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An Assessment of the Possibility of Using Unmanned Aerial Vehicles to Identify and Map Air Pollution from Infrastructure Emissions

Agata Jaroń [1,*], Anna Borucka [2], Paulina Deliś [3] and Aleksandra Sekrecka [3]

[1] Doctoral School, Military University of Technology, 00-908 Warsaw, Poland
[2] Faculty of Security, Logistics and Management, Military University of Technology, 00-908 Warsaw, Poland; anna.borucka@wat.edu.pl
[3] Faculty of Civil Engineering and Geodesy, Military University of Technology, 00-908 Warsaw, Poland; paulina.delis@wat.edu.pl (P.D.); aleksandra.sekrecka@wat.edu.pl (A.S.)
* Correspondence: agata.jaron@wat.edu.pl

Abstract: Sustainable development and the creation of smart, green cities requires cooperation in many scientific fields, including those related to ecology, mobility, or sustainable management, among others. Environmental protection is a particularly important element here. Atmospheric pollution, due to air movements, spreads over very large areas; therefore, air quality monitoring is crucial to ensure protection from harmful substances. One of the most severe sources of air pollution, accounting for as much as approximately 25% of total annual emissions within the EU, is road transport. Therefore, the European Union has set an ambitious target to reduce total emissions to 55% for cars and 50% for vans by 2030. In recent years, unmanned aerial vehicles (UAVs) have become increasingly popular in many scientific fields, including environmental protection and photogrammetry. The use of UAVs to identify harmful pollutants allows them to gain an advantage over conventional detection methods, due to the possibility of remote (therefore safe for humans), faster, and area-based measurements. Given the ever-expanding scale of the use of this technology, this paper presents the possibilities of using UAVs to identify and visualize (map) pollution. The examples presented in the foreign literature, as well as our own research, in imaging the altitude distribution of air pollutants; gaseous pollutants: C_6H_6, HCHO, SO_2; and particulate matter: PM_1, $PM_{2.5}$, PM_{10} demonstrate the validity of such measures. This research was carried out in the area of one of Poland's key A4 highways. The maps obtained allow for an area-wise and altitude-wise presentation of one of the significant air pollutants in the EU. In addition, they can be a valuable source of information for the implementation of future projects and the improvement of road infrastructure, thus contributing to the reduction of air pollution and the creation of so-called "green cities".

Keywords: intelligent air pollution measurement; air pollution mapping; drones in environmental protection; sustainable development; environmental protection

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1. Introduction

Air pollution in large urban agglomerations is currently causing great concern. The ease of diffusion in air compared to water or soil means that the sources of air pollution are global. Suspended dust is the most dangerous due to its very small size and easy penetration through the lung alveoli and then into the bloodstream. The penetration of these air pollutants into the bloodstream is associated with causing numerous diseases of the circulatory system, respiratory system and allergies, and in extreme cases it also contributes to earlier deaths. In the EU, as much as 25% of the total annual air pollution emissions come from transport, of which as much as 71% from road transport. By 2030 year, the European Union has decided to reduce exhaust emissions to 55% for passenger cars and 50% for delivery vehicles [1]. Therefore, it is extremely important to illustrate how air pollution spreads for one of the key sources of pollution in the European Union. Recently, due to their small size, great freedom of movement, ease of use, ability to reach hard-to-reach places and receive real-time results for air quality monitoring, unmanned aerial vehicles have become very popular

Unmanned aerial vehicles (UAVs), are defined as objects capable of performing flight without a pilot-commander on board and in an autonomous or controlled manner from another location within its range [2]. Such technology is widely used in the aspect of military operations but also in the civilian area. Solutions in the field of unmanned aviation are constantly being developed. This determines the possibility of implementing drones in a wide range of activities. Unmanned aerial vehicles are used, among others, in agriculture, transport and logistics services, medical rescue [3], media services [3], air quality research, etc. [2]. Unmanned aerial vehicles are increasingly being used for environmental protection activities [2]. Unmanned platforms have also gained popularity in social areas. In the world, the number of passenger cars increases year after year, and, as a result, the level of air pollution from road infrastructure emissions grows and becomes an environmental nuisance. Using the functionality of unmanned aerial vehicles for monitoring or imaging a given area should contribute to maintaining an appropriate environmental safety level [4]. The literature review conducted shows several main areas of application in this aspect.

