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DRONE-MOUNTED SENSORS. PERFORMANCE AND SUITABILITY ASSESSMENT FOR AIR QUALITY MONITORING

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Air pollution remains a pressing issue, with its effects impacting both public health and the environment. Traditional fixed point air quality monitoring methods present limitations, leading to the accelerated adoption of drones in this field. This paper evaluates the overall performance and suitability of a sensor-equipped drone for air quality assessment. The system is equipped with sensors to measure concentrations of SO_2, NO_2, O_3, PM_{10} and $PM_{2.5}$. In the first phase of the study, measurements were conducted under various atmospheric conditions to compare the performance of the drone-mounted sensors with that of a self-calibrating reference equipment. A significant influence of ambient temperature and relative humidity on the drone's measurements was revealed. Correction factors were calculated for each pollutant and measurement condition using the Ratio Correction Factor and Linear Regression methods. In the second phase, differences in pollutant concentrations between high and low anthropogenic influence areas were assessed, demonstrating the impact of urban activities on air quality. Finally, the Air Quality Index was calculated using data from both monitoring systems, resulting in the same air quality classes. Due to relatively short flight time, drone-mounted monitoring systems are better suited for specific episodic assessments, rather than long-term air quality monitoring.

Keywords: air quality assessment, drones, health impact, sensor performance, Air Quality Index.

INTRODUCTION

Air pollution is a pressing issue, with its effects being felt in the health of the population through a wide range of chronic and acute diseases, as well as in the environment[1]. The main air pollutants with the most widespread negative effects are SO_2, NO_2, O_3 and PM (particulate matter)[2]. Exposing the population to high concentrations over a long period of time can cause a variety of diseases, including respiratory tract and eye infections, lung damage, and the onset or increase in asthmatic episodes[3,4].

Atmospheric pollutants can be grouped into two main categories according to their origin: natural and anthropogenic. Natural sources of pollution include some extreme natural phenomena such as volcanic eruptions and wildfires, but also common events such as soil erosion or plant pollen dispersion. Anthropogenic sources of pollution, which include activities such as industrial operations, transport, and heating systems, are considered the most important due to their high prevalence and significant contribution to air pollution[3–5]. Another way of classifying air pollutants is according to their origin. Primary pollutants are emitted directly into the atmosphere as a result of a process. Secondary pollutants are formed in the atmosphere as a result of chemical reactions[3].

The negative effects of exposure on human health and the environment have highlighted the need for thorough air quality monitoring. Traditionally, this monitoring has been carried out using in-situ equipment at ground level, due to their accuracy, stability, and performance, and the variety of pollutants they can identify. However, these equipment are costly, bulky and do not allow monitoring of pollutants at different heights[6,7]. Ex-situ monitoring of air quality involves remote sensing techniques, such as LIDAR (Light Detection and Ranging), or satellite imagery to assess the distribution of pollutants. These methods are very expensive and not always efficient for continuous monitoring of the same area, with low vertical or horizontal resolutions[1,8].

The limitations of traditional fixed point methods for monitoring air quality have accelerated the adoption of drones in this field. The possibility of monitoring at different heights, access to hard-to-reach areas, low costs and ease of use are just some of the advantages that drones present when we refer to the monitoring of atmospheric pollutants[9–12]. Due to their capabilities to provide real-time data and the possibility to access complex areas in case of natural or technological disasters, drones represent important tools aiding decision making during emergencies. However, air quality monitoring using drones involves certain limitations, mainly due to the limited flight time, the limited availability of high-performance sensors and the difficulty of loading the drone with monitoring equipment[10]. In terms of payload, this directly influences the flight time and stability of the drone. Controlling the drone when the payload is too high becomes difficult and dangerous, as the flight functions, which should help to avoid certain obstacles during flight, are hampered by the need to direct power to the payload lift[13]. The limitations of using drones for air quality monitoring have imposed a strict selection of the sensors that can be mounted on them. They need to fulfill several functions to be feasible for air quality monitoring - small size, high sensitivity and selectivity, chosen according to the species to be monitored, and low response time. The selection of sensors also depends on the atmospheric conditions, due to the significant influences that temperature and humidity have on them[10,14,15].

