Comparative Analysis of Air Pollution Measurements between Compact Mobile Sensors and Standardized Laboratory Methods

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***Abstract*—The article is devoted to the comparison of laboratory methods for measuring the concentration of gases in the air and methods using compact sensors mounted on an Unmanned Aerial Vehicle (UAV). Among the gases studied are carbon dioxide and carbon monoxide, sulfur dioxide, and nitrogen oxide. The description of the tested sensors (Gas analyser GANK-4, aspirator PU-4E, spectrophotometer PE-5400VI, Libelium Waspmote Gas Sensors PRO), measurement methods and equipment for the flight mission are presented. Special attention is paid to the influence of meteorological parameters on the measured concentration. Finally, measurement results are compared with the recommended indices of the content of the investigated gases.**

***Index Terms*—air pollution, environmental monitoring, gas detection, robot sensing systems, unmanned aerial vehicle**

I. Introduction

The level of global urbanization continues to grow: more than 55% of the world's population lives in an urban environment, while for developed countries this figure is approaching 90% [1]. Concentration of the population in cities leads to a global increase in the environmental impact of industry, transport and urban economy and large-scale environmental pollution [2]. More than 91% of the world's population lives in regions in which the presence of pollutants in the air exceeds the figures recommended by World Health Organization (WHO). WHO estimates that about 7 million people die each year from exposure to small particles in polluted air that cause diseases such as stroke, heart disease, lung cancer, chronic lung diseases and respiratory infections.

Thus, the urban environmental situation needs careful control and monitoring, at that in the short term the most relevant activity for the population is the regulation of emissions of enterprises and the inventory of landfills for municipal solid waste and illegal landfills [3], [4]. For urban environmental monitoring services, this task requires major expenditures, state-of-the-art equipment, software, and highly skilled personnel that regularly maintain environmental monitoring tools [5].

For example, quite often the measurements of the state of the environment are carried out by specialists after citizens' complaints when the cost of the measures to eliminate negative externalities already greatly exceed the cost of measures to prevent pollution in the first place [6]. Preservated solid waste landfills require periodic inspection and maintenance to prevent depreservation [7]. Cases of illegal emissions into the atmosphere produced by industrial enterprises are common, and the lack of prompt ways to fix violation leads to the legal difficulty of bringing offenders to responsibility and reducing the quality of monitoring [8], [9].

In recent decades, environmental monitoring technologies have significantly improved [10]. For example, automated sampling stations are used to collect environmental data [11]. Nevertheless, such stations are quite large and expensive, so often sampling takes place in manual mode, especially in countries with insufficient funding for environmental regulation. The collected samples are further analysed in the laboratory, which limits operational monitoring. For these reasons, existing environmental monitoring is characterized by centralization and duration of work.

In the last years, with the advent of IoT sensor systems (for example, from Libelium, Vaisala, Bosh) the process of collecting and processing information became automated, providing the researcher with the final results [12], [13]. They are compact, can be independent from energy sources and are incomparably cheaper (from 1/10 of the cost) than the previous generation of equipment. A network of such sensors installed in various parts of the city is able to quickly obtain information on the concentrations of carbon monoxide CO, nitrogen oxides NO, NO_2, sulfur dioxide SO_2, ozone O_3, and the presence of suspended solids (PM10, PM2.5) [14].

Stationary environmental monitoring can be organized with the help of a network of IoT devices. However, current robotic technologies make it possible to deploy a mobile sensor network that collects and processes environment quality data [15], [16]. There are affordable and popular models of unmanned aerial vehicles (UAVs) that are capable of carrying out flight missions lasting up

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to 20-30 minutes and at the same time lifting up to 0.5 kg of payload, which is more than enough to integrate modern sensors [17]. Similar developments are carried out to monitor water resources — developers offer a variety of unmanned surface vehicles with pre-installed sets of sensors [18]. This greatly increases the effectiveness of monitoring and reduces the cost of its organization [19]. Automation of data processing and modern decentralized technologies provide an opportunity for the commercialization of this sphere, opening the way for the concept of carbon credits [20].

