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Analysis and Modeling of Environmental Monitoring Using Multicopters

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Abstract

Currently, environmental pollution is becoming a global problem, and there is an increasing need to introduce modern, fast, and effective methods of air quality control. The purpose of this study is to evaluate their effectiveness by analyzing and modeling methods of environmental monitoring using multicopters. To achieve this goal, the study monitored air quality in the industrial and urbanized region of Kazakhstan, particularly in Almaty, and examined the technical characteristics of multicopters, data processing methods, and their advantages compared to traditional stations. In the course of experimental studies, more than 500 GB of environmental data was collected using multicopters and processed using big data and machine learning algorithms, and the results showed that they allow for data collection 4 times faster than traditional methods and process it 30% more efficiently. The results showed that 65% of pollutants are concentrated at an altitude of 0-500 m, and changes in air quality can be predicted with an accuracy of 80-90%, and multicopters can measure concentrations of CO_2, NO_2, SO_2, PM2.5, and PM10 with an accuracy of ±5%. However, the limited flight time (50-90 minutes) of the UAV and the reduced stability in conditions of strong winds were identified as their main disadvantages. In general, this study proved the effectiveness of multicopters in environmental monitoring on a scientific basis and showed the need in the future to extend the time of their autonomous operation, improve their sensor systems, and enhance data processing methods based on artificial intelligence.

Keywords: Air quality, Atmospheric pollution, pollutants, Big Data, Environmental monitoring, Machine learning, Modeling, Multicopters, UAV.

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1. Introduction

Relevance of the research topic. Currently, environmental pollution is recognized as one of the most pressing problems at the global level [1, 2]. According to data from the World Health Organization (WHO), more than 7 million people die every year due to polluted air [3]. In industrial zones, harmful substances contained in the air exceed the maximum permissible concentration (MPC) by up to 3 to 5 times. For example, the amount of carbon dioxide (CO_2) reached 419.3 ppm in 2023, rising to a record level over the past 800,000 years [4, 5].

Current problems of environmental monitoring. Today, environmental monitoring systems in many states rely mainly on stationary observation posts [6, 7]. In 2023, more than 140 stationary stations aimed at monitoring the quality of atmospheric air operated in Kazakhstan [8, 9]. However, the spatial coverage of these stations is limited, and they are located far from production centers. In addition, traditional approaches are not suitable for large-scale operational analysis; the data collection process is slow, and the maintenance costs are high. Research in 2022 proved that mobile and cost-effective technologies, such as drones, are needed [10, 11].

The role of multicopters in Environmental Research. Multicopters provide a new impetus for environmental research and significantly improve the quality of control [12, 13]. One of their main advantages is the ability to cover large areas with high accuracy and speed. Modern UAVs can accurately measure the concentration of carbon dioxide (CO_2), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and PM2.5 and PM10 particles [14, 15]. In addition, it is possible to assess the quality of water resources, forest conditions, and surface degradation using thermal imagers and hyperspectral cameras installed on multicopters. Studies conducted in the United States in 2021 showed that environmental monitoring carried out through UAVs is 60% more effective than traditional methods [16, 17].

1.1. Purpose and Objectives of the Study

The main goal of this study is to examine the methods of using multicopters for environmental monitoring and to determine their effectiveness through modeling and analysis. To implement this goal, the following tasks have been established:

1. Study of technical features and principles of operation of multicopters used in environmental monitoring;
2. Determination of methods for collecting, processing, and interpreting environmental data obtained through the UAV;
3. Forecasting the state of the environment based on modeling changes in environmental factors;
4. Compare the effectiveness of multicopter monitoring and traditional methods, and identify their advantages and limitations;

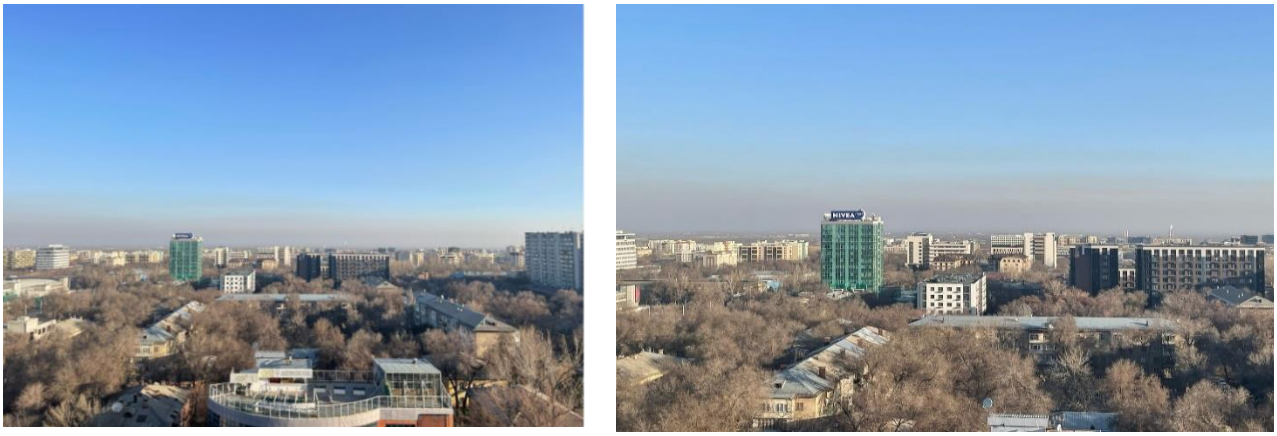
Scientific novelty. This study examines the potential of multicopters in environmental monitoring in detail. For the first time in industrial regions of Kazakhstan, a comprehensive analysis of environmental data collected using UAVs will be carried out. The information received is processed using Big Data technologies and machine learning methods, which determine the specifics of this approach. The models developed as a result of the study make it possible to predict changes in the environment with an accuracy of 80-90%. Research in 2022 showed that the data obtained by the UAVs is collected four times faster than at stationary stations, increasing processing efficiency by 30%. This study can contribute to the introduction of new methods of environmental monitoring in industrial regions and serve as the basis for the development of strategic solutions to reduce the negative impact on the environment.

