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Mobile systems for assessing air quality: available solutions and application examples

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Abstract. Air quality is of interest to many institutions and individuals, including, above all, the informed residents of monitored areas. The state of the air and its pollution level very important to the health, life and functioning of any community living in urban areas. A poor state of the environment has inevitable health consequences; in the case of the air, these are mainly respiratory or cardiovascular diseases. This element intensifies during the heating season when compounds from the combustion of banned substances and materials are emitted into the atmosphere. The quality of the lowest layer of the atmosphere can be studied using various recording systems and detectors. These include continuous monitoring of the state of the air by spatially dispersed stationary measuring stations operating in the State Environmental Monitoring system. Their location is usually associated with significant traffic intensity in their immediate vicinity rather than high local residential density. The measurement network is also co-created and densified by alternative point air-quality-monitoring systems proposed by private companies or community organizations (e.g., Airly, Sensor. Community, LoVo). A precious source of reliable local air quality data is mobile recording systems, which use unmanned aircraft or vehicles – objects in motion – and carry out periodic inspections, control missions or measurements. Examples of such solutions in the Polish market are Sniffer4D, Nosacz II and AirDrone. This paper aims to analyze and compare the available mobile measurement systems in terms of technical and usability for air quality research, along with a description of example areas where they are being used and implemented in practice. In addition, selected results of tests carried out with the Sniffer4D system at three testing grounds in Toruń are presented as part of a measurement campaign using an unmanned aerial vehicle and a passenger car.

Key words:
air pollution,
mobile system,
UAV,
Sniffer4D,
Nosacz II,
AirDrone

Introduction

Environmental assessment, with particular emphasis on air quality research, is a critical component of modern environmental monitoring. In an era of intensive industrial and urban development, atmospheric pollution is a growing health problem for a significant part of the population, especially residents of urban areas. The spread of agglomerations, population growth, and increased population density result in increased emissions and reduced capacity for effective removal of pollutants, leading to their periodic accumulation. Intensive and high urban development hinders the dispersion of pollutants, mainly by significantly reducing wind speeds in the near-surface layer. New buildings are an obstacle to eliminating pollutants outside their area of occurrence and are additional sources of municipal emissions, mainly from heating systems.

In addition, ever-increasing emissions from traffic sources caused by increased vehicle numbers exacerbate the problem. Insufficient traffic flow, resulting from suboptimally configured traffic signals and insufficient traffic infrastructure capacity, intensifies emissions. Other anthropogenic sources of atmospheric pollution are particulate emissions from the fuel and energy industry, particularly the electric power and heating sectors, which generate mainly fly ash. The contribution of the iron and steel metallurgical industry is also significant, with metallurgical dust accounting for more than half of emissions. Dust emissions are also associated with the activities of the chemical industry, especially the inorganic, fertilizer and plastics industries, as well as the building materials industry (mainly the cement sector) (Sala and Zinko 2010).

Scientific studies show that air pollution has a significant impact on the length and quality of life. During periods of increased concentrations of air pollution, higher rates of hospitalization and death are observed. Children are particularly vulnerable, with exposure to fine particulate matter confirmed to increase the incidence of respiratory diseases and asthma. Another high-risk group is the elderly, in whom long-term exposure to high concentrations of air pollution leads to an increased risk of death from lung cancer and respiratory and cardiovascular diseases (Manisalidis et al. 2000; Krajewska-Kułak et al. 2007; Erickson et al. 2017; Jędrak et al. 2017; Godłowska 2019). Air pollutants also negatively affect the plant world by interfering with photosynthesis, transpiration, respiration and reproduction. In addition, aerosols in the atmosphere can directly affect the climate by scattering and absorbing solar radiation and indirectly affect the radiation properties of clouds as cloud condensation nuclei. This can lead to climate change on local (e.g., droughts and increased insect outbreaks) and global scales (e.g., the greenhouse effect and ozone depletion) and to polluted water and soil through any form of acid precipitation falling from the atmosphere in rain, snow or hail, or even as dust. This, in turn, increases the content of lead, copper, zinc, aluminum and even cadmium in water supplied to residential homes (Jońca et al. 2022).

Reducing pollutant emissions is a priority for many states, local governments and public institutions. However, it is also important to ensure that the effectiveness of these measures is adequately verified by monitoring pollution levels. Accordingly, many countries have established appropriate air quality standards and adopted measurement methods for identifying key atmospheric constituents and pollution levels (Skoczko et al. 2018).

Mobile measurement systems are helpful and are increasingly used to study air quality issues. The most common platforms for such systems are road vehicles and unmanned aerial vehicles (Villa et al. 2016b). The term “Unmanned Aerial Vehicle” (UAV) refers to a type of aircraft that does not require a crew. Such an aircraft performs flight autonomously using remote control programs. Another term you may come across is “Remotely Piloted Aircraft” (RPA), which describes a type of aircraft remotely piloted by an operator on the ground using a radio transmitter or other computer device (Parczewski 2023). A term used just as often is “drone”, defined as an autonomous, unmanned flying apparatus programmed to fly according to specific routes using GPS (Becmer and Romanek 2011). In the Polish literature, the nomenclature and definitions of these devices varies, with extensive and constantly evolving meanings. However, the most appropriate term for this paper will be “unmanned aerial vehicle”.

Unmanned aerial vehicles equipped with air sampling systems and detectors can provide precise data on pollutants and their distribution in the atmosphere. This makes it possible to analyze in detail the composition of the air in specific atmospheric layers (Karpińska and Kunz 2023). The small size and weight and low energy requirements of UAVs and the relatively low cost of purchasing and operating the platform make them suitable tools for air quality monitoring. In addition, unmanned aircraft can autonomously perform flight operations from takeoff to landing. Unlike traditional aircraft, UAVs can operate at low altitudes without risk to the pilot and the environment, which is important for monitoring pollution and ensuring operational safety. The operational capabilities of different types of UAVs in monitoring air quality depend on the purpose of the study. There are two main categories of UAVs – fixed-wing drones, known as “airframes”, and multi-rotor drones. Multi-rotor drones can be divided according to the number of rotors into single-rotor, tricopters, quadcopters, hexacopters and octocopters. These units’ air pollution monitoring applications typically choose smaller units with four or six rotors (Chamola et al. 2021). Airframes can cover larger areas in less time and offer the flexibility of sensor mounting. However, their lack of hovering capability and minimum operating height requirements result in high spatial diversity at the expense of lower spatial resolution. In contrast, multicopters have lower operating speeds, but allow hovering, which is advantageous for close-range inspections. They achieve higher spatial resolution at the expense of lower spatial diversity. Advances in inspection technology have made these platforms more reliable and easier to operate, reducing the risk of damage and accidents (Villa et al. 2016a).

UAVs are also effective tools for monitoring and managing pollution in emergency management. They can provide data of high spatial and temporal resolution over large areas or specific locations. They can be used locally depending on the data collection type and the platform's characteristics. UAVs increase the spatial and temporal resolution of air quality data, provide insight into the vertical distribution of pollutants, facilitate the detection of emission sources, and monitor and control the distribution of pollutants around fixed facilities such as ports or industrial plants (Motlagh et al. 2023).

Air quality monitoring under the national and social system

The State Environmental Monitoring (SEM) is a system established under the *Environmental Protection Inspection Act* of July 20, 1991, and the *Environmental Protection Law* of April 27, 2001. SEM includes measurements, assessments and forecasts of the state of the environment, as well as the collection, processing and dissemination of environmental information (https://powietrze.gios.gov.pl). The main objective of the SEM is to support environmental protection activities by regularly informing the authorities and the public about the quality of natural elements, compliance with environmental standards, areas of their violations, changes in the quality of natural elements, and the causes of these changes.

One of the key elements of SEM is air quality monitoring, which aims to improve air quality and ensure compliance with legal standards. Implementing this task involves obtaining information on the levels of airborne substances in all zones of the country and on air quality standards and other assessment criteria. This makes it possible to identify areas needing air quality improvement and to monitor the effectiveness of air quality measures and management through air protection programs and short-term action plans.

The air quality monitoring system involves collecting data on the sources and volumes of pollutant emissions, conducting air quality measurements to obtain information on levels of substances in the ambient air, and developing assessments of compliance with air quality standards. It is also crucial to ensure the quality of measurements and assessments so that the information obtained is reliable and useful for effective air quality management (https://www.gov.pl/web/gios).

Table 1. Permissible levels of air pollution in Poland for selected substances and adopted periods of averaging of measurement results

Substance	Averaging period of results	Permissible level [μg/m^3]
benzene (C_6H_6)	year	5
nitrogen dioxide (NO_2)	1 hour	200
	year	40
sulfur dioxide (SO_2)	1 hour	350
	24 hours	125
carbon monoxide (CO)	8 hours	10,000
PM10 dust	24 hours	50
	year	40
PM2.5 dust	year	20
lead (Pb)	year	0.5

Source: National Inspectorate of Environmental

Currently, the following substances are monitored by the national air quality monitoring system as part of health protection: Sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), benzene (C_6H_6), ozone (O_3), PM10 particulate matter (up to 10 μm in diameter), PM2.5 particulate matter (up to 2.5 μm in diameter), heavy metals (lead, arsenic, nickel, cadmium) determined in PM10 particulate matter, and benzo(a)pyrene determined in PM10 particulate matter (Tomala 2023). The permissible levels of air pollutants and the periods for which the results are averaged are presented in Table 1.

The one-hour automatic air pollutant measurement results are available on the "Air Quality" portal and in the GIOŚ "Air Quality in Poland" mobile applications. Data from manual measurements and archival measurement data are available on the "Air Quality" portal in the Measurement Data Bank. The results of manual measurements of PM10 particulate matter, the content of benzo(a)pyrene, lead, arsenic, cadmium and nickel in PM10 and PM2.5 particulate matter are made available approximately 1–1.5 months after sampling, which is due to the procedures involved in making such measurements.

