one 10-15-minute profile to continuously monitor phases of certain ABL (Atmospheric Boundary Layer) developments by successive ascents and descents throughout a flight of 50-60 minutes in the morning and evening. Nocturnal low-level jets generate steep turbulence below and near the surface due to boundary layer wind profiles, which cause wind shear and turbulent flux effects in ABL. Aircraft-measured parameters were compared to wind profiler/RASS, solar/RASS, tower, radio soundings, and microwave radiometer profiler. These measurement systems' sampling strategies matched well. Hence, as noted by their work, quick temporal changes were not noticed by the present standard observation sensors, but this aircraft was able to display variations with fast response sensors of 30Hz frequencies and a vertical ascending rate of 3ms−1, enabling parameter resolutions of 10cm. The UAV profiles give instantaneous local measurements at multiple points in space and time together with the flight track, unlike the other system, which provides temporary average data.

(Aggarwal et al., 2019) Has demonstrated a lightweight low power consuming compact laser-based sensor in his work. It is designed specifically for measuring the trace gas species for the UAV platform. They used non-intrusive optical sensing to detect GHG content in the planetary boundary layer with unequaled horizontal and vertical resolution. GHG, CO_2, CH_4, and water vapor were measured by the sensor. For lower drive electronics power and sensitive multi-harmonic wavelength modulation spectroscopic techniques, vertical cavity surface emitting lasers (VCSELs) were the fundamental breakthrough. They kept the sensor's weight between 1.0 and 2.0 kg, including batteries, and each consumed less than 2W of electricity. The sensors were battery-operated to maintain autonomy for long-term operations in different sensing situations. When atmospheric boundary layer fluxes occur in land/atmosphere, laser-based trace gas sensors for UAVs provide high-spatial parameter mapping. Plume mapping from varied sources near the ground is suitable for them. They added the sensor might be modified to investigate trace gas species with improved sensitivity and selectivity in mid-infrared spectral regions. The sensor was exhibited on a helicopter (T-RexAllign700E) and was easily adaptable to various UAVs and ground-based sensors (where power is limited in remote regions). Its plans included vertical GHG profiling from tall tower sensors and atmospheric gas profiling. We can achieve precision with this technology that satellite-based or suborbital aircraft systems cannot.

UAV Type	**Capabilities**	**Drawbacks**	**Reference**
Multirotor	Stable Hovering for images, videos, various sensor payloads	Multiple motors mean potentially shorter flight time	
Single Rotor	Hovering, faster forward flight	Less stability than multirotor, more difficult to operate	
Fixed Wing	Cover large areas quickly, remain airborne for long periods	Runway required, more difficult to operate	

VTOL	Easy takeoff and Difficult to land covers large	Difficult to operate, fewer areas stable	

Fig. 5 Distinguishing between various Wing-Types UAV

(Ali et al., 2021) has focused on CCS(carbon capture and storage) monitoring for greenhouse gases by using UAVs or MUAVs for this work. In this, they have presented an autonomous gas-sensitive micro-drone for GHG monitoring and, more specifically, CO_2. Here, they have introduced two different methods for this task. Initially, for the research of petrol distribution mapping, they used predefined sensing trajectories, and alternatively, they provided an adaptive sampling method based on the APF (artificial potential field), similar to his earlier work. (Skorup & Haaland, 2020a) (Campi et al., 2016a) (McCall, 2019a) (Boukoberine et al., 2019a). In this work, they have focused more explicitly on the CO_2 storage areas with the multi-layered surveillance system (Chandhar & Larsson, 2019a). After conducting a series of experiments in Tuscany (a geochemically activated region), they concluded that GDM using the autonomous gas-sensitive micro drone in an uncontrolled environment was a challenging field of research because the micro-drone may not be suitable for repeated monitoring under low-wind conditions when quantitative reproducibility is needed. (Jensen, 2016) (Javaid et al., 2021) (Mohd Noor, 2018). The data still has potential application in tracing the origin of a petrol leak. Yet, there needs to be adequate time between each measurement operation to let natural gas distribution recuperation. They noticed a difficulty with the memory effect in sensors' responses, leading to delayed recoveries, in the botanic garden area. Rotor motions altered gas measurements, resulting in a reduced limit of CO2 detection, which severely limited their work in monitoring subterranean storage locations and for the usability of micro-drone in such regions, notably CCS areas. (Abdulrazaq et al., 2020) (M. L. Smith, 2015). The major drawback is the time limit of 20 mins that does not allow the monitoring to be done for large-scale areas. A faster response time is required to reduce the measurement time so that a large area can be covered (Nouacer et al., 2020). The position uncertainty by the GPS also affected the gas distribution mapping. Additionally, micro-drones may be employed for boosting the spatial resolution of detecting the gases and finding the leakages when the permanently installed monitoring systems activate the alert.