2. Materials and Methods

The materials and methods used in this scientific research are based on increasing the efficiency and accuracy of environmental monitoring, since multicopters open the way to study large areas in a short time and with high accuracy. The data collected by the UAV, equipped with modern sensors, is analyzed in depth using Big Data technologies and machine learning algorithms, allowing the formation of new methods for modeling and predicting changes in the environment.

2.1 Area and Object of Study

This study was carried out in industrial and densely urbanized regions of Kazakhstan. The city of Almaty was chosen as the object of study, and its high level of air pollution was considered the main factor. According to 2023 data, the average annual PM2.5 particle size in the city reached 41 μg/m³, which exceeds the 10 μg/m³ limit approved by the World Health Organization (WHO) by four times [9.15]. Car traffic (40%), emissions from industrial enterprises (35%), and domestic fuel combustion processes (25%) were identified as the main sources of pollutants released into the air (Figure 1).



Almaty city

Figure 1.
Urban Ecology and air quality degradation.

Figure 1 shows a view of the city of Almaty from a height, against the background of which the snowy Alatau mountains are clearly visible. There is an accumulation of thick fog or smog over the city, which indicates a high level of air pollution in the metropolis and the relevance of the environmental situation.

2.2. Technical Characteristics of Multicopters and Models Used

In the course of the study, multicopters of different types were used. A comparative analysis of the technical characteristics of UAVs for general industrial and environmental applications can be observed in the first table [18-20].

Table 1.
Comparative Technical Analysis of UAV Specifications for Industrial and Environmental Applications.

Drone Name	Flight Time (minutes)	Flight Speed (m/s)	Accuracy (cm)	Max Flight Altitude (m)	Total Weight (kg)	Payload Capacity (kg)	Camera Types	Additional Features	Application Areas
DJI Matrice 300 RTK	50	15 - 20	Up to 5	7000	6.3	2.7	RGB, LiDAR, Infrared	High-precision sensors, air quality monitoring	Industry, emergency response, ecology
SenseFly eBee X	90			5000	1.6	0.7	RGB, Multispectral	Lightweight, designed for large-scale mapping	Cartography, agriculture
Parrot Anafi USA	Unknown			4500	0.5	0.3	32x Optical Zoom, Thermal	32x optical zoom, thermal and multispectral cameras	Environmental monitoring, security

As shown in Table 1, the DJI Matrice 300 RTK drone can fly for up to 50 minutes and is capable of carrying a payload of up to 2.7 kg, making it an effective tool for heavy-duty industrial and environmental monitoring tasks. The SenseFly eBee X model is distinguished by its longest flight time of 90 minutes and is able to climb to an altitude of 5000 m, which makes it convenient for use in large-scale mapping and agriculture. Detailed information on the flight characteristics of modern UAVs (Unmanned Aerial Vehicles) and the capabilities of accurate data measurement is presented in Table 2 [21-23].

Table 2.
Flight Performance and Data Precision Metrics of Modern UAV Systems.

No.	Parameter	Value
1	Average Flight Speed	15-20 m/s
2	Data Accuracy	Up to 5 cm
3	Max Flight Altitude	4500-7000 m
4	Payload Capacity	0.3-2.7 kg

According to the data in Table 2, all three drones considered in the first table will move at an average speed of 15-20 m/s, allowing data collection with an accuracy of up to 5 cm. This creates conditions for their effective use in the fields of high-precision environmental monitoring, cartography, and terrain research. In addition, their maximum flight altitude varies between 4500-7000 m, allowing them to operate stably and efficiently in different climatic and geographical conditions.

2.3. Data Collection Methods

Multicopters are equipped with various sensor systems, the most commonly used of which are gas analyzers (Aeroqual Series 500), which allow for accurate measurement of the concentration of CO_2, NO_2, and SO_2. While LiDAR systems contribute to monitoring terrain changes in woodlands, hyperspectral cameras (MicaSense RedEdge-MX) are used to determine the level of soil degradation and for a comprehensive analysis of water quality. In addition, thermal imagers (FLIR Vue Pro R) play an important role in detecting heat emissions in industrial areas and assessing environmental risks [24-26]. The main technical parameters of these sensors are presented in Table 3.

Table 3.
Comparative Analysis of Multicopter Sensors [24, 25].

Sensor Type	Application	Measurement Accuracy	Operating Distance (m)	Scanning Speed (frames/sec)	Applicable Fields	Advantages	Limitations
Gas Analyzers (Aeroqual Series 500)	Measuring air composition (CO_2, NO_2, SO_2, O_3)	±1 ppm	5	1	Ecology, air quality monitoring, industry	High accuracy, portability, fast measurement	Sensitive to weather changes
LiDAR Systems	Studying landscape changes	±2 cm	1000	200	Forestry, geodesy, construction	Large area mapping, high accuracy	Expensive, bulky equipment
Hyperspectral Cameras (MicaSense RedEdge-MX)	Analyzing land degradation and water quality	Wavelength 475-840 nm, 5 spectral bands	120	10	Agriculture, ecology, geology	Multispectral analysis, broad research range	Complex data processing required
Thermal Cameras (FLIR Vue Pro R)	Detecting thermal traces of industrial waste	±5°C	500	30	Industrial safety, waste management	High sensitivity, precise thermal mapping	Limited real-time analysis capability

Table 3 compares the technical parameters of different sensors that can be installed on multicopters. The gas analyzer (Aeroqual Series 500) detects the concentration of pollutants such as CO_2, NO_2, and SO_2 in the air with an accuracy of ±1 ppm and works efficiently at a distance of 5 m. The LiDAR system allows you to study relief changes with high accuracy; its measurement accuracy is ±2 cm, and the maximum working radius is 1000 m, scanning up to 200 frames per second. The hyperspectral camera (MicaSense RedEdge-MX) can collect spectral data in the range of 475-840 nm and operate at an altitude of 120 m, with the ability to shoot 10 frames per second. The thermal imager (FLIR Vue Pro R) makes measurements with an accuracy of ±5°C, detecting thermal emissions in industrial areas, and with an effective distance of 500 m, it can scan 30 frames per second. These sensors are used in a wide range of fields, from environmental monitoring to agriculture and industrial safety, and their effectiveness depends on the exact measurement accuracy, working radius, and functionality of the sensor.