As part of the State Environmental Monitoring, Poland has 284 air quality measurement stations, including 86 automatic stations, 125 automatic-manual stations, and 73 manual stations. For example, there are 20 measurement stations in the Kujawsko-Pomorskie Voivodeship: eight automatic, five manual and seven automatic-manual (Fig. 1). SEM activities are coordinated by the Environmental Protection Inspection authorities, where national and regional networks are supervised by the Chief Inspector of Environmental Protection (GIOŚ), and local networks by the Provincial Inspector of Environmental Protection (WIOŚ) in consultation with the Chief Inspector of Environmental Protection.

The market is seeing an increase in air quality monitoring systems developed through community initiatives and by commercial companies. An example of such activity in Poland is the company Airly (https://airly.org/pl/), which offers an advanced system for monitoring air pollution in real-time and forecasting trends and changes in air quality for the next 24 hours. The Airly system consists of two types of sensors: the first measures the concentration of particulate matter, and the second monitors the concentrations of nitrogen dioxide (NO_2) and ozone (O_3). The system is based on a technique using algorithms and artificial intelligence (AI) elements, which is an effective tool for identifying sources of pollution using data from a more extensive measurement network. Currently, Airly's sensor network has 2,800 devices in Poland, 193 of which are located in the Kujawsko-Pomorskie Voivodeship (Fig. 2). The largest number in the entire province was installed in Toruń (52) as part of

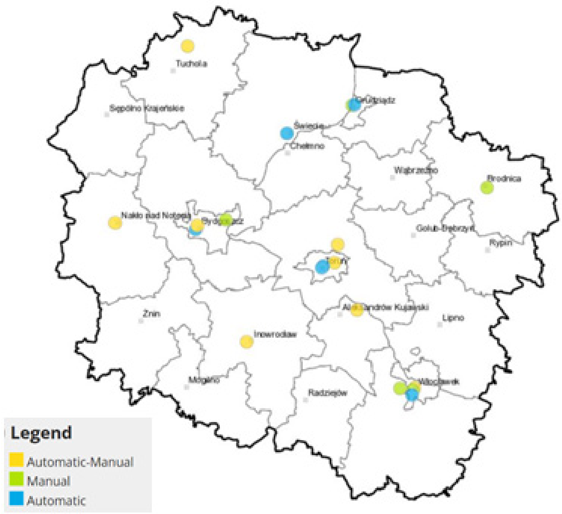

Fig. 1. Distribution of GIOŚ measuring stations on the territory of the Kuyavian-Pomeranian Voivodeship
Source: own evaluation

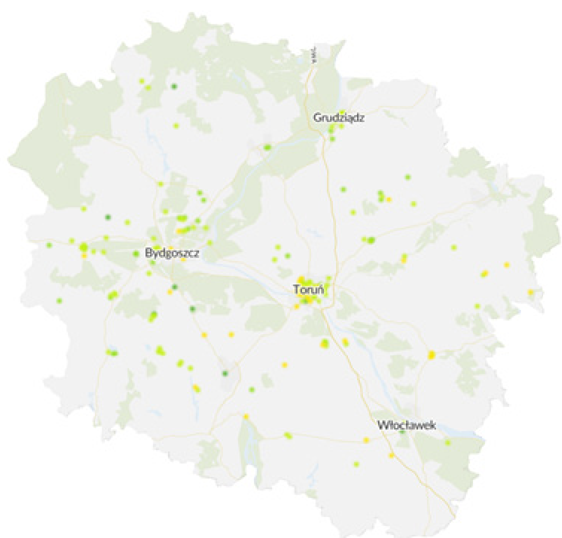

Fig. 2. Distribution of measurement sensors of the Airly system on the territory of the Kuyavian-Pomeranian Voivodeship
Source: own evaluation

the project financed by the "STOP SMOG – urban air quality monitoring system for the City of Toruń" participatory budget. In other, larger district cities of the Kujawsko-Pomorskie Voivodeship, 11 Airly system sensors are installed each, both in Bydgoszcz and Grudziądz, while Włocławek lacks sensors of this system.

An alternative solution is the Sensor.Community initiative, formerly named Luftdaten.info, which aims to monitor air quality using a global network of inexpensive and easy-to-install sensors (https://sensor.community/en/). The fundamental premise of the project is to collect data on the state of the air by the community and make it freely available on the project's website, with an eye toward the widest possible audience. The project uses sensors that measure PM2.5 and PM10 dust concentrations. In addition, it is possible to connect additional sensors to measure temperature, humidity, or atmospheric pressure parameters. The data are transmitted via a wireless network, and the project itself is based on open-source software for data collection and processing. The collected information is visualized in real-time on maps available on Sensor.Community. Anyone can join the project by purchasing a dedicated sensor and installing and configuring it according to the detailed instructions on the website. Currently, the network of sensors in Poland has 743 units, 55 of which are located in the Kujawsko-Pomorskie Voivodeship. The largest number of sensors in the district cities of this province is registered in Bydgoszcz – 26, Toruń – six, and one in Grudziądz. The project raises awareness about air pollution and its impact on health, although DIY sensors may not be as precise as other widely used sensors. Sensor.Community is an example of a successful citizen science project that combines technology, community and science to address air pollution on a global scale.

Another air quality monitoring solution is the Internet of Things (IoT), based system developed by LoVo (https://www.lovo.pl/en/), which aims to improve the quality of life in cities through precise and continuous monitoring of air conditions (Stith 2023). The system has several key components that work together to provide accurate and reliable air quality data. The main component is sensors that measure concentrations of PM2.5 and PM10 particulate matter hourly. An open, proprietary radio network (e.g., LoRa) enables real-time wireless data transmission to a central server and is used in monitoring various parameters of the geographic environment (Karpińska and Kunz 2019, 2021, 2022; Erwiński et al. 2023). In the system's dedicated application, the collected data are processed using advanced algorithms and artificial intelligence techniques to generate reports, alerts and visualizations on air quality. The LoVo IoT system is intended mainly for closed local communities, such as municipalities or cities, so there is no detailed information on this network's number of active sensors in Poland.

Mobile pollution measurement systems are used to study the state of the air

Mobile air pollution measurement systems are an important complementary tool in air quality monitoring. Unlike stationary measurement stations, which provide data with limited spatial coverage, mobile loggers allow information to be collected from a wide area, allowing for a more detailed and dynamic assessment of air conditions. There is also a global trend of increasing air quality data collection outside reference stations (Velasco et al. 2016). Mobile loggers are understood to be portable or vehicle-mounted devices equipped with sensors for detecting and measuring concentrations of various atmospheric pollutants (Bucek et al. 2021). Air pollution sensors can be divided into two main categories: those that measure gas concentrations, and those that measure particulate matter (PM) mass or various properties such as light scattering or absorption. All loggers consist of several basic components (Snyder et al. 2013), including:

- a sensing element that responds to the presence of a given contaminant and changes with its concentration in a given volume of sampled air;
- a transducer that converts the recorded responses into electrical signals;
- a data carrier or link to a communication device (e.g., a micro radio transmitter);
- an electrical power source (e.g., batteries or possibly photovoltaic panels).

Monitoring air quality with mobile systems offers several advantages. It allows data collection based on regular or scheduled routes, making observing temporal and seasonal changes possible. The mobility of these systems allows them to be used in various locations and conditions, especially in areas where data are lacking or incomplete. Another advantage is increasing monitoring coverage at a lower cost than traditional fixed devices. With increased data availability, mobile sensors contribute to more reliable air quality forecasting models. In addition, they make it possible to detect points with high concentrations of pollutants at time of emission, and for authorized municipal services to take appropriate administrative and punitive actions (Anjomshoaa et al. 2018).

However, mobile air condition monitoring systems are not without limitations. One of the main challenges is ensuring adequate measurement accuracy under changing environmental conditions. Portable loggers can have lower measurement precision compared to stationary devices. This is a challenge in meeting the data quality requirements set by the European Parliament in *Directive 2008/50/EC on Air Quality and Cleaner Air for Europe* (Malec and Borowski 2016; Konert and Sakowska-Baryła 2020). To complement air quality monitoring networks for scientific research, the data must reach an acceptable level of quality. Additionally, calibrating and maintaining equipment can be logistically challenging, especially during long-term measurement campaigns. These aspects affect the reliability and consistency of the data collected, which in turn may limit the use of mobile systems in some research contexts. However, other criteria for accepting results can be developed and applied for other applications, such as raising civic awareness or community air monitoring (Castell et al. 2017).

Several mobile measurement systems are currently available for monitoring various concentrations of air pollutants, and new devices are periodically introduced to the market (Sladojevic et al. 2024). Within the framework of this article, three measurement systems used in Poland are discussed in detail: the Sniffer4D, the Nosacz II and the AirDrone. The technical and adaptive parameters of the described systems are presented in Table 2, and the available measurement modules are presented in Table 3.