The aim of the present work is to analyze the overall performance and suitability of a drone-mounted commercial sensor system used in air quality assessment. The objectives of the study are structured to address the key aspects of the proposed analysis:

- Intercomparison of measurements by using a high-performance ground-level station and those made using drones;
- Air quality assessment, based on the monitoring results.

EXPERIMENTAL PART

The experimental phase is composed of two main parts:

1) testing the accuracy of the drone-mounted sensor system by comparing its measurements with those taken by a self-calibrating reference instrument under varying meteorological and seasonal conditions;

2) conducting measurements to determine the concentration of target pollutants in both urban areas of Cluj-Napoca, heavily influenced by anthropogenic activity, and in locations sheltered from population-induced effects.

The drone used in this paper is a DJI Mavic 3 Classic (Fig. 1). Under normal conditions, the drone can reach a vertical speed of 6 m/s and a horizontal travel speed of 15 m/s. It can operate efficiently between –10 and 40 °C, and the hover time can be up to 40 minutes, depending mainly on wind speed. The drone was equipped with the Sniffer4D V2 sensor system, produced by the company Soarability, which modified both the mass and height, as well as its mobility and flight time. The sensor system is made of aluminum, significantly reducing the electromagnetic interference generated by the drone's motor and other electrical components. Its main components include an air intake system capable of directing a 5 l/min airflow to the sensor chamber, two air vents for air circulation and a fan to keep the system at an optimal temperature. The Sniffer4D V2 can include various sensors for monitoring different air pollutants, chosen according to individual objectives. SO_2, NO_2, O_3, PM_{10} and $PM_{2.5}$ sensors were used for this experiment. The last sensor calibration was performed in November 2022, about 14 months before the start of the experiment.

The reference laboratory is equipped with various sensors for measuring air quality, including the SO_2 analyzer model T100, the NO/ NO_2/ NO_x analyzer model T200 and the photometric O_3 analyzer model T400 developed by Teledyne Technologies and the PM analyzer model EDM 180 developed by GRIMM Aerosol Technik Ainring GmbH & Co. KG (Fig. 2). The analyzers used for the measurement of gaseous pollutants are equipped with self-calibration systems, which periodically take an air sample from a container with a known concentration of the pollutant in question and use it to recalibrate the sensors. The PM analyzer undergoes a periodical calibration process, carried out by specialized personnel. It is also equipped with a membrane which is designed to lock in excess moisture from the sample without heating it, thus avoiding the risk associated with subsequent dehydration and fragmentation of the PM in the sample. The present work followed two main phases. The *first phase* consisted of testing the drone-mounted sensors, where a number of nine sets of measurements for SO_2, NO_2, O_3, PM_{10} and $PM_{2.5}$ were carried out under different temperature and humidity conditions, in order to highlight their influence on the accuracy of the measurements.

Figure 1. DJI Mavic 3 and Sniffer4D V2.

Figure 2. Reference equipment.

The nine sets of measurements were conducted in Cluj-Napoca during autumn 2023 and spring 2024, in the courtyard of the Faculty of Environmental Science and Engineering. These measurements involved simultaneous measurements at the same location using both the drone-mounted system and the reference auto-laboratory's measuring equipment. By testing air samples from the same area, the accuracy of the drone's sensors in comparison with those of the auto-laboratory was observed. Due to the limited flight time of the drone, the measurements were carried out by strategically placing the drone on the top of the auto-laboratory, without taking off, so that the suction port of the sensor system mounted on the drone was close to the suction system of the auto-laboratory. This configuration brought two major benefits to the experiment – an increase of the measurement time, not being influenced by the hover time, and more accurate air sampling due to the positioning of the two suction systems, thus reducing influences that could have affected the samples.