Because of the gas's erratic movement, pinpointing its origin using moving vehicles or robots is a difficult process, (DUNN, 2013) developed an integrated solution for GSL employing a bio-inspired and particle filter-based algorithm and a micro-drone. Using a micro-drone sensitive to gases, they demonstrated a pseudo-gradient plume tracking technique and a particle filter-based source declaration approach method. They compared the modeling and experimental results of their proposed system using two popular tracking algorithms optimized for aerial expeditions. (Kyrkou et al., 2019a) (Ayamga et al., 2021) (Berkowitz, 2014a) (*Full Article: Applications of Multirotor Drone Technologies in Construction Management*, n.d.) (Boyle, 2015) (*Progress on Drone Technology and Their Applications: A Comprehensive Review: AIP Conference Proceedings: Vol 2030, No 1*, n.d.). Real-world testing has shown that the micro-drone can successfully re-capture the plume, even during times of radically shifting wind conditions. With the pseudo gradient-based and zigzag algorithms, they found a strong agreement between the simulated and real-world data. Thus, they are the most promising algorithms to utilize with micro-drone, especially when combined with their surge-cast method. It was demonstrated that plume tracing is achievable in the actual world, however, it was found to be challenging to pinpoint gas sources in the presence of variable wind and significant turbulence. As a result, they heuristically adjusted a number of the PF-based algorithm's parameters in an effort to reduce the problem's complexity. (Boukoberine et al., 2019a) (Campi et al., 2016a) (McCall, 2019a). Future work will focus on optimizing these parameters, and there is plenty of space for development in the PF-based method. Long-term testing may be performed by increasing the monitoring duration, allowing a broader region to be covered. (Kim, 2017)has presented the unmanned research aircraft for investigating the vertical and horizontal distribution of ultrafine particles in ABL. They miniaturized a small payload for ALADINA, two CPC and one OPC (Optical Particle Counter) by re-arranging them to save space (Boukoberine et al., 2019a) (Kindervater, 2016) (Nayyar et al., 2020) (Chandhar & Larsson, 2019a). They calibrated and characterized each system with test aerosols. The difference in the number of concentrations of two CPCs indicated new particle and meteorological sensors gave the turbulence and thermodynamics of the boundary layer. They conducted demonstrations in 2 days of October in Melitz near Leipzig, Germany. Ground-based long-term atmospheric monitoring instruments provided important additional background information to validate airborne results (Wich & Piel, 2021) (DUNN, 2013) (Azari et al., 2018). Portable Raman lidar Pollux gave the development of a boundary layer and an overview of the vertical structure of particles in the atmosphere. They sampled the air for more than 1 hour and compared the ALADINA and ground-based aerosol data. Simultaneously, MASC (Multipurpose Airborne Carrier) was operated with various patterns equipped with the same meteorological instruments. A vertical profile up to 1000m in altitude was taken. They detected almost neutral stratification and two significant aerosol layers (Nasir et al., 2016a) (Parks, 2016) (Ltd, 2022) (Irizarry et al., n.d.). They observed a significant difference in both CPC above the region of 500-600m. This represented particle burst in the ABL during morning time, and no particle burst was detected at ground level, but an internal layer in ABL was present (9th October). This shows the potential of the airborne system as it gave comparably reliable results when compared with ground-based instruments (Abdulrazaq et al., 2020) (Tkáč & Mésároš, 2019). From August through December of 2014 in Hangzhou, China, an unmanned aerial vehicle equipped with mobile sensors collected 3D data on fine particulate matter ($PM_{2.5}$) mass concentration in 16 flights between an altitude of 1000m and a 4km x 4km region. (Sandbrook, 2015) (Smythe, 2021). He proved that UAVs may be used in conjunction with mobile monitoring gear, in particular for tracking the vertical profile of pollutants. The findings revealed a difference in Pm2.5 concentration between flights in the morning and afternoon. (Anderson, 2013) (Lidynia et al., 2017) (Burgués & Marco, 2020). With the appearance of an air T inversion layer, however, the concentration falls with altitude. Fluctuations in PM2.5 concentration throughout an extra time of day are revealed by distinct regression models in the horizontal layer, and sudden variations become practically uniform after afternoon flights (directly related with the extent of atmospheric mixture). Distribution between sheer and ground-based observation is well described, according to several regression models. The effects of four observed parameters (air T, relative RH, air pressure, and height) on the vertical distribution pattern are explained by their regression coefficients, leading to the conclusion that air T and relative RH primarily affect the vertical distribution of $PM_{2.5}$ concentration. (Watkins et al., 2020) . It is observed that the UAV, when combined with mobile sensing devices/equipment, is more feasible for collecting the air pollutant concentration data and for vertical profiling.