1.1. The Use of UAVs to Identify Air Pollution

Devices equipped with specialized sensors, software, and optical equipment are used for the identification of air contamination. There are several ways to use them. UAVs are capable, among others, of effectively mitigating environmental risks [5]. Their small size, combined with appropriate equipment, allows them to easily reach places that are difficult for a human to reach. In a very short time, they can move over very large areas. After lowering their altitude, they are able to take precise photos of a given area, taking into account details such as vegetation and terrain relief or conducting necessary measurements. All of this results in the fact that UAVs can prove to be extremely useful in terms of the identification and mapping of air pollution from, among others, road infrastructure emissions [6,7].

1.2. The Use of UAVs for Pollution Mapping

Drones are also used for pollution mapping, studying air quality in a designated area. The sensor installed is designed to detect the air pollution level. In addition, the devices can be upgraded with sensors to detect substances, the source of which is road infrastructure. An unmanned aerial vehicle is capable of recording the area in which air pollution concentration is the highest, collecting a sample and analyzing it. The results are then transmitted by a mobile outdoor unit [8]. Exceeded levels of gaseous air pollutants, such as CO_2, SO_2, NxOy, and particulate matter, such as PM_1, $PM_{2.5}$, and PM_{10}, demonstrate the validity of such measures and provide important information for environmental protection services. In addition, a special drone equipped with a sensor can create a smog map showing the most polluted areas [8–11].

The air in Poland is among the most polluted in Europe; the number of premature deaths related to this problem is estimated at nearly 45,000 per year. Air pollution mainly contributes to diseases of the upper respiratory tract, such as chronic bronchitis, respiratory failure, and allergic diseases, and it can also lead to the development of cardiovascular diseases [12].

Based on the measurements conducted, maps and reports on air quality were created, showing the concentration of individual chemical compounds. This allows for an identification of the sources of emissions and the effective carrying out of corrective actions. This study was carried out semi-automatically, with supervision by trained operators experienced in acquiring air quality data. The study results were available online in real time, on a geoportal. By using UAVs, air quality maps can be created even in hard-to-reach areas. By taking measurements at different altitudes, it was possible to indicate how pollutants propagate through air corridors. The result of such activity was an air quality map, combined with a descriptive report on the work carried out. It contains technical data on the tests performed, the time of their implementation, the measured parameters, and the recorded values of chemical compound concentrations. In addition, the conclusions include the most important information-noticed irregularities, analysis of the map, and a summary [13,14].

1.3. The Use of UAVs for Pollution Mapping, the Source of Which Is Road Infrastructure

Unmanned aerial vehicles (UAVs), thanks to their mounted sensors and air sampling containers, can provide accurate information on pollution distribution, the source of which is exhaust emissions from road infrastructure, which can allow for an in-depth analysis of air composition in specific layers of the atmosphere. Air sampling can take place in any area, including over highways and national and local roads [15,16]. It is common knowledge that the source of harmful pollutants from vehicles includes gases generated in the engine system [17]. A harmful waste caused by burning oil or gasoline is CO_2, a greenhouse gas that is particularly dangerous to the Earth [18]. Other pollutants that are harmful to health are SO_2 gases; NxOy; formaldehyde (CH_2O); volatile organic compounds (C_6H_6); ozone (O_3); and particulate matter PM_1, $PM_{2.5}$, and PM_{10}.

An apparatus mounted on a drone can be used to collect samples for further analysis in a stationary laboratory or can be adapted for a real-time analysis of the samples. The example set described in [2] for sampling was built with a mini vacuum air pump, a microcontroller, a relay, a DC–DC converter (powered by a 12 V LiPo battery), and an atmospheric pressure sensor. The housing contained a sample tube and a suspended sample bag. The communication and control of the mini vacuum pump was via a radio signal from a transmitter, the function of which was provided by a tablet/smartphone with a preloaded app.

The second type of apparatus, which allowed for the real-time measurement of contaminants, was additionally equipped with a set of electro-chemical sensors or detectors using visible and infrared light (VIS and IR) radiation technologies. With their help, the air was analyzed at regular intervals, while information on specific compounds was sent in real time to the operator on the ground. The collected data could also be recorded in memory for further analysis or for the mapping of particularly polluted zones. The types of chemical compounds to be monitored depended on the chosen set of sensors [19,20].

Current knowledge shows that rotorcraft, including hexacopters and octocopters [2], which have the ability to conduct pollution surveys in close proximity over the source-emitter, are the most practical for measuring airborne emissions and also do not require a runway, because the drone takes off and lands vertically [21].

