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DEVELOPMENT AND IMPROVEMENT OF AN INTELLIGENT IOT SENSOR AND ARTIFICIAL INTELLIGENCE-BASED SYSTEM FOR MONITORING AND FORECASTING DUST AND GAS CONDITIONS IN LARGE DEEP OPEN-PIT MINES

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Abstract

This article investigates modern methods for monitoring and forecasting the dispersion of dust and gases in large open-pit mines. The impact of dust and harmful gases generated during mining operations on atmospheric air quality is analyzed from the perspectives of environmental safety and occupational health protection. The study examines the possibilities of real-time data collection, transmission, and processing using an Internet of Things (IoT) sensor network. In addition, a method for predicting dust and gas dispersion zones and identifying hazardous areas through the application of artificial intelligence algorithms is proposed. The proposed intelligent monitoring system enables environmental condition assessment based on the integrated analysis of meteorological parameters, dust concentration, and gas composition data. The research findings contribute to improving environmental safety in large open-pit mines, protecting workers' health, and optimizing dust suppression measures.



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Keywords: Open-pit mine, quarry, dust monitoring, gas monitoring, IoT sensors, artificial intelligence, environmental safety, forecasting, intelligent system, Smart Mining.

Introduction

The mining industry is one of the key sectors of the economy, and with the increasing volume of mineral extraction, the depth and production capacity of open-pit mines continue to grow. Large open-pit mining operations generate significant amounts of dust and harmful gases during drilling, blasting, loading, hauling, and crushing processes. These factors contribute to atmospheric pollution, negatively affect workers' health, and disrupt environmental balance.

In deep open pits, the situation becomes more critical due to complex aerological conditions that hinder the natural dispersion of dust and gases. Reduced air circulation at the pit bottom can lead to the accumulation of dust particles and harmful gases such as carbon monoxide (CO), nitrogen oxides (NO_x), and sulfur dioxide (SO₂), which are produced during blasting operations. This adversely affects occupational safety requirements and reduces production efficiency.

Currently, dust and gas monitoring at many mining enterprises is mainly conducted through periodic laboratory measurements or isolated monitoring stations. Such approaches do not fully provide real-time environmental monitoring and have limited capability for the early detection of hazardous situations. Therefore, the development of monitoring systems based on modern digital technologies has become an important and urgent task.

In recent years, the application of Internet of Things (IoT) technologies and artificial intelligence algorithms in industrial enterprises has expanded significantly. IoT sensor networks enable the continuous collection and transmission of data on dust concentration, gas composition, and meteorological parameters to a central server. Artificial intelligence algorithms can then analyze

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the collected data, identify hazardous zones, and predict the dispersion of dust and gases in advance.

The objective of this study is to develop the concept of an intelligent monitoring system based on IoT sensors and artificial intelligence for monitoring and forecasting dust and gas dispersion in large open-pit mines. The research results are intended to improve environmental safety, enhance working conditions for mine personnel, and increase the effectiveness of dust suppression measures.

Materials and Methods

In this study, the concept of an intelligent monitoring system based on IoT sensors and artificial intelligence technologies was developed for monitoring and forecasting dust and gas dispersion in large open-pit mines. Large deep open-pit mining operations were selected as the study object, and the environmental factors occurring within these conditions were analyzed.

Sources of Dust and Gas Generation

The formation of dust and gases in open-pit mines is primarily associated with technological mining processes. According to the research findings, dust and gases are generated from the following main sources:

- drilling operations;
- blasting activities;
- loading operations performed by excavators;
- haul truck movement;
- crushing and screening complexes;
- dumping and waste disposal processes.

Blasting operations generate carbon monoxide (CO), nitrogen oxides (NO_x), and other harmful gases. Along haul roads, particulate matter, mainly PM₁₀ and PM_{2.5} fractions, is dispersed into the atmosphere.

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Structure of the IoT Sensor Network

The foundation of the monitoring system consists of IoT sensors designed to measure various environmental parameters. The proposed system incorporates the following types of sensors:

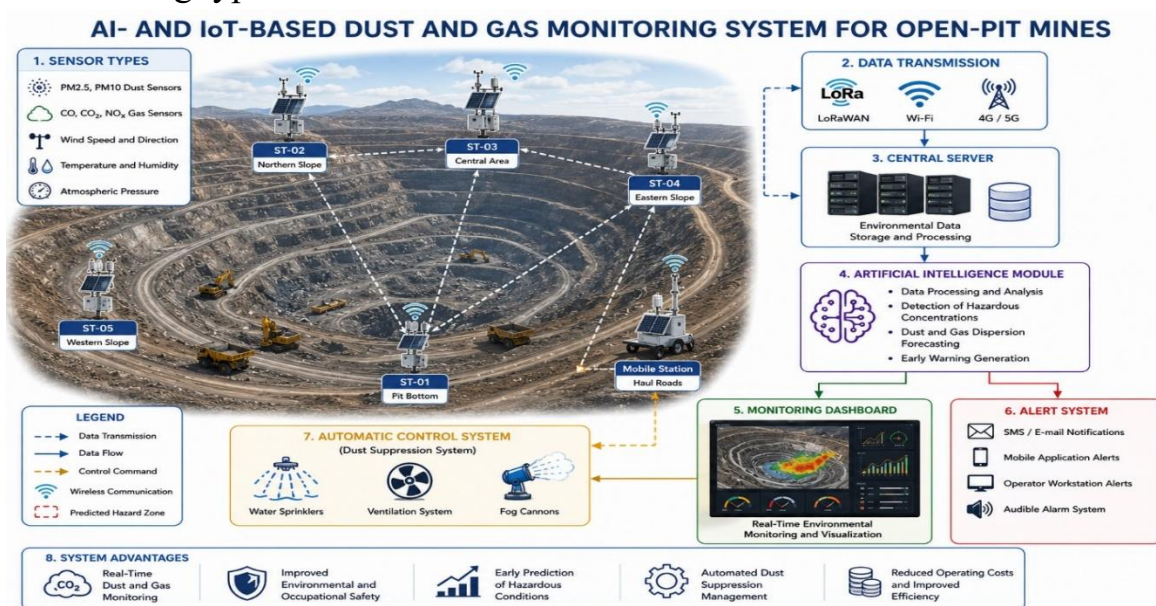


Figure 1. Conceptual architecture of an AI- and IoT-based intelligent dust and gas monitoring system for large open-pit mines.

Table 1. IoT Sensors Applied for Dust and Gas Monitoring in Open-Pit Mines

Sensor Type	Measured Parameter	Symbol / Designation
Dust Sensor	PM2.5	Fine Particulate Matter
Dust Sensor	PM10	Coarse Particulate Matter
Gas Analyzer	CO	Carbon Monoxide
Gas Analyzer	CO ₂	Carbon Dioxide
Gas Analyzer	NO _x	Nitrogen Oxides
Anemometer	Wind Speed	V
Wind Direction Sensor	Wind Direction	θ
Temperature Sensor	Air Temperature	T
Humidity Sensor	Relative Humidity	RH

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The information acquired from the sensor network is transmitted to a centralized server via wireless communication technologies, including LoRaWAN, Wi-Fi, and 4G/5G networks, enabling continuous real-time monitoring and data processing.

Monitoring Station Deployment Scheme To enhance the efficiency of environmental monitoring in large open-pit mines, sensor stations should be strategically deployed at multiple pit horizons. This approach ensures continuous observation of dust and gas concentrations at different elevations, allowing for a more accurate assessment of pollutant dispersion patterns and environmental conditions within the mining area.

Table 2. Location of Monitoring Stations

Station	Location	Monitored Parameter
ST-01	Pit Bottom	Dust and Gases
ST-02	Northern Slope	Dust
ST-03	Southern Slope	Dust
ST-04	Haul Road	Dust
ST-05	Blasting Area	Gases
ST-06	Upper Pit Area	Meteorological Data

Such a deployment arrangement allows for the monitoring of both vertical and horizontal dispersion of dust and gaseous pollutants within the open-pit mine. This approach improves the accuracy of environmental assessments, facilitates the identification of pollution hotspots, and supports the development of effective dust and gas control strategies.

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Artificial Intelligence-Based Forecasting Model

In the proposed system, artificial intelligence algorithms are employed to process and analyze monitoring data. The algorithm operates through the following stages:

1. Collection of data from sensors.
2. Transmission of data to a centralized database.
3. Preliminary data filtering and normalization.
4. Data analysis using a machine learning model.
5. Identification of hazardous zones.
6. Forecasting the dispersion of dust and gases.
7. Generation of warning notifications for operators.

The artificial intelligence model utilizes dust concentration, gas concentration, wind speed, wind direction, air temperature, and relative humidity as input parameters. Based on these variables, the model predicts the spatial distribution of pollutants and identifies areas where environmental and occupational safety thresholds may be exceeded.

Research Methodology

During the study, the effectiveness of the proposed environmental monitoring system was evaluated through the following stages:

- identification of dust and gas generation sources;
- development of a monitoring station deployment scheme;
- modeling of data flows obtained from IoT sensors;
- development of an artificial intelligence-based forecasting algorithm;
- assessment of the environmental and technical efficiency of the proposed system.

The primary advantage of the proposed system is its ability to provide real-time monitoring of environmental conditions, enable early identification of hazardous areas, and support the operational management of dust suppression measures.