However, the introduction of new monitoring systems requires the testing of methods and equipment for the automatic collection of environmental data. Before carrying out activities for the official commissioning of mobile recording equipment, it is necessary to perform experiments designed to establish the potential of these solutions. In particular, it is necessary to find out whether the accuracy of classical laboratory methods for analysing pollution in atmospheric air and new operational methods using compact sensors are comparable. Therefore, in this paper, this issue is investigated for the mobile pollution detection system, which is a UAV with sensors installed on it.

The paper is organized as follows. Section 2 focused on the description of air pollutants. Section 3 describes the recording equipment and measurement methods, and the fourth section describes the course of the measurement. The fifth section presents the measurement results. The question of the influence of air temperature on sensor readings is addressed in section 6. The findings are summarized in the last section.

II. Air Pollutants

This article analyses the following air pollutants: carbon monoxide CO; carbon dioxide CO_2; sulfur dioxide SO_2; nitric oxide NO.

Sulfur dioxide, nitrogen oxides, carbon monoxide are the main pollutants, their volume in the atmosphere is regulated by national and international air quality standards. Carbon dioxide is not a toxic substance, however, an increased level is considered to be the cause of the "greenhouse effect" [21].

Anthropogenic emissions of sulfur oxides are greater than natural emissions. Technogenic sources of sulfur oxides in the atmosphere — fuel energy (55%), metallurgical industry (25%), refining and processing of oil and coal (10%), chemical industry, transport and other human activities (10%). Sulfur dioxide dissolved in water forms acid rain, these destroy plants, acidify the soil, increase the acidity of lakes. Even with an average content of sulfur oxides in the air of the order of 100 $\mu g / m^3$ (frequent level in the city), the plants become yellowish [22].

Sulfur dioxide is an irritant to the eyes, skin, mucous membranes and the respiratory system. Respiratory diseases, such as bronchitis, increase with increasing levels of sulfur oxides in the air. A long-term effect of sulfur dioxide on a person leads first to the loss of taste sensations, constrained breathing, and then to irritation or swelling of the lungs, problems in the heart activity, impaired blood circulation and cessation of breathing [22], [23].

Nitrogen forms seven oxides, of which only monoxide and dioxide, are dangerous pollutants [24]. Man-made sources of nitrogen oxides in the atmosphere are: energy; fuel combustion; motor transport; industry (non-ferrous metallurgy, coke-chemical and petrochemical industries). The main source of the formation of technogenic nitrogen oxides (up to 80% of the total volume) is fuel nitrogen. The process of burning fuel in any engines appears nitrogen monoxide. Then NO is oxidized to nitrogen dioxide NO_2 in the troposphere. Nitrogen oxides rank second after sulfur dioxide in increasing acidity of precipitation. Breathing air with a high concentration of nitrogen oxides can irritate the respiratory tract of the human body. Its action can increase respiratory diseases, especially for patients with asthma [22], [25].

Carbon monoxide is produced by burning organic material (coal, wood, paper, gas). Motors of vehicles produce from 55 to 60% of the total amount of CO of artificial origin. Carbon monoxide is a toxic gas, entering the human body reduces the ability of hemoglobin to transport and supply oxygen. The acute effects of carbon monoxide on humans include impaired visual perception at concentrations in the air of 10 ppm (parts per million); dizziness, headache, and fatigue (100 ppm); loss of consciousness (250 ppm); and fast death (1000 ppm and higher). The chronic effects of long-term carbon monoxide include disorders of the respiratory and cardiovascular systems, including arrhythmia and myocardial ischemia [22], [26].

III. Equipment and Measurement Methods

Measurement of the temperature and contents of gases in the air were carried out in open air conditions (outdoors) synchronously with the simultaneous use of methods:

- Measurement by gas analyser GANK 4;
- Taking air samples using an aspirator PU-4E and subsequent spectrophotometric determination;
- Measurements with Libelium Waspmote Gas Sensors PRO sensors installed on the drone.