An example of such a UAV is the air contamination platform. It is used to measure air pollution at altitudes of up to 500 m. For this purpose, the device is additionally equipped with a battery that allows it to fly at high altitudes. The entire structure of the drone is made of aluminum, and selected parts of the casing are printed on a 3D printer; its weight is only 3 kg [2]. The pollution measurements obtained can be transferred by various mapping interpolation techniques to the terrain, thus obtaining pollution maps [16].

One example of cartometric products onto which the results of air pollution measurements can be plotted is an orthophotomap, created in the results of processing low-altitude aerial photographs or satellite imagery. It differs from traditional photos in its projection. As a result of orthorectification, the process of developing an orthophotomap from terrain photos includes aerotriangulation (the determination of projection center coordinates and camera angles), orthorectification, and tessellation [22,23].

Another example is the paper described in [24] where a research group conducted a survey campaign near an elevated highway in China. The UAV used was a DJI Matric 600 UAV Hexacopter, which was equipped with portable sensors which was equipped with portable sensors from Kprosystem company from South Korea (DustTrak TMMonitor aerosols DRX 8534 TSI, AE51 aethalometer (AethLabs) and Onset HOBO U12-013 data logger (Onset Computer, Bourne, MA, USA)) to monitor PM, BC, relative humidity, and air temperature. The flight route was in a horizontal plane, in two perpendicular directions to the road. During the experimental campaigns, the intensity and type of traffic recorded with a high-resolution visible-range imaging camera and an infrared camera mounted on the drone were studied and manually calculated. Based on the results, the road configuration was found to have a significant impact on the spread of the pollutants measured.

The use of sensors placed on UAVs for air quality monitoring is steadily growing. The technique used is increasingly adopted around the world. The authors of the paper in [24] presented a mobile sensor node for monitoring air pollution and noise; in practice, the developed system was installed on an RC drone, which quickly monitored large areas. The use of UAVs for mapping is presented by Scheller et al. in [25], where they mapped the concentration of methane emitted from peatlands in the Zackenberg Valley in Northeastern Greenland. In [26], the authors studied the vertical distribution of particulate matter from a cemetery in Poland using sensors placed on a UAV.

Based on the literature review, it is possible to conclude that the UAV is a fairly common platform, effectively used in the measurement of air pollutants, including those from road infrastructure emissions. There are a small number of papers devoted to UAVs and the mapping of pollution from the exhaust emissions of road infrastructure. Therefore, the following research problem was defined:

Q1: What are the possibilities of using drones for mapping pollution emitted by road infrastructure?

An attempt to answer this research question was given based on the author's research presented further in the paper.

2. Materials and Methods

2.1. Measurement Device

In order to answer the research question posed, a Yuneec Typhoon H Plus drone was used. The drone is equipped with six motors with a total weight of 1645 g. The drone is capable of reaching a maximum flight speed of 13.5 m/s with a data transmission range of 1.6 km. A sensor is mounted on the drone. The sensor used in this study is a laser particle sensor for $PM_{1.0}$, $PM_{2.5}$, and PM_{10}, with semiconductor sensors for other substances from Winsen, Gravity, SGX Sensortech. The value of all the pollutants detected by the Mapair sensor is modified by a normalization parameter, which causes the pollutants to be presented for their respective atmosphere (288.15 K and 1013.25 hPa), which then allows for a direct comparison of pollutants from the sensors regardless of atmospheric conditions. This is done by taking data from the weather station that is closest to the sensor. This data are used to calculate the normalizing parameter. This parameter is refreshed every 5 min to ensure its accuracy and to maximize sensor responsiveness. The sensor allows for a real-time reading of measurement data on both mobile and stationary devices. Appropriately defined parameters allow for the automatic indication of points in the area where a significant exceedance of permissible air pollution emission standards occurs. Data recording takes place both on the internal memory card and on the server. The sensor is capable of quantifying and qualitatively determining the following gaseous pollutants: sulfur dioxide (SO_2) [ppm]; nitrogen dioxide (NO_2) [ppm]; formaldehyde (CH_2O) [ppm]; volatile organic compounds (C_6H_6) [ppm]; ozone (O_3) [ppm]; and particulate matter: PM_1, $PM_{2.5}$, and PM_{10} [$\mu g/m^3$]. The sensor records a measurement every 4 s during a raid. It is equipped with a GPS system that allows it to determine the exact measurement location, i.e., altitude, latitude, and height above sea level. A photo of the measuring station is shown in Figures 1 and 2.