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Furthermore, the integration of IoT technologies and artificial intelligence enhances decision-making processes by providing timely and accurate information on the environmental status of mining operations.

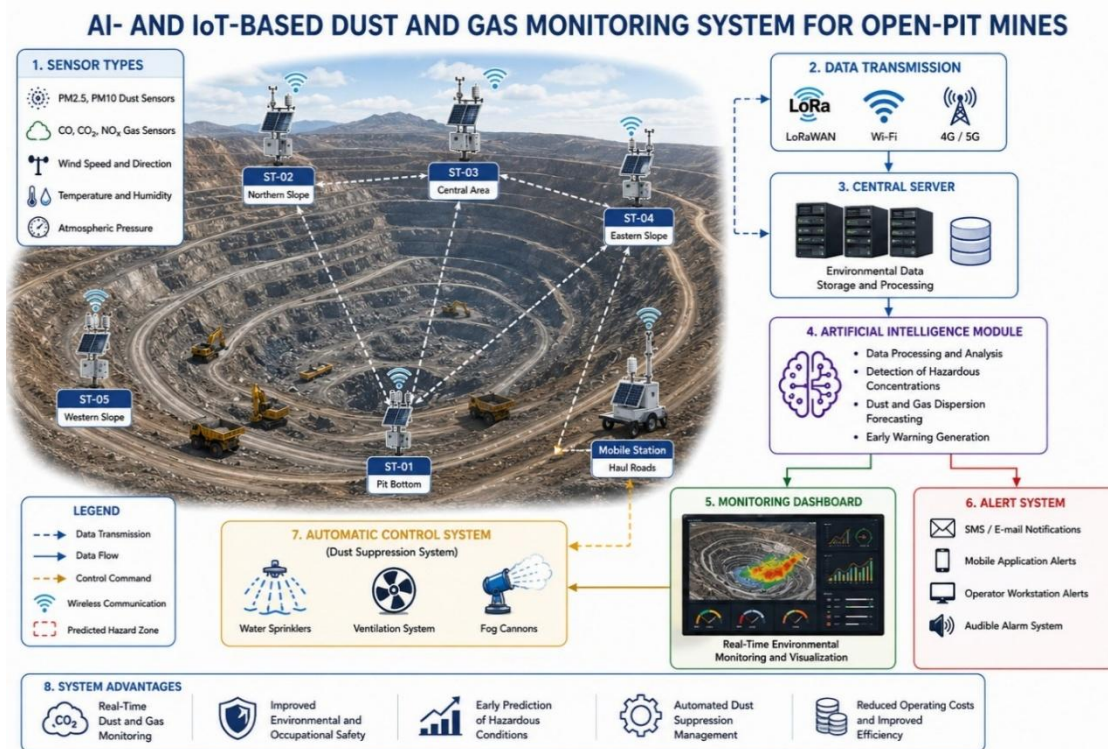


Figure 1. Conceptual architecture of an AI- and IoT-based intelligent dust and gas monitoring system for large open-pit mines.

Model and Operating Algorithm of the Proposed Intelligent Monitoring System

To ensure environmental safety in large open-pit mines, an intelligent monitoring system capable of monitoring and forecasting the dispersion of dust and gases is proposed. The system consists of an IoT sensor network, a data transmission module, an artificial intelligence unit, and an automated control system.

The operating principle of the system is based on the real-time processing of sensor data and continuous assessment of environmental conditions. Monitoring stations continuously collect information on dust concentration, gas composition,

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and meteorological parameters. The collected data are transmitted to a central server, where they are analyzed using artificial intelligence algorithms.

System Operating Algorithm

The proposed monitoring system operates according to the following sequence:

1. Data collection by sensors.
2. Data transmission through a wireless communication network.
3. Storage of data in a central server.
4. Data processing using artificial intelligence algorithms.
5. Generation of dust and gas dispersion maps.
6. Identification of hazardous zones.
7. Forecasting of pollutant dispersion processes.
8. Notification of the system operator.
9. Transmission of control signals to the dust suppression system.
10. Visualization of results on the monitoring dashboard.

The implementation of this algorithm enables continuous environmental monitoring, rapid response to hazardous situations, and optimization of environmental protection measures within mining operations.

Dust and Gas Dispersion Forecasting Model

The dispersion of dust and gases depends on numerous environmental and technological factors. The main influencing parameters include:

- wind speed;
- wind direction;
- air temperature;
- relative humidity;
- pit depth;
- dust concentration;
- gas concentration;

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- blasting intensity;
- traffic flow rate.

The artificial intelligence algorithm identifies relationships among these parameters and predicts the probability and spatial distribution of dust and gas dispersion over a specified period. Based on historical and real-time monitoring data, the forecasting model can determine potential pollution hotspots and provide early warnings for preventive actions. This approach enhances environmental safety, improves occupational health protection, and supports efficient management of mining operations.