The spectrophotometric analysis of solutions and solids is a physicochemical method based on the study of the absorption spectra in the ultraviolet (200–400 nm), visible (400–760 nm) and infrared (> 760 nm) spectral regions [27].

During spectrophotometric analysis a PE 5400 VI spectrophotometer was used. Its principle of operation is based on the study of the spectra of the visible range.

GANK-4 gas analyser is designed for automatic continuous or periodic monitoring of the concentration of harmful substances without sample processing in atmospheric air. Sequential measurements of the concentrations of harmful substances are carried out on interchangeable chemcassettes, the principle of which is based on the spectrophotometric method with opto-isolator and on built-in electrochemical sensors (electrochemical method of measurement) [28].

Libelium Waspmote Gas Sensors PRO is an electrochemical gas sensor system that can measure 17 types of gases (Table I). The kit also includes temperature, humidity, pressure, and dust sensors. The readings of the gas sensors are measured in units of ppm (parts per million). When expressing the concentration of substances, ppm is the molar concentration. The following formula is used for converting to mg / m^3:

$$Y = 0.0409XM, \tag{1}$$

where Y is the gas concentration, mg/m^3; X is sensor readings, ppm; M is the molecular weight.

TABLE I. LIBELIUM SENSOR PARAMETERS

Params	Range	Calibration
Temperature,°C	−40 to + 85°C	±1◦C (±0.5°C at 25°C)
Relative Humidity	0 to 100% RH	±3% RH (at 25°C,20–80% RH)
CO_2	0 to 5000 ppm	±50 ppm (0–2500 ppm) ±200 ppm (2500–5000 ppm)
CO for low concentrations	0 to 25 ppm	±0.1 ppm
SO_2 high accuracy	0 to 20 ppm	±0.1 ppm
NO for low concentrations	0 to 20 ppm	±0.2 ppm

The humidity sensor measures relative humidity (RH% — Relative Humidity) and characterizes the moisture content compared to the maximum amount of moisture that a substance can hold in a state of thermodynamic equilibrium.

Libelium sensors were installed on a DJI Matrice 100 quadrocopter. Characteristics of the quadrocopter: flight duration: up to 20 minutes; flight speed: 0–50 km/h; payload mass: up to 1 kg; max flight length: 12 km.

For processing and network data transfer from the sensors to the quadrocopter, Raspberry Pi 3 single-board computer was installed.

IV. PARAMETERS AND PROCESS OF MEASUREMENTS

Measurements were taken on 10.26.2018 from 1 pm to 3 pm local time (GMT + 3). Place of sampling: Russia, St. Petersburg, Mitrofanevskoe highway, 7, at a distance of one meter from the highway.

Weather conditions during sampling:

- Atmospheric pressure: 749 mm Hg;
- Air temperature: +4 °C;
- Wind speed: calm;
- Precipitation: no precipitation.

In the process of testing, the measurements were initially carried out at outside temperature (period 1, 0.00–10.53 minutes). Then, to simulate the field measurement conditions (for example, the restoration of the drone batteries), the UAV was moved inside (period 2, 10.53–25.83 minutes). Then it was taken outside again to continue synchronous measurements (period 3, time 26.12–41.87 minutes).

V. MEASUREMENT RESULTS

The results of measurements performed by standard methods are presented in Table II. The results of measuring the content of gases and air temperature using Libelium sensors are shown in Fig. 1.

Some of the results were compared with recommended concentrations of gases set by WHO. As a result, the measurements from gas analyser HANK 4 and photometric methods, it was established that at the time of the measurements at the place of their conduct the content of sulfur dioxide and carbon monoxide does not exceed the WHO recommendation. On the other hand, sensors installed on the drone (drone sensors) indicate that the recommended concentration of sulfur dioxide is exceeded in the second measurement period.