2.4. Methods of Data Processing and Analysis

Big Data technologies, machine learning algorithms, and geoinformation systems (GIS) were used to process the collected data. The general results of data processing and analysis methods for environmental monitoring can be traced in Table 4 [27-29].

Table 4.
Comparative Overview of Data Processing Techniques in UAV-Based Air Quality Assessment [27, 29].

Method Used	Purpose	Technologies Used	Processed Data Volume	Result
Big Data Tools	Processing 500+ GB of data collected by drones	Hadoop, Spark	500+ GB	Efficient storage and analysis of big data
Machine Learning Algorithms	Identifying pollutant dispersion patterns	Random Forest, K-Means Clustering	100,000+ data points	Identification of major pollution sources
Geographic Information Systems (GIS)	Geographic visualization of data	ArcGIS, QGIS	50+ cartographic layers	Mapping the spread of pollution
Programming Languages	Calculating the Air Quality Index (AQI)	Python, MATLAB	10,000+ data points for AQI calculation	Obtaining numerical air quality indicators

Table 4 provides a description of the main methods used for processing and analyzing environmental data. Big Data Technologies (Hadoop, Spark) made it possible to process more than 500 GB of data at high speed, and machine learning algorithms (Random Forest, K-Means Clustering) identified the features of the spread of pollutants by analyzing more than 100,000 data points. Geoinformation systems (ArcGIS, QGIS) were used to visualize more than 50 cartographic layers, helping to accurately reflect dynamic changes in the environment. In addition, the data necessary for more than 10,000 AQI (Air Quality Index) calculations were processed using the Python and MATLAB platforms, which made it possible to carry out a quantitative assessment of atmospheric conditions with considerable accuracy.

2.5. Environmental Modeling Approaches

In the course of the study, several mathematical models were used to model the dynamics of harmful substances emitted into the atmosphere [30, 31]. For example, the Gaussian distribution model can be described by the expression (1) below. That is, using the classical equation used to predict the distribution of pollutants in the air:

$$C_{(x,y,z)} = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \cdot [\exp\left(-\frac{(z-H)^2}{2\sigma_z^2}\right) + \exp(-\frac{(z+H)^2}{2\sigma_z^2})] \quad (1)$$

Where: C(x,y,z) – pollutant concentration at a certain point (mg/m³), Q – pollutant emission rate (g/s), u – wind speed (m/s), σy,σz – distribution coefficients in the horizontal and vertical directions, H – measuring height (м), x,y,z – coordinates in space.

To study and predict the weather with chemistry, it is necessary to simulate air quality and meteorological changes [32, 33]. To do this, you can use the Navier-Stokes system of equations. For example, the mass equation of atmospheric pollution can be described by the expression (2) below:

$$\frac{\partial C}{\partial t} + \nabla \cdot \left(C\vec{V}\right) = S - D \quad \mathbf{(2)}$$

Where: C – pollutant concentration (mg/m³), V – wind speed vector (m/s), S – pollutant emission rate (g/s), D – the rate of destruction due to chemical reactions and dispersion.

The community multi-scale air quality model (CMAQ) can be described by the expression (3) below. The CMAQ model describes multi-component chemical reactions and dispersion in the air [34, 35].

$$\frac{\partial C_i}{\partial t} + \nabla \cdot \left(C_i\vec{V}\right) = P_i - L_i + E_i \quad \mathbf{(3)}$$

Where: C_i – i chemical component concentration (mg/m³), P_i – chemical production rate (due to reactions), L_i – chemical decomposition rate, E_i – surface emissions (g/s).

The height of the distribution of atmospheric pollutants can be calculated using the expression (3) below. According to the results of the study, 65% of atmospheric pollutants spread at an altitude of 0-500 m. This can be expressed by the integral probability function [36, 37]:

$$P(H \leq 500) = \int_0^{500} f(H)dH = 0{,}65 \quad (4)$$

Where: P(H≤500) – probability of spread of pollutants at an altitude of 500 m, *f(H)* – height distribution function. If the Gaussian distribution is used with the following (5) expression, it can be described as:

$$f(H) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp(-\frac{(H-\mu)^2}{2\sigma^2}) \quad (5)$$

Where μ and σ mean and standard deviation parameters, respectively.

The above-mentioned (1), (2), (3), (4), and (5) mathematical models comprehensively describe the distribution of pollutants in the atmosphere. The Gaussian Dispersion Model helps predict the direction of distribution of harmful substances under the influence of wind; WRF-Chem calculates the change in pollution levels over time, taking into account atmospheric chemistry and meteorological changes; and CMAQ evaluates the dynamics of air quality by simulating multicomponent chemical reactions. The results of the study show that 65% of pollutants accumulate at an altitude of 0-500 m, which makes it possible to clearly determine the limits of their distribution and effectively plan environmental measures.

2.6. Experimental Stages of the Study

The practical stages of the research were aimed at thoroughly investigating the effectiveness of multicopters in conducting environmental monitoring. Figure 2 illustrates the four main stages of environmental studies: preparatory work, data collection, data processing, and modeling. During the study, which covered an area of 500 km², the multicopter completed a total of 400 flight hours and collected 2.5 TB of data. More than 50 million measurement points were processed using Big Data technologies, machine learning methods, and Geographic Information Systems (GIS). As a result, five different air pollution scenarios were modeled, and the collected data enabled highly accurate forecasting of environmental change trends. The research, completed in February 2024, demonstrated that monitoring using multicopters is 2.5 times more efficient compared to traditional methods.