The *second phase* of the experiment consisted of drone measurements on different days during the spring of 2024, in two high urban traffic influenced areas in Cluj-Napoca (during rush hours), and two rural areas without any traffic. The measurements were carried out on days with low humidity (≈ 40%) and normal temperatures (16–20 °C). This phase is also aimed at analyzing the variability of the results depending on the measurement conditions – stationary or in flight. The first day of measurements took place in the Fânațele Clujului rural area with low anthropogenic influence, and in the Iris urban area with high anthropogenic influence. The second day of measurements took place in the Făget rural, and in the Grigorescu urban areas. In compliance with national regulations governing drone use in urban areas, these measurements were conducted at a fixed height of 1.5 meters above ground level, with the drone remaining stationary. In rural areas, measurements were performed at varying altitudes, incrementally increasing by 10 meters, up to a maximum of 30 meters above ground level. Furthermore, due to the drone's limited flight time, measurements were taken at shortened time intervals to ensure data collection efficiency. Therefore, the obtained values cannot be directly compared with the maximum allowable concentration limits for air pollutants established by current legislation. Instead, they represent specific conditions that provide a momentary view of air quality at the time the measurements were taken.

RESULTS

This section presents the results obtained from the two phases, highlighting the accuracy analysis and the overall performance of the drone sensors compared with the reference system.

Phase one

This phase contains the results obtained from the intercomparison of the concentration values obtained with the drone and those obtained with the reference system. Two distinct cases for different temperature and humidity ranges will be presented.

Case one

The first case presents the results obtained from measurements made under low temperature (≈ 5°C) and high relative humidity (≈ 80%) conditions (Fig. 3).

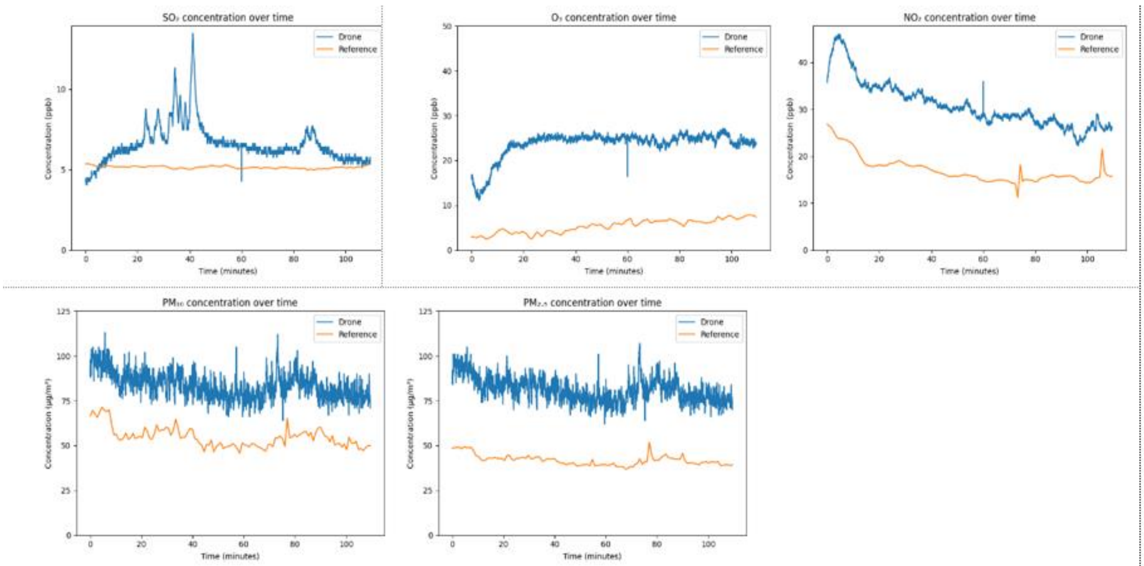

Figure 3. Results obtained from measurements made under low temperature and high humidity conditions.