(Skorup & Haaland, 2020a; Troy, 2015) built an air core that can quantify mole fractions of greenhouse gases from a UAV (CO_2, CH_4 and CO). Unlike passive air sampling systems, this one made use of the pressure differential in the atmosphere to collect data. The air sample was obtained by the Air Core by forcing air through a tube using a pump while in flight, allowing for a spatial sampling of the atmosphere. The samples were collected in the same morning and afternoon on the same day from five separate flights near the atmospheric measuring station at Lutjewad, Groningen, Netherlands. The used active Air Core weighs around 1.1 kg. They analyzed the material for mole fraction of parameters using a CRDS (Cavity Ring-Down Spectrometer) no more than 7 minutes after landing. The data from the active Air Core were checked against those from the Lutjewad station at 60m. (Chandhar & Larsson, 2019b) (McCall, 2019b). They even detected a CH_4 hotspot. It is observed that this new system can capture both vertical and horizontal trace gas profiles and, when combined with UAV, has capabilities to measure at the locations where no other techniques have any sort of practical access, making this a more feasible method for further work related to air-based monitoring/sampling (Aydin, 2019a) (Dering et al., 2019b).

TABLE 1

Sr. No.	Author	Type of UAV	Flight Time	Take off type	Application	Parameters	Algorithm
1	(Neumann et al., 2013)	Microdrone (Airrobot AR100-B)	20 min	Vertical	Wind Vector estimation & Gas distribution mapping	CO_2, T, RH	YES Kernel DM+V/W algorithm
2	(Martin et al., 2011)	M2AV CAROLO (fixed wing)	15min	Horizontal	Meteorological profiling	T, RH & Wind	NO
3	(Abualigah et al., 2021a)	TREX Allign 700 E V2	ND	Vertical	Trace gas, WMS detection & onboard data acquisition	GHG (H_2O, CO_2&CH_4)	YES
4	(Neumann et al., 2013)	Microdrone (Airrobot AR100-B)	20min	Vertical	Identification of gas location	CO_2	YES
5	(Ma et al., 2020)	Microdrone (Airrobot AR100-B)	30min	Vertical	Gas source localization	Environmental gases	YES
6	(Baltsavias et al., 2008)	Carolo P360 "ALADINA" (fixed wing)	20min	Horizontal	Observing horizontal & vertical distribution of ultrafine particles	T, RH & aerosol	NO
7	(Peng et al., 2015)	UAV	ND	Vertical	Measurements of Vertical distribution of air pollutant concentration	T, RH, air pressure and height	YES