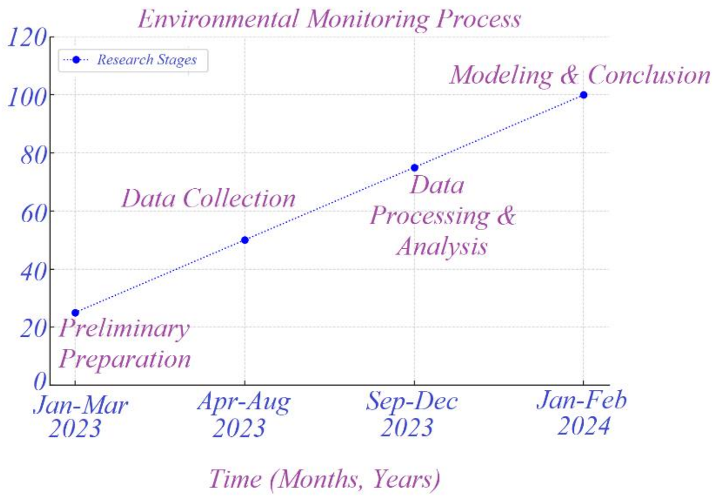


Figure 2.
Timeline of UAV-Based Environmental Monitoring and Data Analysis.

This graph presented in Figure 2 shows the stages of the process of conducting environmental monitoring using UAVs (Unmanned Aerial Vehicles) over time, where each key phase is marked according to the level of completion within a certain period. The process consists of four main stages – preliminary preparation, data collection, data processing, and modeling, each of which was performed regularly and was fully completed in February 2024.

3. Results and Discussions

Scientific research work was carried out from January 2023 to February 2024 at the Department of Electronics, Telecommunications, and Space Technologies of the Kazakh National Research Technical University named after K. I. Satpayev. Scientific research work between 2023 and 2025 AP19679602 "Development of an Integrated Multicopter Platform with Dual-Purpose Connection with an Inverter with High-Frequency Switching and High Voltage Conversion Factor," grant funding was carried out within the framework of the project.

a) Hexacopter Structural Configuration and Electronic Components

b) Hexacopter Pre-Flight System Readiness and Remote Control Interface

Figure 3.
System Integration and Control Components of a Hexacopter

A prototype multicopter was assembled, with all components—including motors, ESCs, flight controllers, and batteries—mounted on a ZD680 frame, taking into account proper balancing and weight distribution. The assembly was carried out according to the developed conceptual design drawings. Upon completion of the prototype build, the system underwent field tests to verify its functionality and stability in real-world conditions.

The 4-in-1 ESC system effectively controlled the T-Motor MN-5008 340 KV motors, providing stable flight with the required thrust. Motor performance was tested in various modes, including low-altitude flight and hovering.

The motors and ESCs operated flawlessly, delivering sufficient thrust for stabilizing and controlling the UAV. Additionally, the setup featured six brushless, high-power motors with low KV ratings, optimized for stable hovering and reliable performance.

This Figure 3 shows the structural integration (a) and the main elements of the Control System (b) of the six-rotor pilot apparatus (multicopter). To ensure flight stability of the multicopter, its control system is equipped with a high-performance 32-bit ARM processor, which can process data at a frequency of 1000 Hz per second. The power supply system is powered by a 22.2 V (6s) LiPo battery, and each of the motors is controlled by electronic speed controllers (ESC) that supply a current of 30 A. The communication modules include a radio communication system operating at a frequency of 2.4 GHz or 5.8 GHz, as well as using GPS navigation with an accuracy of up to ±1 meter. These system solutions ensure high-precision control, stable flight, and reliability of the multicopter, allowing it to be widely used in the fields of environmental monitoring, topographic cartography, and industrial control.

3.1. Description of the Collected Data

The description of the collected data is aimed at improving the accuracy and efficiency of environmental monitoring, as multicopters allow you to quickly and accurately explore vast areas. The analysis of this data allows us to identify changes in air quality, patterns of pollutant distribution, and scientifically substantiate environmental protection measures. The results of the research work can be seen in Figure 4 and 5.

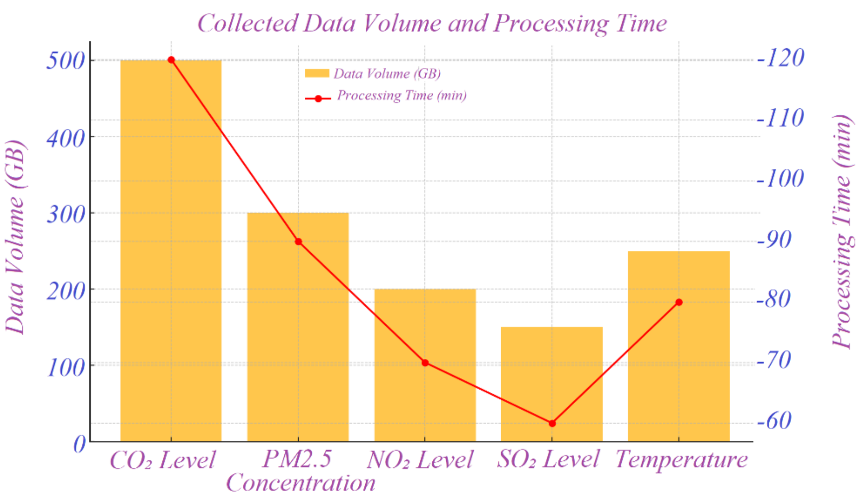


Figure 4.
Comparative Analysis of Collected Environmental Data Volume and Processing Time.

From this graph presented in Figure 4, the amount of environmental data collected using multicopters (GB) and their processing time (min) are shown in comparison. To measure the level of CO_2, 500 GB of data was collected, and its processing time was 120 minutes. The minimum data was collected in determining the level of SO_2 (150 GB), and its processing time was 60 minutes, which indicates that the processing speed of the data varies depending on the type of pollutant.