Sniffer4D System

Sniffer4D (Fig. 3, left) is a hyperlocal mobile system used for air quality monitoring developed by Singapore-based Soarability (https://www.soarability.com). The device provides multi-component detection of gases and particulates and real-time monitoring of their concentrations in 2D and 3D space. A key feature of this product is its ability to quickly adapt to different measurement tasks, supported by its lightweight and compact design, measuring 112×105×872 mm and weighing about 477 grams with the UAV mount (21 grams less without the

Table 2. Selected technical parameters of mobile air pollution measurement systems used in Poland

Parameter	Sniffer4D	Nosacz II	AirDrone
Dimensions (without suction nozzle)	112×105×87 mm	180×95×70 mm	200×156×60 mm
Dimensions (with suction nozzle)	156×105×87 mm	680/1,180×95×70 mm	1,200×156×60 mm
Weight	456 g	650 g	1,200–2,000 g
Weight of UAV holder	21 g	dependent on adapter	no data
Weight of car holder	1,145 g	no data	no data
Integration and mounting platform	UAV, car, quad, bike	UAV	UAV, car
SIM slot	yes (1)	yes (1)	no
SD slot	yes, micro	yes, micro ×2	yes, micro
Power supply	5V 2.5A	9V	7.2V
Maximum number of measurement modules	9	6	5
Data presentation	application	terrestrial station	terrestrial station, web service

Source: own elaboration

Fig. 3. Mobile air pollution measurement systems integrated with UAV: Sniffer4D (left; photo by: Mieczyslaw Kunz), Nosacz II (middle; source: www.nextron.pl), AirDron (right; source: www.navigate.pl)

Table 3. List of available sensor modules that can be installed in mobile measurement systems

Measurement module	Substance	Measuring range	Sniffer4D	Nosacz II	AirDrone
PM1.0		0–500 µg/m³	+	+	+
PM2.5	particulate matter	0–1000 µg/m³	+	+	+
PM10		0–1000 µg/m³	+	+	+
O_3+NO_2	ozone + nitrogen dioxide	0–20,000 µg/m³	+	-	-
CO_2	carbon dioxide	0–90,000 mg/m³	+	-	+
CO	carbon monoxide	0–1,150 mg/m³	+	-	+
SO_2	sulfur dioxide	0–40,000 µg/m³	+	-	+
LZO	volatile organic compounds	0–100 ppm	+	+	+
CH_4	methane	0–50,000 ppm	+	-	-
NO_x	oxides of nitrogen	0–20,000 µg/m³	+	+	+
HCL	halogens	0–150 mg/m³	+	+	+
H_2S	sulfide hydrocarbons	0–140,000 µg/m³	+	+	+
HCN	hydrogen cyanide	0–110 mg/m³	+	+	+
PH_3	phosphorus hydrogen	0–2,500 mg/m³	+	-	+
NH_3	ammonia	0–70 mg/m³	+	+	+

Source: own elaboration

mount), making it easy to transport and prepare for field use. The device integrates with a variety of UAV platforms (Fig. 4, left), including multi-rotors and airframes, and can be mounted on vehicles such as cars (Fig. 4, middle), quad bikes and bicycles, allowing air quality measurements along various traffic routes and in specific measurement transects. Thanks to its operator portability (Fig. 4, right), the Sniffer4D is suitable for collecting data in hard-to-reach places such as gated estates, cemeteries, ruins or industrial plants, and for taking spot measurements at a preset height, such as 1-meter above ground level.

The Sniffer4D is characterized by an automated calibration system, providing high sensor-dependent measurement accuracy, a wide operating temperature range, fast response time and long service life (*Sniffer4D* ... 2023). The device's modular design allows the sensors to be adapted to different measurement needs, with each module responsible for detecting a specific type of contaminant. The system can be equipped with up to nine recording modules, allowing the acquisition of data on particulate matter (PM1.0, PM2.5 and PM10), ozone (O_3), carbon dioxide (CO_2), nitrogen oxides (NOX), carbon monoxide (CO), sulfur dioxide (SO_2), volatile organic compounds (VOCs), methane (CH_4), hydrogen chloride (HCL) and hydrogen sulfide (H_2S). In addition, the logger records meteorological parameters such as air temperature, humidity and atmospheric pressure. Particulate matter concentration is measured by

Fig. 4. Integration of the Sniffer4D system with a DJI Matrice UAV(left), with a car (middle) and a pedestrian (right)
Source: Photo by Mieczyslaw Kunz

laser scattering photometry (PM1.0 in the range of 0–500 μg/m^3, and PM2.5 and PM10 in the range of 0–1,000 μg/m^3), and carbon dioxide concentration by electrochemistry. An integral component of the Sniffer4D system is the intuitive-to-use Sniffer4D Mapper software, which enables real-time data transfer between the measurement unit and the base station (Zboralski and Kunz 2024). The software supports comprehensive analysis and visualization of telemetry data, management of data sets, and creation of color thematic maps, contour maps and interactive point maps in the form of a 3D point cloud. The collected measurement data are presented in a regular measurement grid, and the actual size of the basic field expressed ultimately in meters is the resultant of the adopted eigensize available in the application multiplied by the cosine of the latitude.

With a built-in GPS receiver and possibly an RTK solution, the software allows the display of the real-time status of work with high spatial accuracy (centimeters) and automatically records the coordinates of measurement data in three dimensions. Synchronization between the recording module and the computer provides real-time transmission and visualization of results against raster maps (satellite images, aerial photographs, or topographic maps). The program allows automatic creation of final reports in *pdf* format based on built-in templates and data export to *csv*, *png* and *geotiff* formats for easy sharing, such as in the cloud. The *pdf* reports contain, among other things, information about the date and time of measurements, the number of samples taken, the area surveyed, the measurement grid used, and the results of pollutant concentrations in the form of average, minimum and maximum values, along with the coordinates locating the places of extreme recorded values.

Nosacz II System

The Nosacz II is an example of a domestic device designed for mobile measurement of pollutants in the atmosphere. It is a professional detector designed by the Gliwice-based Flytronic company to detect the level of air pollution emitted by various sources, most often those coming directly from both domestic and industrial chimneys. The device has high functionality due to its readiness to work only 90 seconds after startup. The dimensions of the measuring module are 180×95×70 mm, and its weight is 650 grams. The structure was designed and manufactured to have the least impact on battery life and to be optimized for UAV operation (Fig. 3, middle). Nosacz II is integrated from the underside for DJI Matrice 200-series aircraft via a SkyPort with a special adapter for other commercially available carrier platforms.

The sensor's dedicated, removable measuring probe comes in two sizes – half a meter and a meter. Thanks to such lengths, very close measurements of pollution sources are possible without exposing the equipment and the carrier platform to unexpected accidents. The Nosacz II continuously takes samples from the smoke that comes out, which are then analyzed by the sensor. The device's advanced measurement chamber has been designed as a modular system that allows the installation of up to six additional chemical sensors. The modularity of the design also allows for their free configuration. The basic sensors installed in the device include measurements of temperature, humidity, particulate matter (PM1.0, PM2.5 and PM10) and volatile organic compounds (VOCs). The detector can be retrofitted with additional optional sensors: hydrogen chloride (HCL), hydrogen cyanide

(HCN), nitrogen oxides (NOX), hydrogen sulfide (H_2S) and ammonia (NH_3).

Information on the detected substances, along with coordinates, exact date and time, goes to the external unit (Ground Station) just ten seconds after the measurement. The Ground Station can be mounted and integrated into an apparatus or viewing monitor for the most convenient and accurate analysis of samples by the testing team. Survey information is also recorded through a GSM network and dual recording arrangement on MicroSD cards. It is also possible to track survey results from anywhere on the ground in real-time and create smog maps in the dedicated FlyConnect system.

AirDron System

The AirDron solution (Fig. 3, right) is an advanced measurement head by SoftBlue of Bydgoszcz. The device's structure, with dimensions of 180×95×70 mm, is designed to integrate with an unmanned aerial vehicle while operating autonomously. The head's weight does not exceed 2 kg and allows it to be used on various commercially available multicopter models. AirDron collects gas samples into special bags, which are then transferred for laboratory analysis. The device can also operate autonomously on a mobile measurement station like SmogBus. Thanks to its specially designed monitoring system, the AirDron provides data on detected substances in real-time, enabling quick, precise and safe assessment of the situation and taking measurements from a safe distance from pollutant plumes that are potentially dangerous to users.

Particulate matter concentrations are measured using laser scattering photometry. Particles are classified by size in 16 or 24 compartments, which allows precise determination of PM1.0, PM2.5 and PM10 fractions. Gas sensors are individually selected according to research requirements, considering the type of substance being measured, measurement ranges and accuracy. Measurements include gases such as carbon monoxide (CO), carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrogen oxides (NOX), hydrogen chloride (HCI) and the hazardous gases hydrogen cyanide (HCN), ammonia (NH_3), hydrogen sulfide (H_2S) and hydrogen phosphide (PH_3), as well as concentration analysis of volatile organic compound (VOCs). The system measures five selected gases, and also acquires data on environmental conditions such as temperature, relative humidity and atmospheric pressure.

The system also allows wireless communication with the Ground Control Station, where measurement results can be visualized, and the head can be remotely controlled using dedicated software. Measurement results are presented as numerical values of measured parameters, which are highlighted when an alarm threshold is reached. In addition, the system generates graphs of selected parameters, which are updated in real-time, and creates area maps of pollution and UAV flight path maps. An automatic report generator makes it possible to create comprehensive test reports. The location of the survey head is plotted on the map in real-time. The system manages the data, allowing export to csv file format of measurement results from selected measurement campaigns or any other time interval.

Selected examples of the use of mobile measurement systems in practice

Practical implementations of the systems discussed above are numerous. Most of the research focuses on measuring air pollution in urban areas, mainly from anthropogenic sources such as transportation, household fossil fuel combustion, industrialization and energy production. Nevertheless, there are also studies on the use of the systems for natural sources of air pollution, such as volcanoes and forest fires.

The Sniffer4D system in Natural Sources Research was used to monitor volcanic gas emissions as part of the Turrialba volcano surveillance in Costa Rica. For this purpose, the device was mounted on UAVs that flew directly to the active Turrialba crater to record gas emissions. The units used in this mission were a Mavic 3 and a Matrice 600-Pro, to which the Sniffer4D was attached using a specially designed mounting bracket printed using 3D printing technology. Powering the UAV allowed for about 20 minutes of operational time, depending on environmental conditions. The UAV was launched from the main vantage point on

Turrialba volcano, on the south side of the central crater, and measurements were taken at an altitude of about 9 meters above the crater floor, with the entire mission covering an area of about 2,424 square meters. The study included measurements of sulfur dioxide (SO_2), volatile organic compounds (VOCs), carbon monoxide (CO), carbon dioxide (CO_2), ozone (O_3), nitrogen dioxide (NO_2), particulate matter (PM1.0, PM2.5, PM10), temperature and humidity. The collected data were sent in real-time to the volcanology team. The results of the Sniffer4D system measurements showed, among other things, that SO_2 and CO_2 levels were stable, which is an important indicator for volcanic activity and the research conducted (Godfrey et al. 2022).