According to the graphs from Fig. 3, major discrepancies can be observed between the concentration values obtained with the two systems. The main factors contributing to these differences are high humidity, as the drone-mounted sensor system lacks a moisture removal mechanism, and low temperature[16]. These differences highlight the necessity of developing correction coefficients to align the drone-measured values as close as possible to the ones from the reference equipment. 2 different methods have been used to determine these coefficients:

a) Ratio Correction Factor

Correction coefficients were calculated for each pair of auto-lab and drone values by determining the ratio of the measurements obtained from the reference equipment to those from the drone-mounted sensor system. An overall correction coefficient was then calculated as the average of these individual coefficients.

Under these conditions, five empirical equations have been determined, one for each of the air pollutants monitored.

$$SO_{2\,laboratory} = SO_{2\,drone} * 0.801 \tag{1}$$
$$NO_{2\,laboratory} = NO_{2\,drone} * 0.554 \tag{2}$$
$$O_{3\,laboratory} = O_{3\,drone} * 0.217 \tag{3}$$
$$PM_{10\,laboratory} = PM_{10\,drone} * 0.66 \tag{4}$$
$$PM_{2.5\,laboratory} = PM_{2.5\,drone} * 0.519 \tag{5}$$

b) *Linear regression method*

We applied the linear regression method between the values obtained with the reference system and those obtained with the drone. Thus, we determined the slope (m) and the intercept (c), which were used to bring the values obtained by the drone as close as possible to those obtained by the auto-laboratory.

$$Value_{corrected} = m * Value_{drone} + c \tag{6}$$

Therefore, 5 other equations were obtained for each monitored pollutant, where ‘c’ is the corrected concentration:

$$SO_{2\,c} = 0.014 * SO_{2\,drone} + 5.23 \tag{7}$$
$$NO_{2\,c} = 0.533 * NO_{2\,drone} + 0.60 \tag{8}$$
$$O_{3\,c} = 0.239 * O_{3\,drone} - 0.48 \tag{9}$$
$$PM_{10\,c} = 0.598 * PM_{10\,drone} + 5.12 \tag{10}$$
$$PM_{2.5\,c} = 0.305 * PM_{2.5\,drone} + 17.27 \tag{11}$$

Case two

The second case presents the results obtained from measurements made under high temperature (19–23°C) and low humidity (38–55%) conditions (Fig. 4).

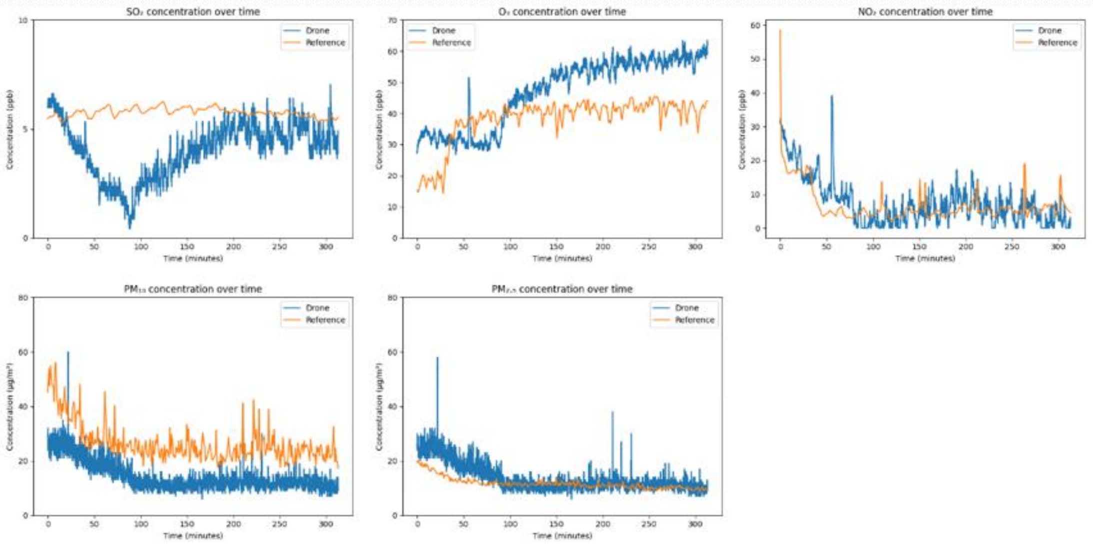

Figure 4. Results obtained from measurements made under high temperature and low humidity conditions.