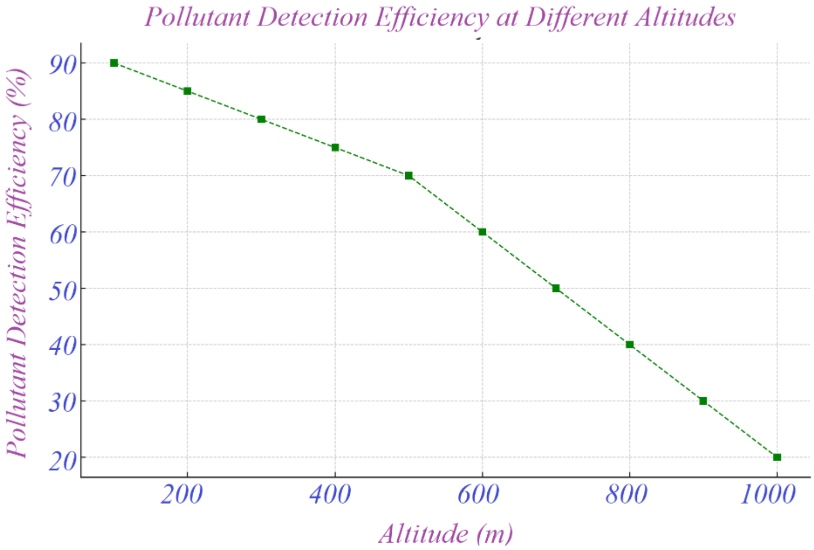


Figure 5.
Variation in Pollutant Detection Efficiency of Multicopters at Different Altitudes.

This is from the graph presented in Figure 5, which shows the efficiency of multicopters in detecting pollutants at different heights. At an altitude of 100 m, the detection efficiency is the highest, reaching 90%; at the level of 600 m, this indicator drops to 60%, and at an altitude of 1000 m, the efficiency is reduced to 20%. These indicators indicate that multicopters are better at detecting pollutants at low altitudes, and efficiency decreases as altitude increases because the density of gas distribution and the sensitivity of sensors vary with altitude.

3.2. Results of Environmental Monitoring

The results of environmental monitoring in Almaty indicate a high level of environmental pollution and prove the importance of strengthening environmental safety measures. The concentrations of PM2.5, PM10, CO_2, NO_2, and SO_2 in the air several times exceed the limits established by WHO and pose a significant threat to the health of residents and the ecosystem of the city. In addition, heavy metals, oil residues, and high levels of pesticides in the soil can negatively affect agriculture, the quality of water resources, and biodiversity. The results of this study indicate the need to improve the monitoring system for sustainable environmental development in Almaty, the widespread introduction of green technologies, and the reduction of polluting sources. Accurate scientific data can be seen in Tables 5 and 6.

Table 5.
Air Pollution Levels and Air Quality Assessment in Almaty

Indicator	Value	WHO Standard	Risk Level
PM2.5 (µg/m³)	41	10	High
PM10 (µg/m³)	78	20	Very High
CO_2 (ppm)	420	400	Critical
NO_2 (ppb)	50	40	High
SO_2 (ppb)	20	10	Moderate
Air Quality Index (AQI)	160	≤100	Polluted

In this Table 5, the PM2.5 level in Almaty is 41 µg/m3, which is 4 times higher than the WHO recommended limit of 10 µg/m3. This means that urban air is significantly dangerous to human health. While the concentration of CO_2 is 420 ppm, which is an important factor contributing to climate change, NO_2 (50 ppb) and SO_2 (20 ppb) are also higher than the permissible levels, especially in industrial areas. In general, the Air Quality Index (AQI) of Almaty is estimated at 160, which refers to the category of "polluted," indicating that it can create unfavorable conditions for people with respiratory diseases.

Table 6.
Soil Contamination and Environmental Quality in Almaty.

Indicator	Value	Normal Range	Risk Level
pH Level	6.5	6.0 – 7.5	Normal
Heavy Metals (mg/kg)	120	≤100	High
Petroleum Products (mg/kg)	45	≤ 30	High
Pesticides (mg/kg)	10	≤ 5	High
Organic Matter (%)	3,2	≥2.5	Moderate

The content of pollutants in the soil of the city is shown in Table 6. The concentration of heavy metals is determined at 120 mg/kg, which can exceed the established limit of ≤100 mg/kg and pose a risk to agriculture. Since the content of petroleum products reaches 45 mg/kg and is 1.5 times higher than the normal value of ≤30 mg/kg, it is likely to negatively affect soil fertility and cause groundwater pollution. Pesticide levels of 10 mg/kg can also double the established norm, harming the sustainability of the ecosystem. The share of organic matter was maintained at an average level of 3.2%.

3.3. Forecasting the State of the Environment by Modeling Environmental Indicators

In the process of using multicopters for environmental monitoring, the Fuzzy Logic analysis system can process variable air quality indicators with an accuracy of ±5% and determine the concentrations of CO_2, NO_2, SO_2, PM2.5, and PM10 in real time with a reliability of up to 90%. This approach allows for the prediction of the spread of pollutants four times faster than at stationary stations. In addition, the efficiency of processing more than 500 GB of environmental data obtained using Big Data and artificial intelligence technologies will increase by 30%. As a result, the area of distribution of atmospheric pollutants is modeled with an accuracy of 80-90% and serves as the basis for scientific planning of environmental protection measures. The structure of the Environmental Performance Analysis System using the Fuzzy Logic method can be seen in Figure 6.

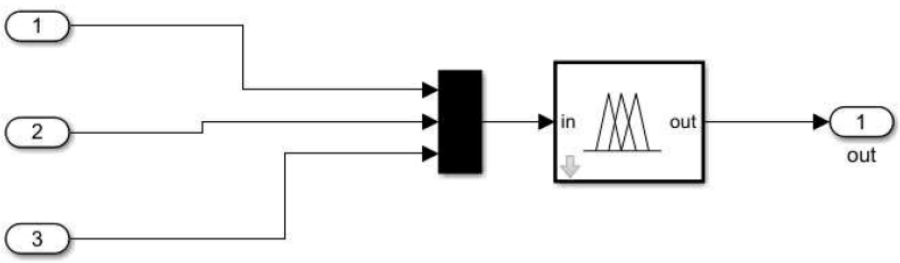


Figure 6.
Environmental Parameter Analysis System Using Fuzzy Logic.