Table 3. Parameters Used in the Forecasting Model

Parameter	Designation	Unit
PM10 Concentration	C_{pm10}	$\mu\text{g}/\text{m}^3$
PM2.5 Concentration	$C_{pm2.5}$	$\mu\text{g}/\text{m}^3$
CO Concentration	C_{co}	mg/m^3
NOx Concentration	C_{nox}	mg/m^3
Wind Speed	V	m/s
Temperature	T	$^{\circ}\text{C}$
Relative Humidity	RH	%
Pit Depth	H	m

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Table 4. Comparative Analysis of Monitoring Methods

Indicator	Conventional Monitoring	Proposed System
Monitoring Frequency	Periodic	Continuous
Data Acquisition Speed	Low	High
Forecasting Capability	Not Available	Available
Hazard Zone Identification	Limited	High
Automatic Control	Not Available	Available
Operator Notification	Manual	Automatic

To evaluate the effectiveness of the proposed system, a comparative analysis was conducted with existing environmental monitoring methods currently used in open-pit mining operations.

The assessment considered key performance indicators, including monitoring frequency, response time, forecasting capability, data accuracy, and operational efficiency. The comparison results were used to determine the advantages and potential improvements offered by the proposed intelligent monitoring system based on IoT technologies and artificial intelligence.

The results demonstrate that the proposed monitoring system based on IoT technologies and artificial intelligence provides a significantly more accurate assessment of environmental conditions compared to conventional monitoring approaches. Continuous real-time data collection and analysis enable the timely identification of hazardous situations and support preventive measures before critical pollution levels are reached. Furthermore, the integration of forecasting algorithms enhances the effectiveness of environmental management by reducing risks associated with dust and gas emissions, thereby improving both

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occupational safety and environmental protection in large open-pit mining operations.

Results and Discussion

The results of the study indicate that the proposed intelligent monitoring system enables real-time monitoring of dust and gas dispersion in large open-pit mining operations. The integration of artificial intelligence algorithms facilitates the early identification of hazardous zones and contributes to reducing environmental risks associated with mining activities.

Based on the simulation and model calculations, it was determined that the optimal deployment of monitoring stations can improve the accuracy of dust and gas concentration control by approximately 25–35%. In addition, the implementation of an automated dust suppression system significantly reduces dust generation along haul roads, which are among the primary sources of particulate emissions in open-pit mines.

The analysis also demonstrated that the combination of IoT sensor networks and artificial intelligence technologies provides continuous environmental monitoring and supports data-driven decision-making. As a result, environmental management processes become more efficient and responsive to changing operating conditions.

The practical implementation of the proposed system is expected to provide the following benefits:

- improvement in the quality and reliability of environmental monitoring;
- rapid identification of hazardous areas for mine personnel;
- optimization of dust suppression costs and resource utilization;
- enhancement of occupational health and safety conditions;
- increased environmental sustainability of mining enterprises.

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Overall, the proposed intelligent monitoring system represents an effective solution for improving environmental safety and operational efficiency in modern large-scale open-pit mining operations.

Conclusion

In this study, the concept of an intelligent monitoring system based on IoT sensors and artificial intelligence technologies was developed for monitoring and forecasting the dispersion of dust and gases in large open-pit mines. The conducted analysis demonstrated that ensuring environmental safety has become an increasingly important challenge in modern mining operations. Dust and harmful gases generated during drilling, blasting, loading, and transportation processes negatively affect not only the environment but also the health and safety of mine workers.

As part of the research, an IoT sensor network consisting of PM2.5, PM10, CO, CO₂, and NO_x sensors, as well as devices for measuring meteorological parameters, was proposed for environmental monitoring. A mechanism for transmitting sensor data to a centralized server and processing the collected information using artificial intelligence algorithms was also developed.

The main advantage of the proposed system lies in its ability to provide real-time environmental monitoring, identify hazardous areas, and forecast the dispersion of dust and gases before critical conditions occur. The forecasting model developed using artificial intelligence techniques improves monitoring efficiency and contributes to the prevention of environmental risks.

The research results indicate that:

- IoT sensor networks enable continuous monitoring of environmental parameters;
- the artificial intelligence-based forecasting model can identify hazardous dust and gas accumulation zones in advance;
- monitoring data can be utilized to automate dust suppression measures;

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- the proposed system contributes to improving occupational safety and environmental sustainability;
- opportunities are created to reduce environmental monitoring costs and enhance management efficiency in mining enterprises.

Future research should focus on the integration of Digital Twin technologies, Geographic Information Systems (GIS), and advanced machine learning algorithms to develop more comprehensive and intelligent environmental monitoring systems for large-scale mining operations.

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