The following year, research continued with the Sniffer4D system on monitoring volcanic gas emissions at the Turrialba volcano in Costa Rica. A DJI Matrice 300 RTK unmanned aerial vehicle and the Sniffer4D Mapper real-time mapping system were used. Measurements were taken under various outdoor conditions to get a complete picture of volcanic emissions. The system proved very effective due to its ability to operate in harsh conditions (such as turbulence during flights) and the precise calibration of the sensors, which ensured the accuracy and repeatability of the results. The UAV mission also made it possible to quickly identify emission sources and their intensities. The deployment of the Sniffer4D system in volcano monitoring in Costa Rica demonstrated that mobile measurement systems mounted on UAVs can provide valuable data on volcanic emissions, which is crucial for understanding the processes inside a volcano and assessing the risks associated with its activity. This approach enables safe and efficient data collection, particularly important in the harsh and dangerous conditions around a volcano (Godfrey et al. 2023).

The Sniffer4D was also used to monitor air quality in the city of Kandy, Sri Lanka, during the introduction of a new traffic plan. In this study, the device was mounted on a police motorcycle traveling at speeds not exceeding 20 km/h. The device collected real-time data on particulate matter (PM2.5) and nitrogen dioxide (NO2) concentrations, sending them to analysis software. Measurements were taken before and during the introduction of the new traffic plan. Data were collected at four different times of the day: morning (07:00–10:00 am), noon (10:00 am – 01:00 pm), afternoon (01:00–04:00 pm) and evening (04:00–07:00 pm). The sensors were placed vertically on the motorcycle's handlebars to avoid the influence of exhaust fumes on the measurements. Analysis of the data showed that PM2.5 and NO2 levels were generally higher during the introduction of the new traffic plan compared to the period before it, suggesting to the researchers that the new traffic plan had an impact on the city's air quality. Implementing the Sniffer4D system in Kandy showed that mobile air quality monitoring systems could effectively assess the environmental impact of changes in traffic organization (Senarathna et al. 2022).

Sniffer4D was used in a measurement campaign to assess the levels of nitrogen dioxide (NO_2) in the atmosphere in the vicinity of a specific section of the P41 highway characterized by heavy traffic. This section is located on a highway of regional importance near the village of Chistyliv in Ukraine. The Sniffer4D was installed on a DJI M100 multicopter. The measurements were carried out in two series. In the first series, measurements were made at heights of 1 to 5 meters above the ground, recording nitrogen dioxide (NO_2) concentrations at distances of 10–30 m, 40–70 m, 70–90 m, 100–130 m, and 140–160 m from the road. Real-time analysis of the results showed that higher concentrations of NO_2 occurred closer to the road. In the second series, measurements were taken at a constant height of 30 meters above the same section of road, at the same distances. The concentration of nitrogen dioxide (NO_2) decreased significantly compared to measurements taken at lower altitudes, indicating that the main source of this pollutant was emissions from vehicles traveling on the road. Sniffer4D Mapper software installed on the base station computer enabled the researchers to analyze the measurement data in real-time by visualizing the spatial distribution of nitrogen dioxide (NO_2) concentrations at different heights and distances from the road. These measurements and visualizations provided important information to the research group on the atmospheric dispersion of nitrogen dioxide (NO_2) at different altitudes, which provided valuable data for modeling and analysis of air pollution dynamics in the study area (Dyvak et al. 2021; Kim at al. 2021).

An example of implementing the Sniffer4D system in Poland is the PASSport project implemented in the port of Kołobrzeg. The project aimed to improve safety and security in port areas by using unmanned aerial, surface and underwater units. The project responded to EU *Directive 2005/65/EC* requirements, which require extending surveillance systems to port areas. The Sniffer4D system, mounted on a DJI Matrice 300 RTK unit, was used to measure emissions of carbon monoxide (CO), nitrogen oxides (NOx), sulfur oxides (SOx), and particulate matter (PM) from ships' engines during their maneuvers in the port. Conclusions from the project showed that integrated unmanned aircraft systems equipped with modern sensors can effectively improve environmental monitoring in seaports. The PASSport project is an example of a modern approach to monitoring and managing security in seaports using advanced technologies, including the Sniffer4D system (Gucma and Muczyński 2022).

The Nosacz II system was adapted for air quality monitoring during an experiment in the Zabierzów municipality on the outskirts of Cracow. The purpose of the study was to evaluate the effectiveness of an innovative air purification method using shock waves to destroy the structure of the inversion layer, which would allow natural convection movements in the atmosphere and reduce pollution levels near the ground surface. The experiment took place in a built-up area bordering farmland on one side and dense single-family housing on the other. For monitoring, a DJI Matrice 200 unmanned aerial vehicle was used, equipped with the Nosacz II system, which includes temperature and pressure sensors and a laser sensor for measuring dust concentrations (PM10 and PM2.5). Data from the sensors were transmitted via radio to the recorder and averaged for each altitude in five-meter increments. Initially, measurements were made using the Nosacz II system, and then the shock wave generator was activated. The results of the experiment showed that the shock wave generation method was effective in reducing particulate matter concentrations. The Nosacz II system successfully recorded differences in air pollutant concentrations between measurement sessions (Jędrzejek et al. 2021).

To reduce low emissions and improve air quality in Katowice, cooperation was established between the City of Katowice and Flytronic (the manufacturer of the Nosacz II system). As a result of this cooperation, in early 2018, the Nosacz II system was implemented in Katowice, which enabled inspections using unmanned aerial vehicles to monitor air quality and identify waste-burning in household stoves. Six inspection missions were carried out as part of this initiative, each covering an area of 1 km^2, making a total of 6 km^2. Nosacz II analyzed flue gases emitted from an average of 15 of the smokiest chimneys per mission. This analysis included tests with particulate matter sensors (PM1.0, PM2.5, PM10) and a laser particle counter, which analyzed the content of substances such as ammonia and hydrogen chloride. Based on the analysis, six households were identified as burning waste. As a result, two fines were imposed, and four warnings were issued. The efficiency of this method proved significant, as a traditional inspection of these buildings by municipal police officers would have taken about nine months, whereas the mobile measurement systems accomplished the task much faster. Implementing the Nosacz II system in Katowice has demonstrated high efficiency in monitoring air quality and detecting illegal waste-burning. This has contributed to improving control activities in the city and strengthening the image of the Katowice Municipal Police as a modern and professional force in Poland (Sumara 2018).

Mobile air pollution measurement systems, often mounted on unmanned flying units, are increasingly being used by local government units in Poland. The municipality of Biskupiec in Nowomiejski District was in 2021 the first local government in Poland to purchase a Sniffer4D device for monitoring air quality on properties, especially in densely built-up areas in the city and municipality, by the Municipal Guard. During the 2021 reporting period, the municipality did not disclose detailed data on the number of inspections carried out with the Sniffer4D device. However, it reported the detection of sixteen violations, which resulted in the imposition of four fines and the issuing of twelve warnings (*Raport o stanie miasta i gminy Biskupiec*… 2021)

In 2020, the Municipality of Pruszcz Gdański acquired a Nosacz II detector as part of its environmental protection activities, aimed at improving surveillance of waste-burning in household stoves in its area (*Raport o stanie miasta i gminy Pruszcz Gdański*… 2020).

The city of Września conducted anti-smog campaigns in 2018–20. These activities included the city government providing the Nosacz II system and a DJI Phantom 4 unit to city guards to monitor smoke emissions from residential chimneys. In 2018, the Nosacz II system conducted 49 emission measurements, of which 47 were recorded as exceeding acceptable air pollution standards. During the 2019 heating season, the Municipal Police conducted 58 measurements at various hours of the day, detecting one exceedance of the standard, which allowed the service to intervene and confirm the burning of prohibited materials. In 2020, the Nosacz II system carried out 40 measurements in the afternoon and evening hours in Września single-family housing estates, finding no violations during the heating season (*Raport o stanie miasta i gminy Września*… 2018, 2019 and 2020).

In December 2021, using a DJI Matrice 210 platform, the Nosacz II system carried out ecological monitoring in the Białogard, Koszalin, Świdwin, Kołobrzeg, Szczecin counties and the city of Szczecin. The undertaking was carried out as part of smog missions by the "Ronin" association from Białogard, supported by the West Pomeranian Marshal's Office. A total of 12 missions were carried out in two stages, during which more than 200 buildings were inspected. The Nosacz II system sampled pollutants emitted from chimneys, analyzing the concentration of particulate matter (PM1.0, PM2.5, PM10) and volatile organic compounds. As a result, 81 irregularities were detected, and warnings were issued to residents of these properties about the danger they posed. The initiative plans to expand the monitoring system to other regional cities, allowing for more comprehensive air quality management.

In December 2020, air quality in Zgorzelec was measured using unmanned aerial vehicles equipped with the Nosacz II sensor. The study included a detailed analysis of the air over 31 properties, of which the sensor recorded elevated concentrations of volatile organic compounds (VOCs) in two locations. The owners of both properties were then informed in writing of the test results and instructed that repeated confirmation of burning prohibited waste could result in a fine.

The Nosacz II system for monitoring low emissions is also being used by other Polish cities such as Gliwice, Bielsko-Biala, Nowy Targ and Kalisz, and there are plans to implement it in Lubliniec.

As part of activities funded by the civic budget, in early 2024 the city of Tychy acquired and implemented an air quality monitoring system using a DJI Matrice 350 RTK unmanned aerial vehicle equipped with an AirDron measurement head. The system monitors the composition of combustion smoke emitted from chimneys in the city. The measurement head provides precise data on the level of pollutants such as particulate matter (PM1.0, PM2.5, PM10), volatile organic compounds (VOCs), and selected gases (e.g., hydrogen chloride, hydrogen cyanide). The effectiveness of AirDron's deployment is manifested in the rapid response to pollution incidents and in preventive measures that can discourage people who burn inappropriate materials. Due to the recent implementation of the measurement head by the city of Tychy, there is no information yet on the measurements taken and the number of tests conducted. However, the publication of such data can be expected in the next heating season (*Dron Obywatelski*… 2024).