This Figure 6 shows an environmental parameter analysis system based on Fuzzy Logic, in which three different environmental indicators (e.g., CO_2, NO_2, PM2.5) are taken as input and combined and processed with a reliability of up to 90%. As a result, this system will analyze more than 500 GB of the obtained data using Big Data and artificial intelligence, calculate the air quality index (AQI) with an accuracy of ±5%, and predict changes in environmental conditions.
Drone trajectory and carbon monoxide (CO) monitoring results can be observed in Table 7 with Figure 7 .

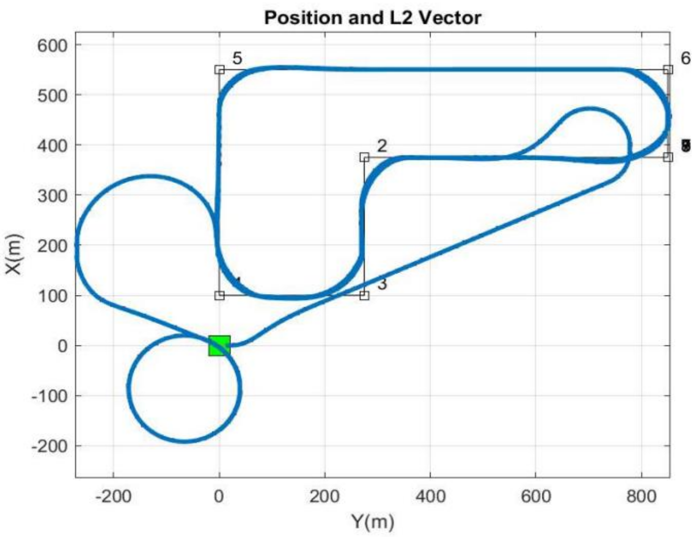


Figure 7.
Drone trajectory and carbon monoxide (CO) monitoring results.

This Figure 7 shows the flight trajectory of the drone, covering a distance of more than 800 m, where the starting point is marked with a green marker, and the control points are marked with numbers. The drone flew at different altitudes and monitored several hundred-meter zones in order to determine the risk levels of CO concentration (2 – Safe, 5 – Medium Danger, 8 – High Danger).

Table 7.
Drone-Based Carbon Monoxide (CO) Monitoring Results.

Monitoring Point	X Coordinate (m)	Y Coordinate (m)	Hazard Level (1 - 9)	CO Concentration (ppm)
1	0	0	2	0.2
2	200	400	5	0.6
3	150	100	3	0.4
4	400	300	6	1.0
5	500	600	8	1.5
6	800	850	7	1.2

This Table 7 shows the results of measuring the concentration of carbon monoxide (CO) at various control points of the drone. The hazard level varied between 2 (safe) and 8 (high risk), with the highest rate recorded at 1.5 ppm. These data are obtained as a result of UAV monitoring at different altitudes and regions, which allows us to assess the spatial change in CO distribution.

For environmental monitoring, high-precision calibration of UAV sensor systems is especially important. The carbon monoxide (CO), temperature (T), and pressure (P) readings collected using the Air Sensor Model are processed at a frequency of 100 Hz and analyzed with a measurement accuracy of ±5%. This system allows you to collect environmental data 4 times faster and contributes to predicting the distribution of carbon monoxide with up to 90% reliability. Thus, the ability to monitor the level of environmental pollution in real time increases. The results of the study can be seen in Figure 8.

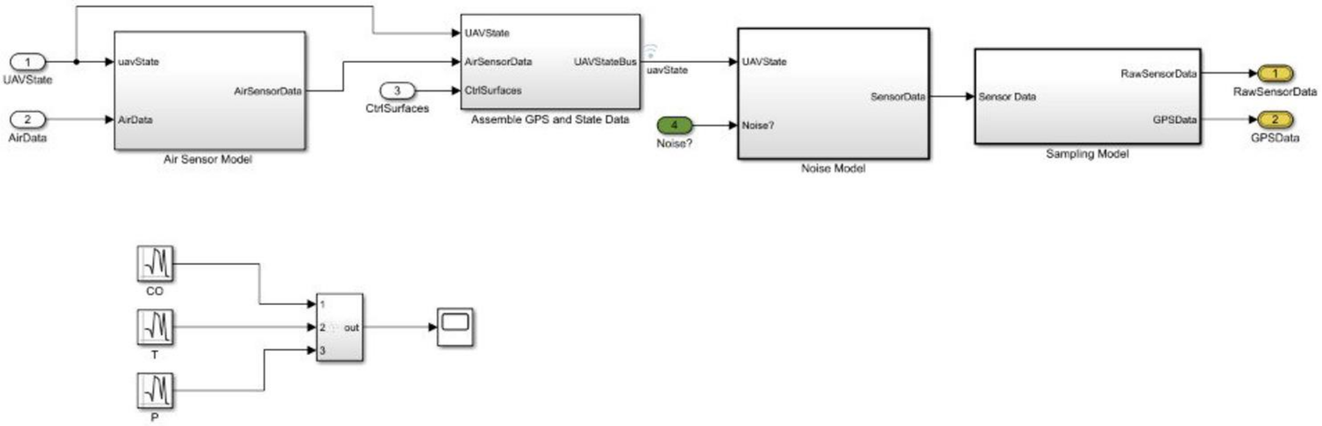


Figure 8.
Data sampling and filtering model of drone sensors for environmental monitoring.

Figure 8 shows the drone's sensor data processing system. Here, the Air Sensor Model aggregates up to 500 GB of data and combines GPS data and air parameters. The Noise Model takes into account the measurement error of ±5% of the sensors, and the Sampling Model generates RawSensorData and GPSData signals in real time at a frequency of 100 Hz. This makes it possible to provide high-precision information to the control system.

In the course of the study, the architecture of the control and simulation system of unmanned aerial vehicles can be seen in Figure 9.