Figure 1. Drone used for pollution mapping. Source: Own elaboration.

Figure 2. Drone taking measurements. Source: Own elaboration.

2.2. Test Site

As shown by the European Environment Agency, about 25% of the total emissions of harmful substances come from transportation, of which 71.7% comes from automobile transport. A health-harmful phenomenon related to emissions from internal combustion engines in vehicles is photochemical smog, or Los Angeles-type smog. It is formed on dry hot days with heavy traffic. One of the roads with the highest volume of traffic in Poland is the highway located in the south of the country connecting the east and west, i.e., the A4 highway. Every day, 200,000 vehicles pass through this section, which is located in Katowice. Due to the key importance of this highway and the high volume of traffic, a section of the A4 highway in Katowice and the adjacent area were selected. The study area's location is shown in Figure 3.

Figure 3. Photo of the surveyed area [27]. Source: https://maps.google.com

2.3. Study Methodology

This study was conducted on 5 July 2023. The air temperature was 31 °C, the relative humidity was 45%, and wind speed was 4.5 [m/s]. This study covered an area of about 1 hectare near a key road in Silesia Province. The drone raid was carried out at five altitudes: 10 m, 20 m, 30 m, 40 m, and 50 m from the ground surface. The raid was carried out in a so-called carpet manner, i.e., perpendicular and parallel to the highway. Taking into account the speed of flight and recording the results, the measurement was conducted every 1 m. The identification of particulate matter was studied for PM_1, $PM_{2.5}$, and PM_{10}, and harmful gases such as benzene (C_6H_6), formaldehyde (HCHO), sulfur dioxide (SO_2), ozone (O_3), and nitrogen dioxide (NO_2) were studied. The values of the last two pollutants (O_3 and NO_2) were not found. A summary of the measurement results and maps of the pollutant distribution are presented in Section 3.

3. Study Results

The average values for individual heights and pollutants are shown in Table 1.

Table 1. Values of pollutant concentrations at particular heights.

Altitude in [m] above the Ground	PM_1 [µg/m^3]	PM_{10} [µg/m^3]	$PM_{2.5}$ [µg/m^3]	C_6H_6 [ppm]	HCHO [ppm]	SO_2 [ppm]
10	13.77	21.65	16.73	0.003	0.03	0.098
20	12.79	19.68	17.71	0.025	0.02	0.098
30	11.81	18.69	16.73	0	0.014	0.098
40	10.825	15.74	14.76	0.005	0.0196	0.098
50	9.84	14.76	13.77	0	0.027	0.098

The concentration values for ozone and nitrogen oxide are 0. The values obtained from the measurements were plotted on the relief using ArcGIS Pro software. Maps for individual pollutants were thus obtained. The maps for each pollutant are shown in Figures 4–9.

Figure 4. Pollution map for PM_1 [µg/m^3] dust. Source: Own elaboration.

Figure 5. Pollution map for PM_{10} [µg/m^3] dust. Source: Own elaboration.

Figure 6. Pollution map for $PM_{2.5}$ [µg/m^3] dust. Source: Own elaboration.

Figure 7. Pollution map for C_6H_6 [ppm]. Source: Own elaboration.

Figure 8. Pollution map for HCHO [ppm]. Source: Own elaboration.

Figure 9. Pollution map for SO_2 [ppm]. Source: Own elaboration.

After the cartographic interpolation of the measurement points on the ground, it was possible to cut a 3D cross-section and drop the image into altitude. The pollution distribution as a function of altitude in meters above sea level was thus obtained. The collected projections are shown in Figures 10–15.