In January and again in November 2020, SoftBlue conducted air quality surveys in Lidzbark using an AirDron mobile measurement head installed on a drone. These activities mainly aimed to identify low emissions sources by analyzing exhaust from local stoves and monitoring atmospheric pollution levels. The AirDron mobile measurement head was equipped with sensors to measure hydrogen cyanide and particulate matter fractions (PM1.0, PM2.5 and PM10). The detailed number of samples taken was not disclosed, although some of the results suggested the presence of low-quality fuel combustion and the use of outdated coal-fired boilers that do not meet current standards (*Drony ponownie sprawdziły jakość powietrza w Lidzbarku*… 2021).

In a study conducted in Cracow, a SoftBlue AirDron measurement head was installed on a DJI Matrice 600 PRO unmanned aerial vehicle to analyze air quality in various locations in the city. The measurement mission occurred in the central part of Cracow, along a traffic route including Aleje Trzech Wieszczów (Słowacki, Mickiewicz and Krasiński avenues) with a length of about 2.5 km. The flight route started from the intersection of Długa Street and Słowacki Avenue (Nowy Kleparz) and ended at the Dębnicki Bridge over the Vistula River. The mission was planned using the Litchi application in "Waypoints" mode. The flight took place at 35 meters above ground level at a speed of 4.0 m/s. The collected measurement data with the SoftBlue AirDron head was processed on the ST10 Spectra Geospatial tablet using the SoftBlue GCS application. Detailed analysis showed several areas with higher concentrations of particulate matter and volatile organic compounds: the Słowacki Avenue area, the Mickiewicz Avenue area, and the Krasiński Avenue area. The highest values of particulate matter were recorded in the area of Nowy Kleparz. Measurement technology using the SoftBlue AirDron measurement head proved to be an effective tool for monitoring air quality in urban areas, enabling rapid inspections of large areas and providing results comparable to laboratory analyses. In addition, the survey head was found to be easy to use and can be integrated with various unmanned platforms (Durło 2021).

Results of measurement missions carried out in Toruń using the Sniffer4D mobile system

The analysis of air quality in Toruń for the 2021/22 season was carried out using the Sniffer4D pollution level measurement system integrated with a DJI Matrice 210 RTK unmanned aerial vehicle (UAV) and/or a self-driving car at several testing grounds. This paper presents the results obtained at three of them: Central Communal Cemetery (CCC), Wrzosy single-family housing estate, and Św. Józefa estate. In the first case (CCC), in the period from October 18 to November 14, 2021, four survey missions were carried out, all by UAVs at a height of 30 meters; at the second site (Wrzosy housing estate) a mission was conducted on October 26, 2021 at a height of 1 meter using a passenger car; and at the third training ground (Św. Józefa estate) on October 27, 2021, both mobile platforms (UAV and passenger car) were combined to acquire data from heights of 30 meters and one meter. In the case of using the UAV, aerial missions were planned using the DJI Pilot application; using the passenger car, efforts were made to plan routes along and across the entire selected area using the road system.

For the dates above, measurement data for PM2.5 and PM10 particulate matter were also collected from those recorded at the two local stations of the State Environmental Monitoring – Przy Kaszowniku and Wały Gen. Sikorskiego – closest to the testing grounds (Table 4). They are, however, distant from the mobile measurement sites by linear distances of about 3 to 4.5 km.

Polygon – Central Communal Cemetery (CCC) is located on Grudziądzka Street in the northern part of Toruń on the Katarzynka estate. It covers 7.5 hectares is bordered to the north and east by wasteland, and to the west and south by important traffic routes of Toruń and warehouse buildings. The target flight route was designed to ensure the reliability of operations with maximum survey efficiency to cover the entire area under study. During the UAV flights, a key aspect was ensuring safety for bystanders and property on the ground. The flight altitude for this mission was set at 30 meters above ground level. Measurement results from the system's sensors were displayed in real-time in the Sniffer4D Mapper application, and they were automatically saved in s4d file format on a microSD card inserted in the survey head.

A total of four survey missions were carried out over the same study area over four weeks, following the same route: the first took place on October 18, 2021, the next took place two weeks later on October 31, the next on November 1, and the last after another two-week interval on November 14. The first recording occurred in the morning, and the other three were carried out in the evening. The averaged results of particulate matter of different

Table 4. Hourly average values of PM2.5 and PM10 particulate matter recorded at State Environmental Monitoring stations in Toruń – Przy Kaszowniku and Wały Gen. Sikorskiego in Toruń on days of acquisition using the Sniffer4D mobile system

Data	Hour	Przy Kaszowniku		Wały Gen. Sikorskiego
		PM2.5 [µg/m³]	PM10 [µg/m³]	PM10 [µg/m³]
18.10.2021	11:00 am	12.7	16.9	10.5
26.10.2021	10:00 pm	23.3	37.4	34.8
27.10.2021	10:00 pm	9.5	11.9	11.0
31.10.2021	10:00 pm	33.5	39.2	42.0
01.11.2021	10:00 pm	30.7	35.5	31.4
14.11.2021	10:00 pm	33.5	36.6	37.3

Source: own elaboration based on SEM data

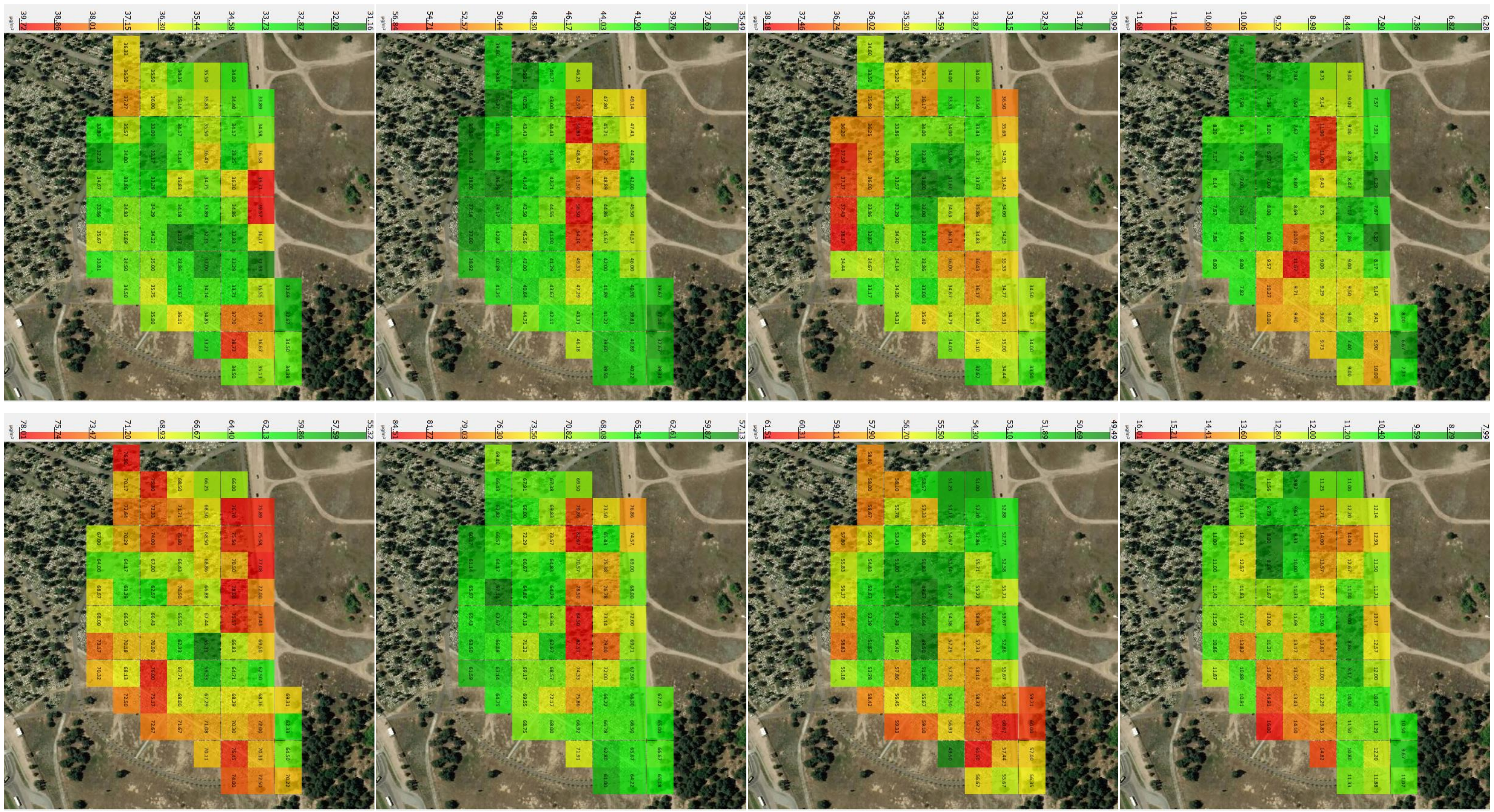

Fig. 5. Spatial distribution of PM1.0 and PM10 dust over the Central Municipal Cemetery in Toruń at a height of 30 meters from the ground surface recorded with the Sniffer4D system on the UAV during data acquisition on 18.10.2021, 31.10.2021, 01.11.2021 and 14.11.2021; presentation of the averaged data in a grid of its own size 53 (32x32 meters), which corresponds to an area of about 1025 m^2; the color palette was independently stretched for each presented data series.