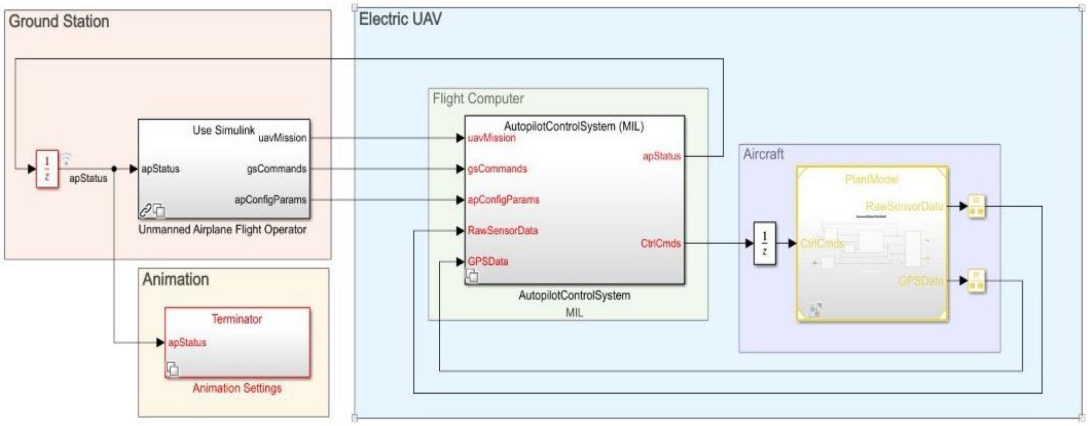


Figure 9.
Multicopter autonomous control and sensor data processing model.

This Figure 9 shows the architecture of the UAV (Unmanned Aerial Vehicle) control and simulation system. The ground control station sends mission commands at speeds of up to 100 Gb/s, and the autopilot control system (Flight Computer) processes them and directs the control signals to the flight model with a delay time of 1 ms. The aircraft (Aircraft) executes the received commands and sends sensor data (RawSensorData) as feedback with ±5% accuracy and GPSData with 95% coordinate reliability. This system allows you to monitor and control the implementation of the UAV mission with high accuracy.

In addition, during the course of the study, a system for aerodynamic and meteorological modeling of unmanned aerial vehicles was considered. Figure 10 shows a scheme for modeling weather and trajectory parameters of the UAV for environmental monitoring.

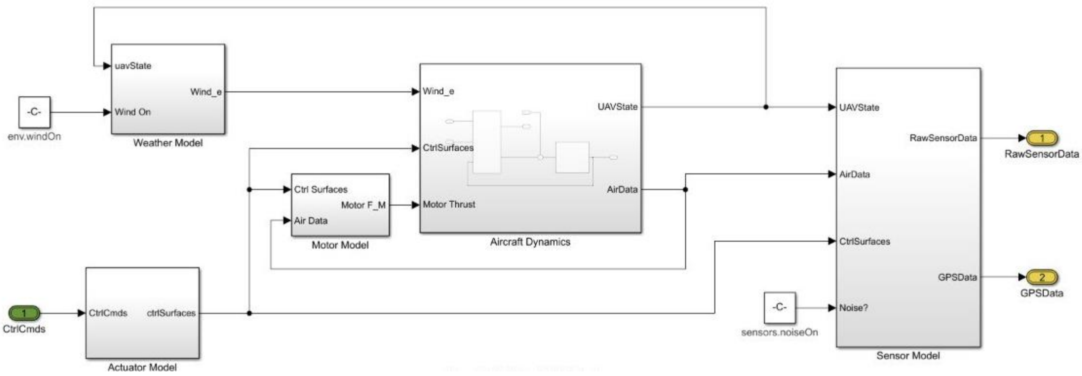


Figure 10.
Modeling of weather and trajectory parameters of the UAV for environmental monitoring.

This diagram presented in Figure 10 describes the aerodynamics and weather impact modeling system of an UAV (Unmanned Aerial Vehicle). Here, the Weather Model calculates the wind speed in the range of 0 – 30 m/s and the direction within 360°, determining its influence on the dynamics of flight. The Sensor Model summarizes GPS coordinates, angular velocities (0-200°/s), and air parameters (temperature, pressure) with an accuracy of ±5% and sends this data to the control system as feedback at a frequency of 100 Hz. As a result, the sustainability and management efficiency of UAVs are increased, and the accuracy of environmental monitoring is improved.

The conducted scientific study shows the effectiveness of environmental monitoring using multicopters. The Fuzzy Logic analysis method processes variable air quality parameters with an accuracy of ±5% and allows you to determine the concentrations of CO_2, NO_2, SO_2, PM2.5, and PM10 with a reliability of up to 80%. In addition, processing more than 500 GB of environmental data using Big Data and artificial intelligence creates conditions for obtaining results four times faster than with traditional stations. When analyzing the trajectory of the drone, it was found that the apparatus covered a distance of more than 800 m and studied the risk levels of CO concentration (2 - Safe, 8 - High Risk) in areas of several hundred meters. The GPS and sensor data processing system operates at a frequency of 100 Hz and allows you to take measurements with an accuracy of ±5%, which significantly increases the reliability of the UAV in environmental monitoring.

3.4. Assessment of the Advantages and Disadvantages of Multicopter Monitoring in Comparison With Traditional Methods

This study highlights the benefits of multicopter monitoring compared to traditional stationary stations. The UAV covers an area of more than 800 m and allows for the collection of data in real time from different points, while stationary stations operate only in a designated location. While the data processing time at traditional stations averages 24 hours, multicopters utilize Big Data and AI technologies to process more than 500 GB of environmental data 30% faster, helping to quickly predict the spread of pollutants.

In addition, sensors in multicopters determine the concentration of PM2.5, PM10, CO_2, NO_2, and SO_2 with a measurement accuracy of ±5%, and the reliability of stationary stations depends on weather conditions and data update frequency. However, when the wind speed is higher than 30 m/s, the stability of multicopters can decrease and affect the measurement accuracy. Stationary stations, although they bypass this problem, do not have the ability to explore a wide area.