8	(Anderson, 2013)Rossi et.al	Hex copter	30min	Vertical	Gas leakage localization with GSS (gas sensing system), Drone mapping	Volatile Organic Compounds (VOC), CO, NO, N_2	YES
9	(Anderson, 2013)	UAV	ND	Vertical	Atmospheric mole fraction measurements	Greenhouse gases	YES
10	(Burgués & Marco, 2020)	Phantom 3 (quadcopter)	23min	Vertical	AQ & Water Quality Surveying	GHG (CO_2, N_2O, CH_4, H2O & O_3) & water samples	YES
11	(Gu et al., 2018)	Hex copter	32 min	Vertical	Air quality parameters	PM $_{2.5}$, NO_2	YES
12	(Peng et al., 2015)	Hex copter	20 min	Vertical	PM measurements	PM 2.5, 10	YES
13	(Shi et al., 2018)	Hex copter	20 min	Vertical	PM measurement & sampling	PM CO_2	YES
14	Tauro, Flavia; Porfiri, Maurizio;	Hex copter	20 min	1000m	PM and VOC	PM 2.5, VOC	YES
15	(Lidynia, Chantal; et.al, 2017)	hex copter	23min	3000m	PM $_{2.5}$	PM $_{2.5}$	YES
16	Ltd, ICB-InterConsult Bulgaria	Hex copter	32 min	300 m		PM $_{2.5}$	YES
17	(Rohi et al., 2020)	Hex copter, quadcopter	20 min	5m-100 m	Particle number concentration	Particle number concentration	NO
18	(Nasir et al., 2016)	Quadrotor	20 min	~1000m	$PM_{2.5}$	$PM_{2.5}$	NO
19	(Nasir et al., 2016)	hex copter	23min	~300m	Aerosol	aerosol	YES
20	(Berkowitz, 2014)	Tethered balloon-based	32 min	100 m to 990 m	PNSD, PNC	PNSD, PNC	YES
21	(Custers, 2016)	Six-rotor	23min	0 to 1000 m	$PM_{2.5}$	$PM_{2.5}$	YES
22	(Huang et al., 2020)	DJI Matrice M600 hex copter	18 min	0-60m 0-40m	CO, PM	CO, PM	YES
23	(Campi et al., 2016)	hex copter	20 min	0–1200 m	Ozone	Ozone	YES
24	(Kyrkou et al., 2019)	tethered mega balloon	12 min	1000 m	PM2.5, SO2, black carbon, O3	PM2.5, SO2, black carbon, O_3	YES
25	(Hussein et al., 2020)	Quadrotor	15 min	1000 m	PM2.5	$PM_{2.5}$	YES
26	(Boukoberine et al., 2019)	hex copter	32 min	500 m	black carbon $PM_{2.5}$	black carbon $PM_{2.5}$	YES
27		Multicopper	20 min	1000 m	VOCs	VOCs	NO

	(Balasingam, 2017)						
28	(Liu et al., 2020b)	Fixed wing	25 min	3500–4000 m	Meteorological Elements and Black Carbon	Meteorological Elements and Black Carbon	YES
29	(Vallet, 2014)	eight-axis rotor	23min	350 m	Aerosol	aerosol	YES
30	(Abualigah et al., 2021)	tethered balloon system	40 min	470 m	PM, black carbon	PM, black carbon	NO
31	(Skorup & Haaland, 2020)	quad multi-rotor	16 min	15 30, 45, and 60	PM10, $PM_{2.5}$, PM1, CO2, and HCHO	PM10, $PM_{2.5}$, PM1, CO2, and HCHO	YES