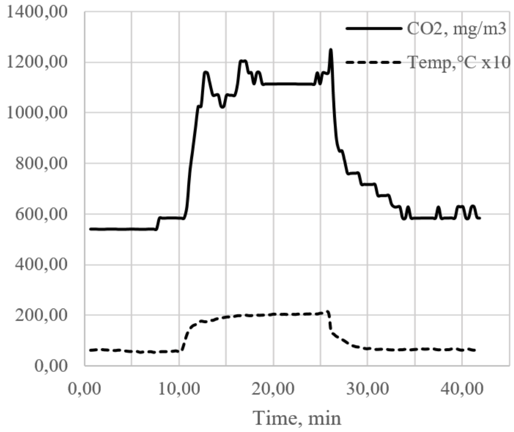
During the measurement period, corresponding to the highest temperature (average — 20.21 °C), drone sensors record the highest concentrations of the gases, with a decrease in temperature, the readings decrease for all test substances (Table II). At the same time, measurements taken during the period of heating and cooling of the drone sensors were not taken into account, only the data that were taken after stabilization of the sensor temperature was used.

In the middle of the test, drone sensors heated up as a result of moving the drone to a room from 5°C to 22°C, and then cooled after returning to the street from 22°C to 5°C. The measurement period in the room shows the results that differ from those on the street.

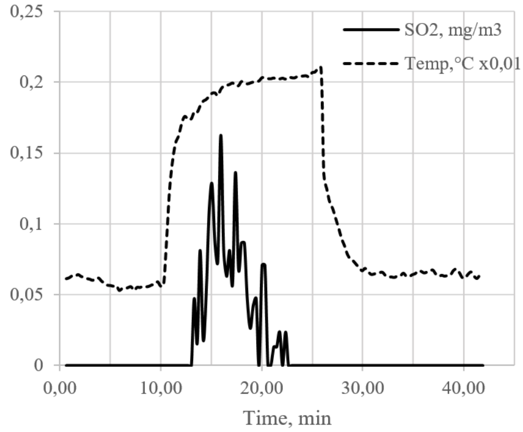
TABLE II. RESULTS OF SIMULTANEOUS MEASUREMENTS

Measurement method	T, °C	a.a.d.	RH, %	a.a.d.	CO2, mg/m3	a.a.d.	SO2, mg/m3	a.a.d.	CO, mg/m3	a.a.d.	NO, mg/m3	a.a.d.
WHO recommendation	—	—	—	—	—	—	0.020	—	7.000	—	—	—
GANK-4	4.00	—	—	—	**2301.3**	—	**0.003**	—	**1.776**	—	—	—
Photometry	—	—	—	—	—	—	**0.003**	—	—	—	0.442	0.061
Libelium, average	11.22	5.87	48.37	11.47	793.3	229.41	0.079	0.03	0.756	0.367	0.025	0.123
Period 1 (before heating)	5.86	0.33	58.92	0.62	541.1	0.27	0.000	0.00	0.241	0.057	0.000	0.000
Period 2 (heated sensor)	20.21	0.22	30.78	0.50	1130.8	24.84	0.052	0.03	1.065	0.069	0.012	0.004
Period 3 (cooled sensor)	6.63	0.34	57.00	1.30	638.3	51.71	0.000	0.00	0.596	0.447	0.106	0.101