Source: own elaboration

Table 5. Average particulate matter values recorded with Sniffer4D system on UAV at 30 m a.g.l. over the Central Communal Cemetery in Toruń

Data	Number of samples	PM1.0			PM2.5			PM10		
		average [μg/m^3]	max [μg/m^3]	min μg/m^3]	average [μg/m^3]	max [μg/m^3]	min [μg/m^3]	average [μg/m^3]	max [μg/m^3]	min [μg/m^3]
18.10.2021	862	8.188	11.667	6.286	10.771	14.455	8.000	11.530	16.000	8.000
31.10.2021	792	34.294	38.167	31.000	50.530	55.333	43.333	55.524	61.500	49.500
01.11.2021	920	41.611	56.833	35.500	61.968	76.000	53.429	67.250	84.500	57.143
14.11.2021	791	34.686	39.714	31.167	61.719	70.000	52.500	70.164	78.000	55.333

Source: own elaboration

sizes are presented in Table 5, and Figure 5 shows their spatial distributions in a grid of about 32 meters.

The lowest values of particulate matter concentrations were recorded on October 18 (average values were PM1.0 – 8.188, PM2.5 – 10.771, and PM10 – 11.530 μg/m). The measurement carried out in the morning affected the lower levels of measured atmospheric pollutants, and the values reported at the same time at the two stationary SEM stations at an altitude of two meters were similar to those recorded by the UAV at an altitude of 30 meters. During the next measurement mission, on October 31, there was a significant increase in the concentration of particulate matter, which coincided with measurements taken in the evening. The higher values may be related to increased anthropogenic emissions during the evening hours. The highest pollutant values during the entire study period were recorded on November 1. Again, the measurements were made in the evening, confirming the tendency for higher pollution levels at this time. The values were particularly high and exceeded daily norms, probably due to the All Saints' Day celebration, during which candles and lanterns were burned en masse at the cemetery, further increasing pollutant emissions. During the November 14 measurements, high levels of pollution persisted, suggesting the existence of persistent emission sources or atmospheric conditions conducive to the accumulation of particulate matter. Analysis of the results indicates that the time of day has a significant impact on air pollution levels, with significantly lower values recorded in the morning compared to the evening. This may be related to both seasonal variations and other anthropogenic factors. The average values of particulate concentrations also showed a stabilization of levels, suggesting that focusing on evening emission sources may be key to more effectively reducing overall levels of atmospheric pollution. At the same time, the recorded measurement values at both SEM sites were relatively high but almost twice as high as at CCC. This is due to the peculiarities of the location of the stationary stations and the different daily distribution of pollutants and their sources. Only values lower than at the reference station were registered during the morning data acquisition, but the difference was not pronounced.

At the second testing ground (Wrzosy estate), the Sniffer4D recorder was used to conduct a detailed analysis of air quality in the ground layer of the atmosphere. For this purpose, the detector was mounted on a passenger car so that the sensor sampled the air from a height of about one meter while eliminating the influence of the vehicle's exhaust emissions. The study was conducted in the housing estate in north-western Toruń, which is characterized by dense single-family housing. The measurements covered most of the estate's streets, which are bounded by the Grudziądzka, Storczykowa, Ugory and Zbożowa arterial roads.

The Wrzosy estate is a zone with a 30 km/h speed limit, though the car-based measurements were taken at a much lower speed to ensure accurate results. The surveys took place on October 26, 2021 at around 10:00 pm, guaranteeing minimal car traffic on the estate due to the late hour. This made it possible to obtain meaningful data on the quality of the air breathed by the residents of the housing development by sampling at a height that corresponds to the breathing level of humans, especially the youngest – children (Table 6).

During the measurements, the average concentration of PM10 particulate matter was 48.796 μg/m^3, which is close to the limit of the national 24-hour standard. Data analysis showed significant deviations in measurements at individual

Fig. 6. Spatial distribution of PM1.0 and PM10 dust in the Wrzosy residential area in Toruń at a height of 1 meter above the ground surface recorded with the Sniffer4D system mounted on a car during the evening acquisition at around 10 pm on 14.11.2021; presentation of the averaged data in a grid of its own size 85 (50x50 meters), which corresponds to an area of about 2500 m^2; the color palette was independently stretched for each presented data series.

Source: own elaboration

Table 6. Average particulate matter values recorded at Wrzosy residential area in Toruń with Sniffer4D system mounted on passenger car at 1 meter a.g.l.

Size of particulate matter	Number of samples	Average [µg/m³]	Max [µg/m³]	Min [µg/m³]
PM1.0	2019	30.515	71.000	18.000
PM2.5	2019	45.119	91.556	26.167
PM10	2019	48.796	97.667	28.000

Source: own elaboration

points of the measurement grid. The highest recorded concentration was 104.000 µg/m³, while the lowest reached 28.222 µg/m³ (Fig. 6). Such variation suggests the presence of local sources of air pollution emissions. To identify these sources more accurately, it is recommended that further studies be conducted at the same locations but at different times of the day. This may help to identify more precisely the sources of elevated pollutant concentrations. The values obtained at the SEM station simultaneously showed significantly lower values, which was related to the lack of traffic and limited activity of residents in this part of the city.

The third testing ground chosen was the Św. Józefa estate, where both mobile platforms (a passenger car and a UAV) were combined, acquiring data from two different heights: 1 and 30 meters. The Sniffer4D system recorded on 27/10/2021 in the evening hours. The Św. Józefa estate is a very specific urban unit with a population of about 2,000 residents, which consists exclusively of low-rise single-family houses and a grid street system. In this area, a section bounded by Truskawkowa, Jesienna, Malinowa and Polna Streets was selected where measurement data could be acquired both from the air and at car level. The purpose of this study was to compare measurement values that are possible to record with the Sniffer4D system in a vertical gradient (Table 7), and the chosen recording time of around 10:30 pm guaranteed comparable conditions and the safety of mission execution.

During registration, 254 measurement samples were acquired in an identical area at a height of 1 meter and nearly 650 samples at a height of 30 meters. Most of the values obtained were higher at the registration height of 30 meters than at the level of 1 meter. Only carbon dioxide measurements indicated slightly lower values. The highest differences were recorded for particulate matter, especially PM2.5 and PM10. For example, the average PM10 value at street level was 14.075 µg/m³; over buildings, it was already 36.927 µg/m³. It is worth noting, however, that the prevailing air temperature was not low, despite the autumn season, so individual heating sources were operating part-time and at partial efficiency. Despite this, it was possible to capture the spatial variability, both horizontally and vertically, of the analyzed phenomenon (Fig. 7). In this figure, the highest value for each recorded parameter is presented by pixels in which there was a takeoff from the surface after a few minutes and an ascent

Table 7. List of available sensor modules that can be installed in mobile measurement systems, along with the results obtained at the Św. Józef residential area on 27.11.2021

Measurement module	Substance	Unit	H = 1 m			H = 30 m		
			average	max	min	average	max	min
Number of samples	–	number	254			643		
Temp	temperature	°C	16.203	16.863	15.490	10.077	10.476	9.771
Hum	humidity	%	39.559	41.176	38.039	55.461	56.268	54.104
PM1.0	particulate matter	µg/m³	10.717	16.000	6.167	22.751	28.814	9.667
PM2.5		µg/m³	13.114	17.833	8.500	33.844	45.877	11.750
PM10		µg/m³	14.075	19.167	8.500	36.927	50.433	11.917
$O_3 + NO_2$	ozone + nitrogen dioxide	mg/m³	0.054	0.060	0.049	0.113	0.116	0.107
CO_2	carbon dioxide	mg/m³	383.036	386.242	380.496	381.079	382.790	378.712