A significant reduction in the differences between the measurements can be observed in case two, especially for NO_2, PM_{10} and $PM_{2.5}$. Thus, it can be confirmed that meteorological factors - temperature and humidity – directly affect the accuracy of the sensors placed on the drone. For SO_2, a major deviation can be observed in the early part of the measurements and the two curves get closer from the third hour. Imposing new correction coefficients for this case can show how close the values obtained with the drone-mounted system are to the values obtained by the reference equipment.

a) Ratio Correction Factor

$$SO_{2\,laboratory} = SO_{2\,drone} * 1.352 \tag{12}$$
$$NO_{2\,laboratory} = NO_{2\,drone} * 0.892 \tag{13}$$
$$O_{3\,laboratory} = O_{3\,drone} * 0.774 \tag{14}$$
$$PM_{10\,laboratory} = PM_{10\,drone} * 1.923 \tag{15}$$
$$PM_{2.5\,laboratory} = PM_{2.5\,drone} * 0.916 \tag{16}$$

b) Linear Regression Method

$$SO_{2\,c} = -0.052 * SO_{2\,drone} + 5.98 \tag{17}$$

$$NO_{2_c} = 0.551 * NO_{2_{drone}} + 2.53 \quad (18)$$
$$O_{3_c} = 0.441 * O_{3_{drone}} + 17.19 \quad (19)$$
$$PM_{10_c} = 1.119 * PM_{10_{drone}} + 10.68 \quad (20)$$
$$PM_{2.5_c} = 0.375 * PM_{2.5_{drone}} + 6.62 \quad (21)$$

Phase two

Considering the accuracy of the drone-mounted sensor system, concluded from the first phase, the days for phase two measurements were selected with high temperature (≈ 16 °C) and low humidity (≈ 40%) conditions.

Figures 5 and 6 present the results of PM_{10} measurements in high-traffic urban areas and low-anthropogenic-influence rural areas, respectively. A significant difference in the concentrations between the two measurements is evident, with urban values being approximately three times higher than those in rural areas.

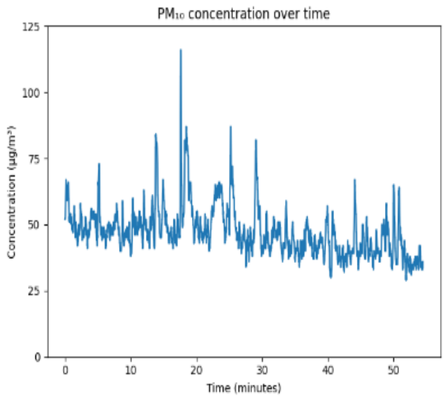

Figure 5. Variation of PM_{10} concentration over time in the anthropogenic influenced area.

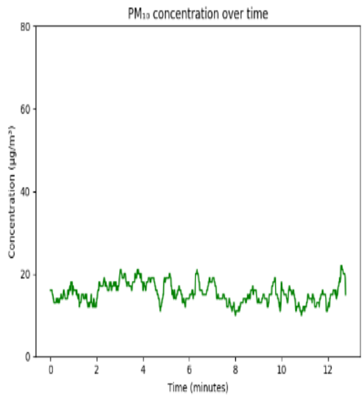

Figure 6. Variation of PM_{10} concentration over time in the area not influenced by anthropogenic anthropogenic.