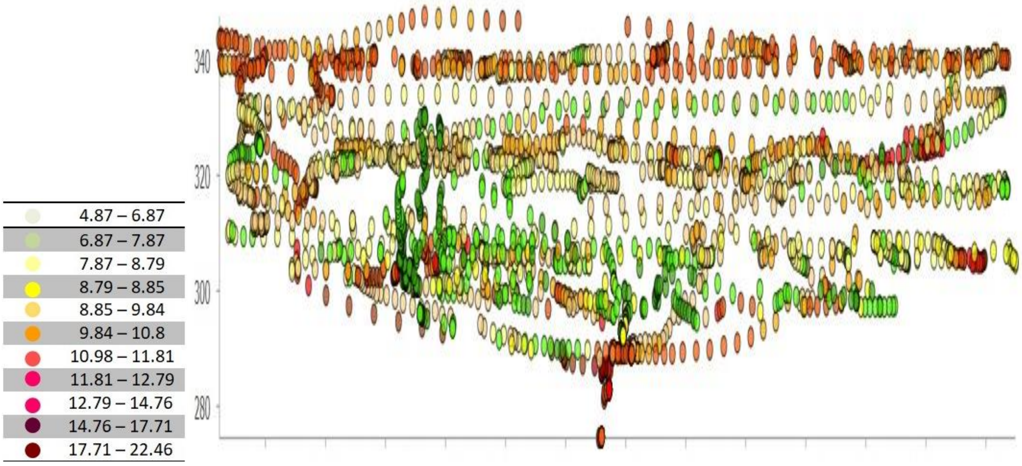

Figure 10. Distribution of PM_1 concentration [$\mu g/m^3$] as a function of altitude. Source: Own elaboration.

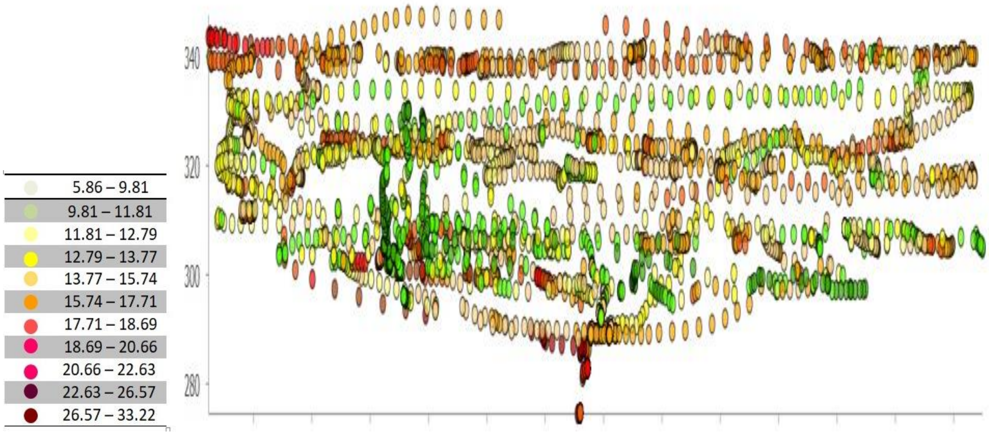

Figure 11. Distribution of PM_{10} concentration [$\mu g/m^3$] as a function of altitude. Source: Own elaboration.

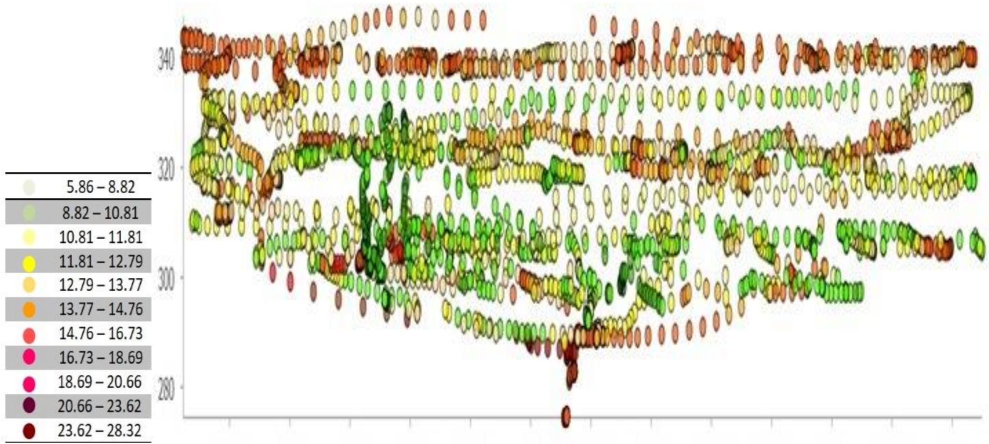

Figure 12. Distribution of $PM_{2.5}$ concentration [$\mu g/m^3$] as a function of altitude. Source: Own elaboration.