Source: own elaboration

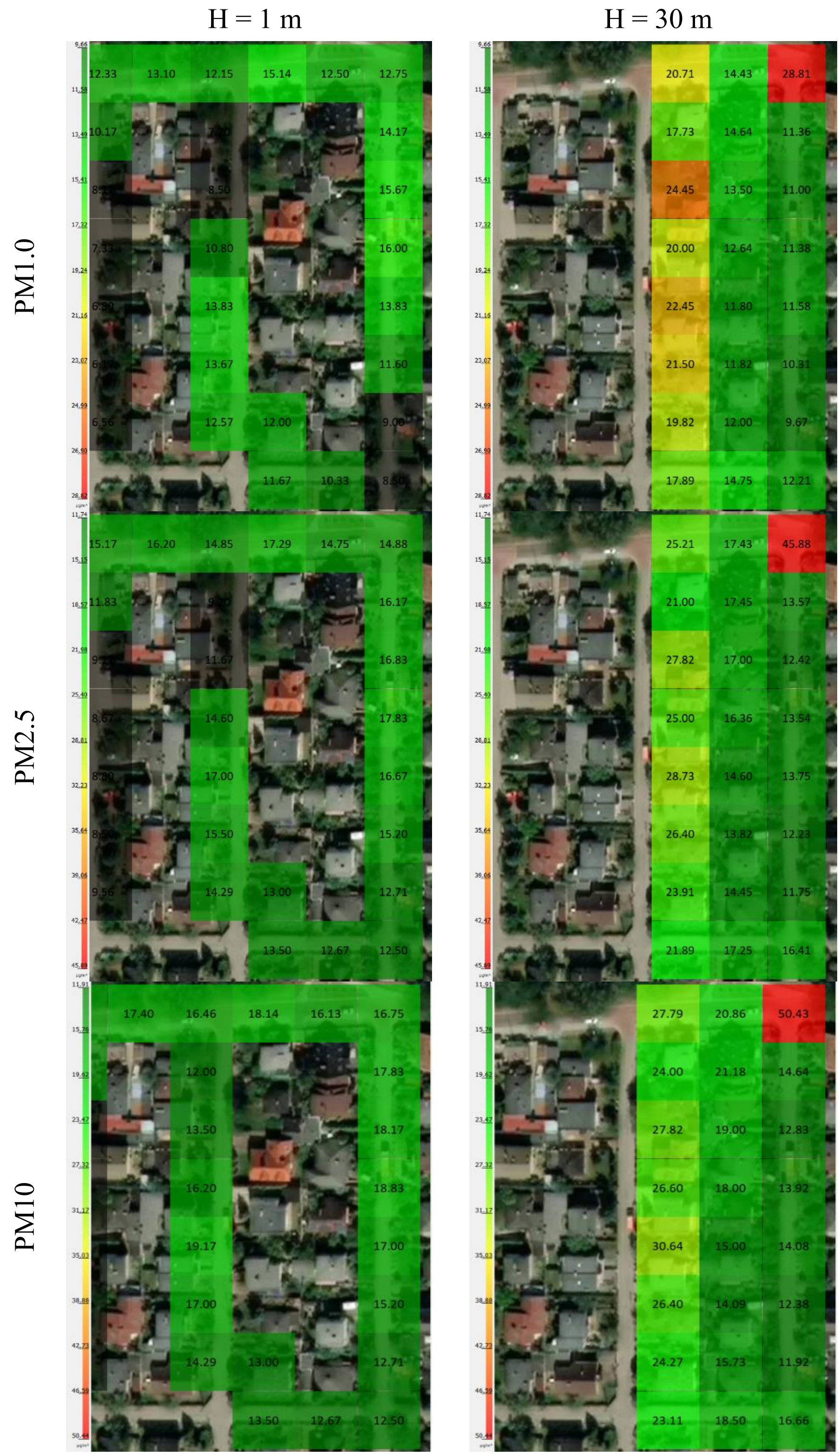

Fig. 7. Spatial distribution of PM1.0, PM2.5, and PM10 particulate matter in the Św. Józef residential area in Toruń at heights of 1 and 30 meters above the ground surface recorded with the Sniffer4D system mounted on a car and UAV during the evening acquisition at about 10:30 pm on 27/10/2021; presentation of averaged data in a grid of own size 35 (21x21 meters), which corresponds to an area of about 450 m^2; the color palette was standardized for each height of data acquisition.

Source: own elaboration

to a preset altitude, as well as a landing. For other training grounds, such situations did not occur.

At the same time, as in other test areas, the average values recorded by the nearest SEM station indicated values below the lowest averages recorded in the area. This is mainly due to residents' daily activity near the measurement point and the spatial structure consisting exclusively of single-family houses.

Summary and conclusions

National air quality monitoring systems, such as the National Environmental Monitoring, are based on a network of stationary measurement stations located strategically, usually in areas with high traffic volumes and not necessarily where larger concentrations of residents predominate. These systems are characterized by a high degree of standardization and homogeneity of measurements, ensuring accuracy and comparability of data on a large scale. Financed with public funds, they can be maintained despite the high infrastructure costs associated with building monitoring stations, limiting their number. Social systems provided by private companies or civic initiatives (e.g., Airly, LoVo, Sensor.Community) often complement national networks. Various measurement points are located in different locations, which allows for an increase in the density of the monitoring network. Although they use cheaper technology, making them more financially accessible, their measurement precision can be lower due to the variety of equipment and methodologies used.

Mobile measurement systems that work with UAVs, such as Sniffer4D, Nosacz II or AirDrone, make it possible, first and foremost, to carry out measurements on the move. They allow data collection from a wide area and real-time air quality monitoring, which is particularly valuable in areas where stationary measurement stations are lacking or the measurement network needs to be dense due to pollution sources. The mobility of these systems allows for a more comprehensive assessment of the quality of given atmospheric layers at different points and times of the day, which is difficult to achieve with static measuring stations. They are also more economical and easily adaptable to different measurement tasks due to their lightweight and compact design. However, they require regular calibration and maintenance, which can pose logistical challenges during long-term measurement campaigns. Data collection by mobile detectors in various variable locations can lead to problems with data representativeness and comparability over extended periods. Mobile systems can also have lower precision than stationary measurement stations, which makes it challenging to meet data quality requirements set by several regulations and directives.

The study showed that the recorded measurement values are mainly influenced by the immediate surroundings, their spatial structure and residents' daily activity. The Toruń SEM stations are located in the surroundings of service buildings and local administration, so traffic or dust emissions activity is highest in the morning. The activity of residents of downtown single-family housing estates is concentrated in the afternoon, when traffic increases in these areas, and in the evening, when individual heating sources are switched on. This has been documented in the studies, especially in the study areas associated with individual housing developments. These issues, mainly in learning about the temporal and spatial variability in the full 3D model, should be the subject of more detailed and targeted research and the conclusions communicated to local decision-makers, planners, urban planners, and residents of these areas.

The procedures involved in using mobile air quality measurement systems using unmanned aerial vehicles include several key steps. To start measurement operations using UAVs in Poland, it is necessary to obtain the appropriate authorizations. Each unit must be assigned an operator number, which is granted after a personal or legal entity registers at drones.gov.pl. Piloting a UAV requires obtaining authorizations, which is possible after registering as an operator, completing online pilot training, and passing the A1/A3 open category test. For UAVs with a higher carrying capacity, authorizations in the A2 category and a specific NSTS are required. The next step is to report each survey mission through the DroneTower mobile application, ensuring operations' safety. Maintaining a flight log, including information about the UAV, category, area and flight time, is also necessary. To conduct a flight, it is also crucial to have a valid insurance policy with a sunset flight option, which covers any damage caused by the UAV. Preparing for the flight includes planning the route and altitude of the flight according to measurement requirements and following safety rules. Before the start of the mission, it is recommended that residents, neighborhood councils, or the local community be informed about the planned activities and the purpose of the mission, which may meet with public approval and facilitate the adaptation of activities to local needs. The collected measurement data are analyzed to assess air quality, including identification of pollutants, emission sources and analysis of time trends. The data are processed using specialized software to produce clear visualizations, such as pollution maps and graphs. Based on the processed data, reports are compiled that include measurement results, analysis of the state of air quality, and recommendations for improving the situation. Such reports are the best way to inform residents and all interested parties about air quality and enable them to take action to improve it. Mobile monitoring systems of the state of air quality will develop intensively in the near future, which will certainly contribute to a better understanding of the horizontal and vertical distribution of pollutants and the mechanisms of their local temporal and spatial variability.

Disclosure statement

No potential conflict of interest was reported by the authors.

Author contributions

Study design: MK; data collection: DZ, MK; statistical analysis: DZ, MK; result interpretation: DZ, MK; manuscript preparation: DZ, MK; literature review: DZ, MK.

References

ANJOMSHOAA A, DUARTE F, RENNINGS D, MATARAZZO TJ, DESOUZA P and RATTI C, 2018, City Scanner: Building and Scheduling a Mobile Sensing Platform for Smart City Services. *IEEE Internet of Things Journal* 5(6): 4567–4579. DOI: https://doi.org/10.1109/JIOT.2018.2839058.

BECMER D and ROMANEK A, 2011, Bezzałogowe Platformy Latające, Wyższa Szkoła Oficerska Wojsk Lądowych im. gen. Tadeusza Kościuszki. Instytut Dowodzenia, Wrocław.

BUCEK P, MARŠOLEK P and BÍLEK J, 2021, Low-Cost Sensors for Air Quality Monitoring – the Current State of the Technology and a Use Overview. *Chemistry-Didactics-Ecology-Metrology* 26: 41–54. DOI: https://doi.org/10.2478/cdem-2021-0003.

CASTELL N, DAUGE FR, SCHNEIDER P, VOGT M, LERNER U, FISHBAIN B, BRODAY D and BARTONOVA A, 2017, Can commercial low-cost sensor platforms contribute to air quality monitoring and exposure estimates? *Environment International* 99: 293–302. DOI: https://doi.org/10.1016/j.envint.2016.12.007.

CHAMOLA V, KOTESH P, AGARWAL A, NAREN, GUPTA N and GUIZANI M, 2021, A Comprehensive Review of Unmanned Aerial Vehicle Attacks and Neutralization Techniques. *Ad Hoc Networks* 111: 102324. DOI: https://doi.org/10.1016/j.adhoc.2020.102324.

Dron Obywatelski. (2024). *Bezpłatny Tyski Tygodnik Miejski* 6(846): 4.

Drony ponownie sprawdziły jakość powietrza w Lidzbarku. (2021). *Bezpłatny biuletyn dla mieszkańców Miasta i Gminy Lidzbark* 10(68): 2.

DURŁO G, 2021, *Analiza jakości powietrza w Krakowie przy użyciu głowicy pomiarowej SoftBlue AirDron*. Available at: https://navigate.pl/blog/analiza-jakosci-powietrza-w-krakowie/ (accessed: 18.07.2024).

DYVAK M, ROT A, PASICHNYK R, TYMCHYSHYN V, HULIIEV N and MASLYIAK Y, 2021, Monitoring and Mathematical Modeling of Soil and Groundwater Contamination by Harmful Emissions of Nitrogen Dioxide from Motor Vehicles. *Sustainability* 13: 2768. DOI: https://doi.org/10.3390/su13052768.

ERICKSON L, GRISWOLD W, MAGHIRANG R and URBASZEWSKI B, 2017, Air Quality, Health and Community Action. *Journal of Environmental Protection* 8(10): 1057-1074..

ERWIŃSKI K, KARPIŃSKA D, KUNZ M, PAPROCKI M and CZOKOW J, 2023. An Autonomous City-Wide Light Pollution Measurement Network System Using LoRa Wireless Communication. *Sensors* 23(11): 5084. DOI: https://doi.org/10.3390/s23115084.

GODFREY I, AVARD G, BRENES JPS, CRUZ MM and MEGHRAOUI K, 2023, Using Sniffer4D and SnifferV portable gas detectors for UAS monitoring of degassing at the Turrialba Volcano Costa Rica. *Advanced UAV* 3(1): 54–90.

GODFREY I, SIBAJA BRENES JP, MARTÍNEZ CRUZ M and MEGHRAOUI K, 2022, Using UAS with Sniffer4D payload to document volcanic gas emissions for volcanic surveillance. *Advanced UAV* 2(2): 86–99.