Air Quality Index

In order to determine the air quality based on the measurements, specific air quality indices (AQI) provided by the National Air Quality Monitoring Network were used. According to them, the measured air quality can vary from good (1) to extremely bad (6), depending on the measured concentrations. The general air quality index is determined by selecting the maximum value of the specific air quality indices[17]. Table 1 presents the concentration intervals for the determination of AQI for each pollutant analysed. The AQI considers hourly average values, but the national legislation in force (Law 104/2001 on ambient air quality – actualized) does not set maximum permissible values for all pollutants (such as PM and ozone) on hourly averages. Based on Table 1, the AQI for the two cases (drone-mounted system versus reference auto-laboratory in different meteorological conditions) can be calculated. These results are presented in Table 2. Thus, in the first case, the air quality falls into category 5 (very bad) and in the second case, the air quality falls into category 3 (moderate) due to the high concentrations of PM_{10}.

Table 1

Specific index concentration.

Specific index	SO_2 hourly concentration (µg/m^3)	NO_2 hourly concentration (µg/m^3)	O_3 hourly concentration (µg/m^3)	PM_{10} hourly concentration (µg/m^3)***
1	0–49.(9)	0–49.(9)	0–39.(9)	0–9.(9)
2	50–74.(9)	50–99.(9)	40–79.(9)	10–19.(9)
3	75–124.(9)	100–139.(9)	80–119.(9)	20–29.(9)
4	125–349.(9)	140–199.(9)	120–179.(9)	30–49.(9)
5	**350***–499.(9)	**200***–399.(9)	180–239.(9)	50–99.(9)
6	>500	>400	>**240****	>100

* hourly limit value for human health protection;
** alert threshold value;
*** no hourly limit or alert threshold value defined in the national legislation

Table 2

Air Quality Index

	Mean SO_2 concentration (μg/m^3)	Mean NO_2 concentration (μg/m^3)	Mean O_3 concentration (μg/m^3)	Mean PM_{10} concentration (μg/m^3)	AQI
Case 1 – drone	18.18	61.35	48.86	80.43	5
Case 1 – auto-lab	14.17	33.96	10.66	83.43	5
Case 2 – drone	11.07	15.25	97.15	14.34	3
Case 2 – auto-lab	15.91	13.42	78.41	26.73	3

DISCUSSION

The results presented in the above section demonstrate the influence of relative humidity and temperature on the measurements. Specifically, lower temperatures and higher relative humidity lead to greater deviations in the values obtained by the drone-mounted system compared to those from the reference system. These findings align with another study[16], which tested various sensors for monitoring atmospheric pollutant concentrations under different conditions. However, the extended period between calibration and measurements may also influence the results, potentially leading to such differences.

The calculated ratio correction factors and linear regression equations can help achieve results more closely aligned with the reference system. However, these results may vary depending on atmospheric conditions and should be interpreted as qualitative rather than quantitative information.

Additionally, the study demonstrated the suitability of drones for air quality assessment. Based on the calculated AQIs, despite the differences between the measurement results from the drone and the reference system, both methods classified the air quality into the same categories.

Furthermore, the study highlighted the significant impact of high urban traffic on air quality compared to areas with minimal anthropogenic influence.

CONCLUSIONS

The aim of this work was to analyze the overall performance and suitability of a drone-mounted sensor system for air quality assessment, based on the intercomparison of the monitoring results obtained with the drone and the reference system used.

Sensor systems deployed on drones can be effectively utilized to monitor air pollutant concentrations, whether anthropogenic or natural origin. However, several factors can affect the accuracy of the measurements, such as atmospheric temperature and humidity, calibration period and quality, and flight altitude. Due to relatively short flight time, drone-mounted monitoring systems are better suited for specific episodic assessments, rather than for long-term air quality monitoring. More advanced sensor systems tend to be larger, requiring the use of bigger drones. However, due to actual legislative constraints, larger drones are often not permitted to operate in residential areas without obtaining a special permit.

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