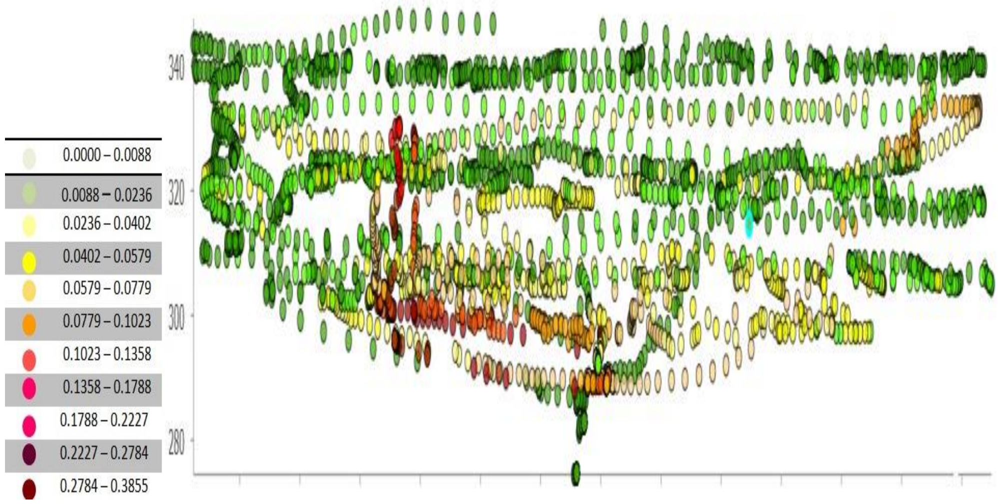

Figure 13. Distribution of C_6H_6 concentration [ppm] as a function of altitude. Source: Own elaboration.

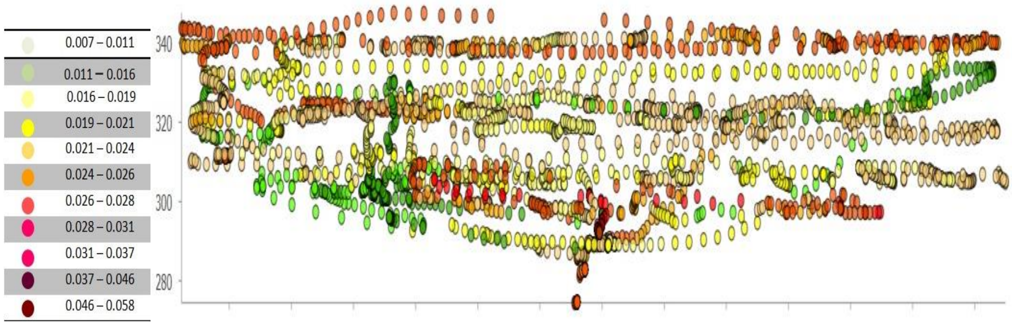

Figure 14. Distribution of HCHO concentration [ppm] as a function of altitude. Source: Own elaboration.

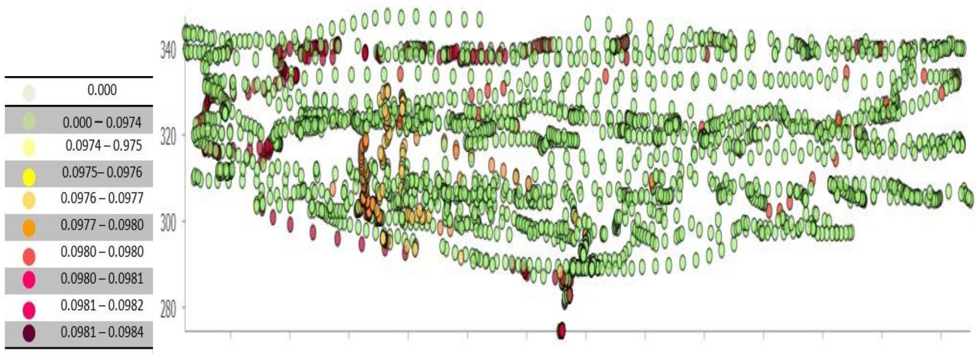

Figure 15. Distribution of SO_2 concentration [ppm] as a function of altitude. Source: Own elaboration.

4. Discussion of the Results

Due to the very small size of the particles and their ability to penetrate the alveoli, suspended particulate matter is the most dangerous to health. Both in Poland and around the world, there are recommended concentration limits for individual pollutants. The World Health Organization (WHO) recommends the following daily standards. The World Health Organization (WHO) recommends the following daily standards. Including data in Table 2.