GODŁOWSKA J, 2019, *Wpływ warunków meteorologicznych na jakość powietrza w Krakowie*. IMGW-PIB, Warszawa.

GUCMA L and MUCZYŃSKI B, 2022, Walidacja projektu PASSport w Porcie Kołobrzeg. *Akademickie Aktualności Morskie* 4(116): 2–7.

JĘDRAK J, KONDURACKA E, BADYDA A and DĄBROWIECKI P, 2017, Wpływ zanieczyszczeń powietrza na zdrowie. Stowarzyszenie Krakowski Alarm Smogowy, Kraków.

JĘDRZEJEK F, GRYBOŚ D, ZYŚK J, LESZCZYŃSKI J, SZARŁOWICZ K, STOBIŃSKI M, KUBICA B and SUWAŁA W, 2021, The Innovative Method of Purifying Polluted Air in the Region of an Inversion Layer. *Frontiers in Environmental Science* 9: 784477. DOI: https://doi.org/10.3389/fenvs.2021.784477.

JOŃCA J, PAWNUK M, BEZYK Y and ARSEN A, 2022, Drone-Assisted Monitoring of Atmospheric Pollution. A Comprehensive Review. *Sustainability* 14(18): 11516. DOI: https://doi.org/10.3390/su141811516.

KIM M-K, JANG Y, HEO J and PARK D, 2021, A UAV-Based Air Quality Evaluation Method for Determining Fugitive Emissions from a Quarry during the Railroad Life Cycle. *Sensors* 21(9): 3206. DOI: https://doi.org/10.3390/s21093206.

KONERT A and SAKOWSKA-BARYŁA M, 2020, Prawne uregulowania w zakresie używania bezzałogowych statków powietrznych przez media. *International Journal of Legal Studies* 8(2): 47–74. DOI: https://doi.org/10.5604/01.3001.0014.6359.

KARPIŃSKA D and KUNZ M, 2019, Light pollution in the night sky of Toruń in the summer season. Bulletin of Geography. *Physical Geography Series* 17: 91–10. DOI: https://doi.org/10.2478/bgeo-2019-0017.

KARPIŃSKA D and KUNZ M, 2021, The Analysis of the visibility and signal strength of the LoRaWAN network in an urbanized area: A case study of the Bielany campus at the Nicolaus Copernicus University in Toruń. *Bulletin of Geography. Socio-economic Series* 54: 137–149. DOI: https://doi.org/10.2478/bog-2021-0039.

KARPIŃSKA D and KUNZ M, 2022, Device for automatic measurement of light pollution of the night sky. *Scientific Reports* 12(1): 1–12. DOI: https://doi.org/10.1038/s41598-022-20624-7.

KARPIŃSKA D and KUNZ M, 2023, Vertical Variability of Night Sky Brightness in Urbanised Areas. *Quaestiones Geographicae* 42(1): 5–14. DOI: https:/doi.org/10.14746/quageo-2023-0001.

KRAJEWSKA-KUŁAK E, ROLKA H, ŁUKASZUK C and MAKAROWSKI T, 2007, Wpływ powietrza na zdrowie człowieka. In: Krajewska-Kułak E. (ed.) *Problemy terapeutyczno-pielęgnacyjne od poczęcia do starości* 2: 234–242.

MALEC A and BOROWSKI G, 2016, Zagrożenia pyłowe oraz monitoring powietrza atmosferycznego. *Inżynieria Ekologiczna* 50: 161–170. DOI: https://doi.org/10.12912/23920629/65489.

MANISALIDIS I, STAVROPOULOU E, STAVROPOULOS A and BEZIRTZOGLOU E, 2000, Environmental and health impacts of air pollution: a review. *Frontiers in Public Health* 8(14).

MOTLAGH NH, KORTOCI P, SU X, LOVEN L, HOEL HK, HAUGSVAER SB, SRIVASTAVA V, GULBRANDSEN CF, NURMI P and TARKOMA S, 2023, Unmanned Aerial Vehicles for Air Pollution Monitoring: A survey. *IEEE Internet of Things Journal* 10 (24): 21687–21704. DOI: https://doi.org/10.1109/JIOT.2023.3290508.

PARCZEWSKI R. 2023, *Bezzałogowe statki powietrzne w bezpieczeństwie ekologicznym Polski na przykładzie województwa lubelskiego*. Wydawnictwo WAT, Warszawa.

Raport o stanie miasta i gminy Września za 2018 rok.

Raport o stanie miasta i gminy Września za 2019 rok.

Raport o stanie miasta i gminy Września za 2020 rok.

Raport o stanie miasta i gminy Pruszcz Gdański za 2020 rok.

Raport o stanie miasta i gminy Biskupiec za 2021 rok.

SALA S and ZINKO I, 2010, Wybrane problemy zanieczyszczeń powietrza. *Rocznik Świętokrzyski. Seria B – Nauki Przyrodnicze* 31: 73–84.

SENARATHNA M, PRIYANKARA S, JAYARATNE R, WEERASOORIYA R, MORAWSKA L and BOWATTE G, 2022, Measuring Traffic Related Air Pollution Using Smart Sensors In Sri Lanka: Before And During A New Traffic Plan. *Geography, Environment, Sustainability* 15(3): 27–36. DOI: https://doi.org/10.24057/2071-9388-2022-011.

SKOCZKO I, SZATYŁOWICZ E, ZAGÓRSKA M, ROSZKOWSKA W, SKOWROŃSKA I, ZAMBRZYCKA A and DĄBROWSKA K, 2018, Ocena jakości powietrza w Polsce. *Inżynieria Środowiska – Młodym Okiem* 37: 127–148.

SLADOJEVIC S, ARSENOVIC M, NIKOLIĆ D, ANDERLA A and STEFANOVIĆ D, 2024, Advancements in Mobile-Based Air Pollution Detection: From Literature Review to Practical Implementation. *Journal of Sensors* 4: 1–17. DOI: https://doi.org/10.1155/2024/4895068.

Sniffer4D V2 Multi-gas Detection & Mapping System – Components & Specs, 2023.

SNYDER EG, WATKINS TH, SOLOMON PA, THOMA ED, WILLIAMS RW, HAGLER GS, SHELOW D, HINDIN DA, KILARU VJ and PREUSS PW, 2013, The changing paradigm of air pollution monitoring. *Environmental Science & Technology* 47(20): 11369–11377. DOI: https://doi.org/10.1021/es4022602.

STITH L, 2023, What Is IoT Based Air Pollution Monitoring. Available at: https://robots.net/tech/what-is-iot-based-air-pollution-monitoring/ (Access 12.07.2024).

SUMARA M, 2018, Propozycje rozwiązań związanych z ograniczeniem niskiej emisji wynikających z uchwały antysmogowej w kontekście podejmowanych działań kontrolnych przez funkcjonariuszy Straży Miejskiej w Katowicach. [In:] Nawrot F and Radecka E (eds.), *Prawne instrumenty ochrony powietrza*. INFOMAX, Katowice: 108–123.

TOMALA M, 2023, Monitorowanie jakości powietrza w Polsce w świetle koncepcji smart city. *Środkowoeuropejskie Studia Polityczne* 1: 45–70. DOI: https://doi.org/10.14746/ssp.2023.1.3.

VELASCO A, FERRERO R, GANDINO F, MONTRUCCHIO B and REBAUDENGO M, 2016, A Mobile and Low-Cost System for Environmental Monitoring: A Case Study. *Sensors* 16(5): 710. DOI: https://doi.org/10.3390/s16050710.

VILLA TF, GONZALEZ F, MILIJEVIC B, RISTOVSKI ZD and MORAWSKA L, 2016a, An Overview of Small Unmanned Aerial Vehicles for Air Quality Measurements: Present Applications and Future Prospectives. *Sensors* 16(7): 1072–1072. DOI: https://doi.org/10.3390/s16071072.

VILLA TF, SALIMI F, MORTON K, MORAWSKA L and GONZALEZ F, 2016b, Development and Validation of a UAV Based System for Air Pollution Measurements. *Sensors* 16(12): 2202. DOI: https://doi.org/10.3390/s16122202.

ZBORALSKI D and KUNZ M, 2024, Optymalizacja kampanii pomiarowej dotyczącej jakości powietrza z wykorzystaniem mobilnego systemu rejestrującego Sniffer4D. In: Młynarczyk A. (ed.) *Środowisko przyrodnicze jako obszar badań* 6, Bogucki Wydawnictwo Naukowe.

Internet sources

https://airly.org/map/pl/ (Access 16.07.2024).

https://airly.org/pl/funkcjonalnosci/sensor-jakosci-powietrza/ (Access 16.07.2024).

https://dron.edu.pl/pogromcy-smogu-i-dron/ (Access 11.07.2024).

https://powietrze.gios.gov.pl/pjp/content/annual_assessment_air_acceptable_level (Access 15.07.2024).

https://powietrze.gios.gov.pl/pjp/content/measuring_air_assessment_measurings (Access 15.07.2024).

https://powietrze.gios.gov.pl/pjp/maps/measuringstation (Access 15.07.2024).

https://sensor.community/pl/ (Access 16.07.2024).

https://softblue.pl/produkty/eco-solutions/airdron/ (Access 07.07.2024).

https://www.gov.pl/web/kppsp-bialogard/strazacy-w-profilaktyce-antysmogowej (Access 10.07.2024).

https://www.lovo.pl/iot/system-do-monitorowania-jakosci-powietrza/ (Access 17.07.2024).

https://www.soarability.com (Access: 08.07.2024).

https://www.wzp.pl/biuro-prasowe/biuro-prasowe/aktualnosci/dron-nad-kominami-w-szesciu-zachodniopomorskich-miastach-pierwsze-zolte-kartki-dla-palacych (Access 09.07.2024).

https://zycie.nastyku.pl/artykul/pierwszy-raport-z-badania-jakosci-powietrza-w-zgorzelcu,3329,1,fdb0d.html (Access 09.07.2024).

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