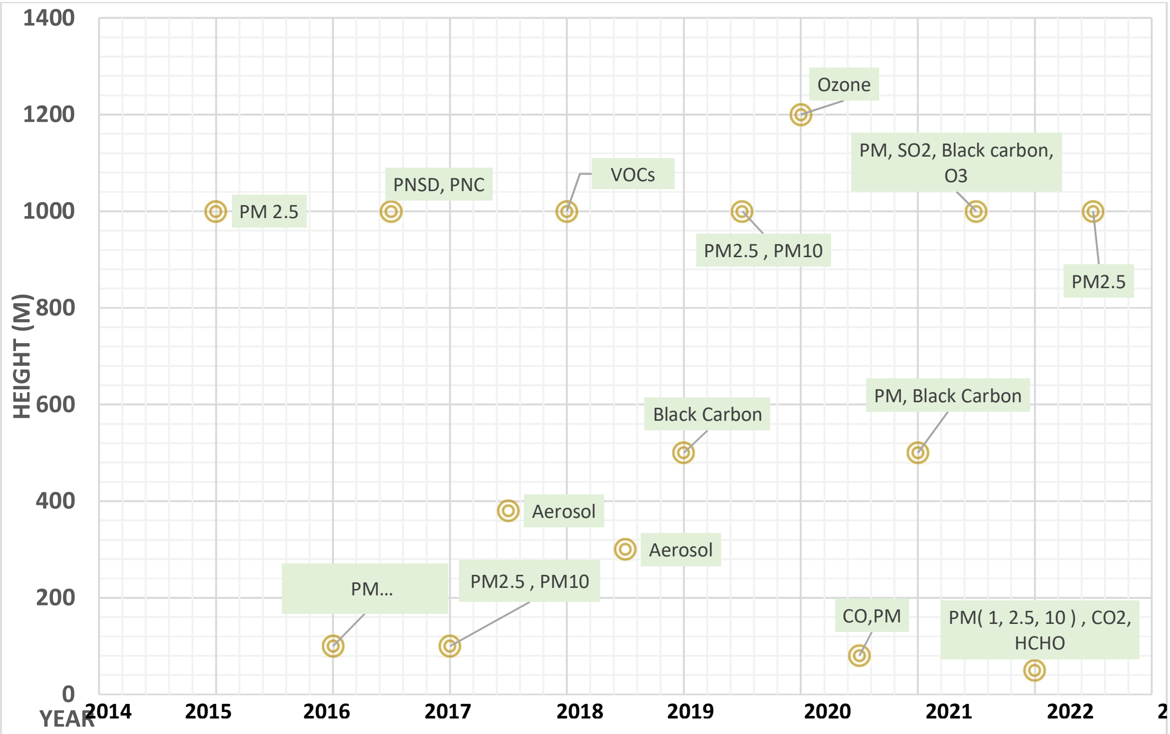

Fig. 6 Year-wise focus on air pollutants

(Huang et al., 2020)has presented a system consisting of a UAV equipped with a set of sensors, a wireless system, microcontrollers, and other accessories. AQ and Water Quality monitoring systems were used in this. The calibrated sensor was used to ensure the reliability of the data. The air quality monitoring system consisted of gas sensors and microcontrollers that measured the concentration of GHG at different altitudes in different Environmental conditions, and the water quality system consisted of water quality sensors, microcontrollers and a water sampling unit that collected a water sample from off-shore and on-shore water sources for quality measurements (Kyrkou et al., 2019a) (Park et al., 2021) (Aydin, 2019b) (Campi et al., 2016a) (Balasingam, 2017c). The system could record the measured data on an onboard SD card as well as wirelessly transfer the data to the ground monitoring unit. It is observed that the method developed by them can take sampling to a different level by combining calibrated sensors with UAVs so that various locations can be reached in both air and water quality monitoring (K. Smith, 2015) (Sandbrook, 2015). Their major limitation was that they used commercially available sensors, and in recent years more reliable and low-cost sensors have been developed, which can be put into this system and will take this work to a different level (Radjawali & Pye, 2017b) (Oertel, 1956b).