Relating the obtained averaged results to WHO recommendations, it can be concluded that on the day of measurements there was no exceedance of concentrations of any of the tested pollutants. Additionally, in the measurement area there is a station of the National Pollution Register.

Table 2. The WHO's acceptable concentrations of individual air pollutants [28].

Pollution	Acceptable Concentration [μg/m^3]
$PM_{2.5}$	25
PM_{10}	50
SO_2	20
NO_2	40
O_3	100

The air quality monitoring stations used are stationary. The results obtained are averaged into an hourly measurement and made available to the public. The stations work based on two methods. The first method is automatic, where sensors are used to measure selected pollutants. Another method for measuring suspended dust is the gravimetric method. It involves measuring the mass of a clean filter flake placed in a special measuring tube and the mass of the flake with absorbed suspended dust. The disadvantage of this method is the measurement time, which lasts seven days. In the testing area there is a station operating based on the automatic method. Averaging time of measurements up to one hour.

The average values of concentrations of individual pollutants obtained from the UAV and the results from the national pollutant register are presented in the Table 3.

Table 3. Comparison of pollutant concentration results [29].

Type of Contamination [μg/m^3]	Averaged Results from UAV	Results from National Pollution Monitoring
PM_{10}	25.1	29.1
$PM_{2.5}$	15.94	15.6
PM_1	11.8	It was not subject to measurement
NO_2	-	71.5
SO_2	0.098	It was not subject to measurement
C_6H_6	0.007	It was not subject to measurement
HCHO	0.022	It was not subject to measurement

The standard deviation values are presented in Table 4.

Table 4. Standard deviation values for individual pollutants.

Pollution	Standard Deviation Value
PM_1	2.24
$PM_{2.5}$	3.07
PM_{10}	3.64
SO_2	0.03
NO_2	0.03
O_3	0.04

The standard deviation values obtained are low, which means a small amount spread around the average value. Moreover, it was noticed that, for the laser sensor, the suspended particles were larger than the total; for semiconductor sensors, the deviation values were less than those combined. By comparing our own measurements with those of the national pollution monitoring, absolute and relative errors were determined for the average values of $PM_{2.5}$ dust pollution concentrations.

Absolute error for $PM_{2.5}$:

$$\Delta x = |x - x_0| \tag{1}$$

$$\Delta x_{PM_{2.5}} = 0.34$$

Relative error for $PM_{2.5}$:

$$\delta = \frac{|x - x_0|}{x} \cdot 100\% \tag{2}$$

$$\delta = 2.17\%$$

The results obtained from a flying measurement platform, unlike those obtained by a stationary point test station, allow for spatial reflection as well as a depiction of the air pollution problem. An example of this, for such research results, is the 3D imaging of the diversity of atmospheric concentrations of particulate matter over a given area (Figures 16–18). Such an approach to the research problem allows for broader knowledge and an understanding of the problem concerning the spread of pollution. Obtaining vertical and horizontal profiles over the ground using a UAV platform provides good overview material for studying the distribution of pollutants in the atmosphere.

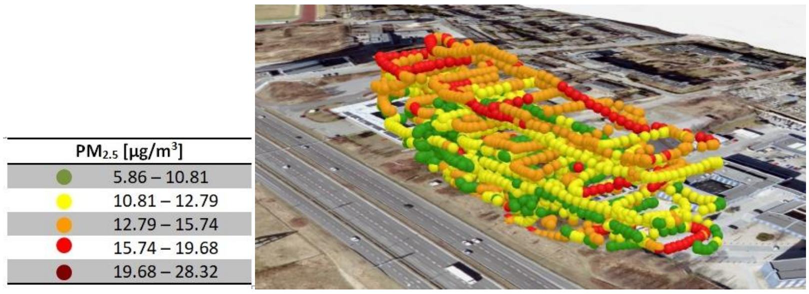

Figure 16. A 3D image of $PM_{2.5}$ spread. Source: Own elaboration.

Figure 17. A 3D image of $PM_{2.5}$ spread—"In front of" view. Source: Own elaboration.