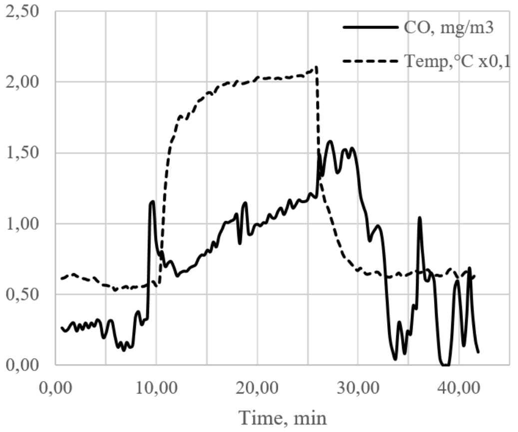
a.a.d — Average Absolute Deviation



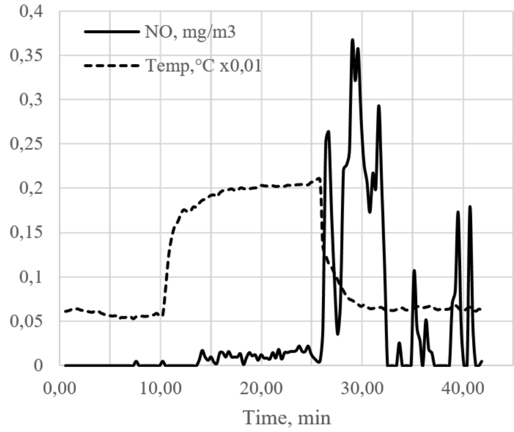
(a) CO_2



(b) SO_2



(c) CO



(d) NO

Fig. 1. Measurement results: the solid line shows concentration measurement in mg/m3, the dashed line shows temperature measurement in °C with scaling.

In the middle of the test, drone sensors heated up as a result of moving the drone to a room from 5°C to 22°C, and then cooled after returning to the street from 22°C to 5°C. The measurement period in the room shows the results that differ from those on the street.

The collected data was statistically processed for excluding 4 outliers from the observation. The exclusion was made using statistical criteria to detect outliers. The obtained concentration values are within the limits of the error of the method, and do not exceed the values indicated in bold.

VI. Air Temperature Effect on Sensor Readings

Considering the interrelation of gas concentration in the atmospheric air recorded by the drone sensors during the entire measurement period, a pronounced connection with meteorological parameters was established (Table III). Research conducted by pair correlations method (Spearman's rank correlation coefficient [29]).

The correlation analysis of the gases concentration in atmospheric air (measured by the drone sensors) with meteorological parameters showed the low dependence (Table IV). The analysis was performed for research periods before and after heating (with the exception of data before readings stabilization) at a temperature of sensors of 5°C to 6°C.

Table III. Correlation of Concentration and Meteorological Parameters

Meteorological param	CO_2	SO_2	CO	NO
T air, °C	0.97	0.56	0.52	−0.63
Relative Humidity, %	−0.98	−0.54	−0.57	0.61

Table IV. Dependence of Concentration on Temperature and Humidity

Period	T/ CO_2	T/ SO_2	T/ CO	T/ NO	RH/ CO_2	RH/ SO_2	RH/ CO	RH/ NO
Heated sensor	0.42	−0.07	0.92	0.29	−0.44	0.13	−0.90	−0.29
No heat. /cool.	0.55	—	0.40	0.43	−0.38	—	0.40	0.43

VII. Conclusion

In general, drone sensors record the content of carbon dioxide, carbon monoxide, sulfur dioxide and nitrogen oxide in atmospheric air at values close to the results obtained by standard methods (GANK 4 gas analyser, spectrophotometry), but have differences within less than orders of magnitude.

Recorded discrepancy between the results of measuring the concentration of carbon dioxide, carbon monoxide, sulfur dioxide and nitrogen oxide in atmospheric air using drone sensors and standard methods (GANK 4 gas analyser, photometry) measurements can be associated with heating of the drone and sensors and its subsequent cooling during testing. To clarify the issue of convergence of results, additional reconciliations are required in various temperature and humidity modes.

The effectiveness of environmental monitoring with the use of UAVs depends largely on the scientific background of its methodological and theoretical foundations, indicators of anthropogenic disturbances and changes in the biosphere, criteria for evaluating various factors. Solving these issues can significantly increase the level of significance of the results obtained during aerial surveys and measurements of various indicators. The monitoring tasks do not require high accuracy of positioning of the models of the earth's surface from the UAV, which allows focusing exclusively on the quality of the obtained data.

It is necessary to intensify research and development work on the creation of specialized complexes of environmental parameters (environmental conditions) measuring means adapted for use on unmanned aircraft.

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