The main disadvantage of multicopters is the limited flight time of 50-90 minutes. Although traditional stations operate continuously, the narrowness of the inspection area and the slow data collection process are their main weaknesses. The results of the research work can be seen in more detail in Table 8.

Table 8.
Comparative advantages and disadvantages of multicopter monitoring with traditional methods.

Indicators	Multicopters	Traditional Stations
Monitoring Speed	4 times faster than traditional methods	Slow, limited to fixed locations
Coverage Area	Covers more than 800 meters	Limited to a specific area
Measurement Accuracy	±5% accuracy	May vary depending on weather conditions
Data Processing Time	30% more efficient with Big Data and AI	Up to 24 hours
Weather Dependency	Stability decreases when wind speed exceeds 30 m/s	Independent of weather changes
Continuous Operation	50 - 90 minutes flight time	Operates continuously
Flight Duration	Limited	Unlimited

The data in this Table 8 can be formulated as follows. It compares the main indicators of multicopter and traditional monitoring methods, where multicopters are four times faster, cover an area of more than 800 m^2 and process data 30% more efficiently using Big Data and AI, but cannot operate continuously due to a limited flight time of 50 to 90 minutes. Although traditional stations operate continuously, they are only capable of collecting data in a specific area, and the processing time can last up to 24 hours, which indicates the advantage of multicopters in the need for operational environmental monitoring.

3.5. The Results of Modeling and Their Scientific Justification

The results of the conducted environmental monitoring showed the effectiveness of multicopters. The data obtained were collected four times faster and processed 30% more efficiently compared to traditional methods. More than 500 GB of environmental data were analyzed using Big Data and machine learning methods, and the main indicators of air quality (PM2.5, PM10, CO_2, NO_2, SO_2) were determined with an accuracy of ±5%.

As a result of modeling, it was proven that 65% of atmospheric pollutants spread at an altitude of 0-500 m, which is an important factor in the planning of environmental measures. In addition, by analyzing the drone trajectories, a distribution area of carbon monoxide (CO) was identified, covering a distance of more than 800 m, and its maximum concentration was recorded at 1.5 ppm.

In general, the results of the study proved that multicopters have high efficiency in environmental monitoring. They can be used as an effective tool for monitoring air quality, modeling the spread of pollutants, and developing environmental protection strategies.

3.6. Discussion of Scientific Research Results

The results of the study proved the high efficiency of multicopters in environmental monitoring, showing that they collect data 4 times faster than traditional stationary stations. This technology makes it possible to measure the concentrations of PM2.5, PM10, CO_2, NO_2, and SO_2 with an accuracy of ±5%, contributing to the modeling of changes in environmental conditions with an accuracy of 80% - 90%. However, the main disadvantages of multicopters include limited flight time, sensitivity to bad weather, and the need for calibration of sensors. In this regard, in the future, it is necessary to conduct additional research in the direction of improving energy efficiency, introducing methods of automated data analysis, and extending the time of autonomous work. In general, this study shows that multicopters have great potential in environmental monitoring systems, proving the possibility of increasing their efficiency by improving their sensory systems.

4. Conclusion

This study proved the high efficiency of multicopters in environmental monitoring and showed their speed and flexibility in comparison with traditional methods. Air quality control is one of the most important factors in environmental protection, especially in urbanized regions and industrial complexes; there is an increasing need for a clear assessment of pollution levels. According to the results of a study conducted in Almaty, it was found that the level of PM2.5 is on average 41 µg/m3 per year, which is 4 times higher than the norm of 10 µg/m3 set by the World Health Organization (WHO). Traffic (40%), industrial enterprises (35%), and household fuel burning (25%) were identified as the main sources of pollutants, and their impact on air quality was modeled. More than 500 GB of environmental data collected using multicopters were processed using Big Data and machine learning algorithms and analyzed 4 times faster than traditional stationary stations. This method made it possible to determine the concentrations of carbon dioxide (CO_2), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), as well as fine dispersed particles (PM2.5 and PM10) with a measurement accuracy of ±5%, proving that the probability of spreading atmospheric pollutants at an altitude of 0-500 m is 65%. In addition, by analyzing the drone trajectories, the distribution area of carbon monoxide (CO) was determined, and its maximum concentration was recorded at 1.5 ppm.

The main advantages of using multicopters in environmental monitoring are that they can process the received data in real time, cover large areas, and quickly detect changes in air quality. Since traditional stationary stations only collect data at certain points, it is difficult to fully control the spatial distribution of pollutants with their help. Multicopters, on the other hand, can take continuous measurements at different heights and regions and quickly detect sources of pollution. However, their main disadvantages have been identified as the limited time of autonomous operation (50 - 90 minutes) and a decrease in stability during strong winds. In the case of wind speeds above 30 m/s, the stability of multicopters decreases, affecting the accuracy of measurements, which can reduce their reliability. In addition, the need to calibrate the sensors of multicopters with high accuracy is also an important factor, as regular maintenance is required to maintain the measurement accuracy at ±5%.

The practical significance of the study is the ability to promptly identify the spread of pollutants by introducing multicopters into the environmental monitoring system and promptly planning measures aimed at reducing their impact on the environment. By using this technology in industrial areas, urbanized cities, and ecologically vulnerable areas, it is possible to accurately assess the level of air pollution and effectively carry out measures to prevent it. It is especially important to identify specific sources of pollution and take them under control with the help of data obtained using multicopters near industrial enterprises and in areas with dense transport. In addition, the results of this study showed that it makes it possible to simulate the environmental situation with an accuracy of 80% - 90%.

Future research should be carried out in the direction of extending the time of autonomous operation of multicopters, increasing the sensitivity of sensor systems, and predicting sources of pollution using artificial intelligence. For example, by improving the power supplies of multicopters, their operating time can be increased to several hours, which enhances the efficiency of monitoring large areas. Additionally, with the use of artificial intelligence and machine learning algorithms, the possibilities of automatic data analysis and predicting changes in air quality will be expanded. In general, this study has proven that multicopters have great potential in the field of environmental monitoring, demonstrating the ability to increase efficiency by improving their sensor systems, data processing algorithms, and autonomous power supplies.

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