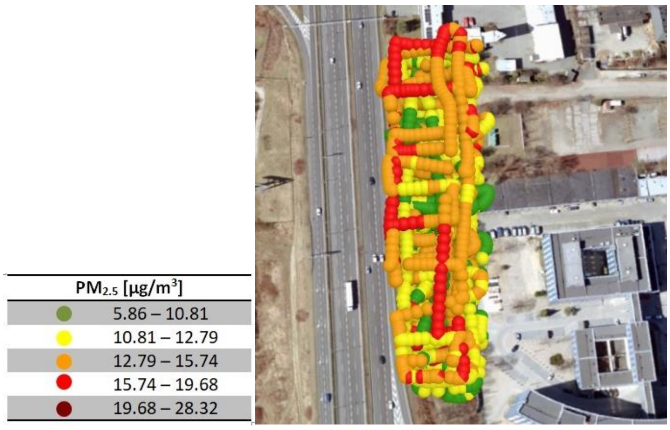

Figure 18. A 3D image of $PM_{2.5}$ spread—"top" view. Source: Own elaboration.

An additional advantage is the fact that the results obtained will allow for the development of a model of the occurrence at individual, isolated heights; concentrations; direction of translocation; and the precipitation of pollutants to the adjacent area, in addition to the development of a model of the impact of the variables of existing meteorological conditions on research results, thus answering the question of how these independent variables affect the results obtained. Therefore, it should be assumed that, with unfavorable meteorological conditions or an upward trend in traffic volume, studies will indicate areas that pose a potential threat to human organisms, and the knowledge gained from the measurements will allow for interventions that affect the state of response in the face of hazards and will allow for the introduction of possible temporary or permanent measures.

Practical research results obtained under field conditions, by assumption, will allow, in a basic form, for a determination of the time at which the ratio of traffic volume to pollutant emissions will reach a critical point, after which the area surrounding the traffic route can be considered potentially hazardous or permanently contaminated. At this point, the undoubted advantage of this research method is that it could illustrate the problem posed by emissions from one of the key sources of air pollution in the European Union.

5. Conclusions

A significant percentage of residual air is emitted from urban sources in these traffic routes. It is extremely important to study, understand and image the air from road infrastructure. Traditional measurement methods used in national air monitoring are based on commercially available measurement stations that are available. However, the measurement result is averaged and, above all, it is a point measurement, not an area measurement.

The literature review shows that due to a number of advantages related to high mobility, small size, ease of use and obtaining results in real time, there is great interest in UAVs for air quality monitoring. UAVs are widely used to identify and control various sources of air pollution. The review also showed that by arming UAVs with appropriate GPS/INS systems, it is possible to develop maps of air pollution from all sources, including linear sources such as road transport routes.

The UAV platform presented in this study, developed for air quality monitoring, was based on a six-engine carrier platform with high performance flight characteristics, equipped with lightweight and precise sensors. Experience has shown that such an aircraft is safe and does not put human health and life at risk; it is easy to operate, and it is capable of performing area-based measurements, taking into account the metrological conditions found. Another advantage of such a measurement station is its mobility, i.e., it can be easily assembled and disassembled, which facilitates transportation to measurement sites and reduces setup time, therefore making it a practical and cost-effective instrument for monitoring air quality near the source of pollution. However, the use of UAVs to create pollution maps also has limitations. Not always and not everywhere does residential infrastructure allow for drone flights. Tall trees also limit the operation of drones. Drones cannot be used within airports or military facilities. Air pollution is measured only during the flight, not 24 h a day, as is the case with national pollution monitoring. The relative error of measuring $PM_{2.5}$ concentration values from UAV and from the national register is 2.17%. This value is small, which indicates that the averaged values are similar to each other, and this is additionally confirmed by the low value of the standard deviation.

With regard to the research question "What are the possibilities of using drones to map pollution, the source of which is road infrastructure?", both the literature review conducted and the author's attempts show that the possibilities of the graphical representation of air pollution in the form of maps, with the source being road infrastructure, are very good. Using UAVs, it is possible to conduct measurements area-wise rather than point-wise, as is currently the case with the national pollution monitoring system. It is assumed that the samples presented can be extended by studying the influence of atmospheric conditions, as well as by a statistical study to find (demonstrate) correlations as a function of altitude as well as distance from a linear pollution source, such as road infrastructure. Obtaining the results of such studies in the future will allow for recommendations for protecting the population from harmful chemicals in the form of, for example, building protective screens, as is the case with noise levels. Eventually, it will be possible to conclude that the UAV is suitable for mapping air pollution while providing substantive information on air quality near the ground up to a certain altitude.

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