Fixed wing has the advantage of being able to carry more payload and have a longer duration of flight time when compared to the rotor UAVs. Still, they are unstable in the hovering category and need a much larger and clear path for take-off.(Aggarwal et al., 2019) In contrast, rotor UAVs can take off in much smaller areas (vertical) and can even be brought to an abrupt halt to hover over the required location.

IV. CONCLUSION

The results show the importance of vertical AQ monitoring in industrial and urban environments. Developed countries like the Republic of China, the USA have attempted maximum experiments on drone-aided aided AQ monitoring in industrial and urban environments. The stability of the UAV based on factors like flight altitude, portability, flight time, etc., has been discussed in this review paper. From the table, we can conclude that 80% of the studies have been considered by using a multirotor drone which is more likely a quadcopter UAV and 20% have used the fixed-wing method. Multirotor UAVs are proven to be the best aerial vehicle for sensor-aided studies in air, water and MSW sites.

The data collection at non-accessible locations can be possible due to strong GPS stability during hovering in 3D space. PM $_{(2.5-10)}$ and other gaseous pollutants can be routinely monitored in the range of 5-600m AGL. The meteorological parameters and drone-aided studies can be conducted above 1200m. The gaseous pollutants such as total VOCs, O_3, CO, SOx, and NOx can be monitored using drone-aided air sensors. Optical PM sensors have gained popularity in the field of real-time AQ monitoring. The results depict that vertical profiling of the parameters in the ABL (atmospheric boundary layer) is a need of present AQ monitoring methods with the help of AI-ML tools. Recent AI-based drones coupled with air quality sensors have opened new dimensions of modelling and mapping air pollutants in 3D space. Air pollutant mapping using an AI algorithm can track the pollutants up to longer distances. Very few studies have been performed using AI-based algorithms and drone-aided AQ data. Therefore, there is a need to explore this domain for saving the time and cost of air quality sampling and monitoring in industrial environments.

Limitations and Future Scope: Drones have a lot of benefits, but there are restrictions that need to be considered. Over the past few months, developing nations have introduced several drone operation rules for commercial activity. The drone pilot certificate is required to operate small and medium-sized drones. Drones have several significant drawbacks like flight time, the attachments they can disrupt, the danger they can pose, and improper use. Few areas such as eco-sensitive zones, airports, and defense training locations have been banned for drone operations. The drones cannot be operated under extreme weather conditions such as high wind conditions, rain, and lightning conditions. However, these limitations could be eliminated soon. Drones are still anticipated to play a significant role, and Government Communications is likely to investigate securing frequencies for drones

Drones have become a popular tool for various industries, mining applications, environmental sample delivery, and surveying. Future Drone technologies will be with artificial intelligence and applications such as robotics arms, bio mimic drones, pollinating drones, firefighting drones, tree plantation drones, radiation detection drones, etc. The market for commercial drones was estimated to be worth $6.51 billion globally in 2021. At a CAGR of 28.58%, it is predicted to reach $47.38 billion by 2028.

Fig. 7 Future Drone for AQ monitoring

Also, more advanced drones such as tethered drones can be very useful in the near future. The drone system depicted in Fig. 7 will be the future environmental monitoring system. Such systems will collect the AQ data periodically in 24 hours. The tethered device will not have the problem of limited flight time and inter-drone data communication. SWARN protocol will communicate the multiple drones to show the hotspots in the urban and industrial environment. With the help of Artificial Intelligence and machine learning toolbox, it is possible to identify the critical locations on landfill sites or industrial gas leakages like methane, benzene, etc. In the future, industrial stack emission monitoring and methane monitoring will be possible using >10 kg payload capacity drone. More applications need to be developed in the domain of AQ monitoring to collect the high-resolution data set. Users can use drones efficiently and safely if they are aware of the rules that govern their use.

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