IJE TRANSACTIONS B: Applications Vol. 39, No. 08, (August 2026) 1802-1811

International Journal of Engineering

Journal Homepage: www.ije.ir

Modeling of Dust Content Control System for Industrial Enterprises in the Mineral Resource Sector

D. V. Gloukhov*, D. V. Suchkov, A. P. Altukhova, D. R. Smirnov

Empress Catherine II Saint-Petersburg Mining University, Saint-Petersburg, Russia

PAPER INFO

Paper history:
Received 01 July 2025
Received in revised form 20 August 2025
Accepted 09 September 2025

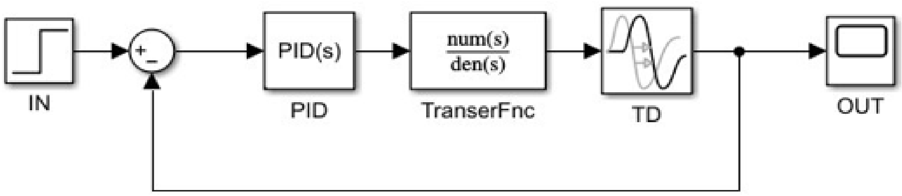
Keywords:
Conceptual Scheme of Automation
Dust Suppression Process Control
Economic Efficiency of Enterprises
Software and Hardware Complex
Dust Suppression

ABSTRACT

The article investigates the problem of creating an effective dust suppression system. The authors, employing methods of systems analysis, mathematical modeling, decision theory, mine time-based measurements of dust concentration changes during ventilation, and numerical modeling of dust concentration changes, developed an automated dust suppression system for an apatite-nepheline deposit. The system architecture was designed, encompassing stages from receiving and processing dust concentration data to generating a response through activating suppression with intensity regulation depending on conditions. A prototype system was created and tested. The core of the system is custom-developed code that automatically regulates dust concentration in the mine using a PID controller and transmits data to a server, enabling real-time system monitoring and control. The annual economic benefit from implementing the system at the study site amounted to 2,170,701 rubles. Beyond the achieved economic benefit, the system will improve working conditions, enhance safety, and reduce harmful environmental impact.

doi: *10.5829/ije.2026.39.08b.02*

Graphical Abstract



NOMENCLATURE

$R(s)$	Controller transfer function	S_{equip}	Equipment maintenance and repair costs (RUB/year)
k_{per}	Proportional gain coefficient (mg/m^3)	O_{cst}	Other costs (RUB/year)
T_s	Integral time constant (s)	K	Initial cost of equipment (tooling) (RUB)
T_D	Derivative time constant (s)	H_a	Monthly depreciation rate for equipment (tooling) (%/month)
s	Complex variable (Laplace operator) (rad/s)	T_{tst}	Useful life (months)
C_T	Operating costs (RUB/year)	E_{Ceff}	Economic effect (RUB/year)
M	Cost of raw materials basic and auxiliary materials (RUB/year)	C_{st0}	Costs before measures implementation (RUB/year)
Z_{mp}	Salary of main production workers (RUB/year)	C_{st1}	Costs after the measures implementation (RUB/year)
A_{exp}	Depreciation expense on the equipment (RUB/year)	T_{pb}	Payback period (years)
S_{tc}	Tooling costs (RUB/year)	Cst_{res}	Cost of research (RUB)
S_{en}	Process energy costs, (RUB/year)		

*Corresponding Author Email: dmitrygloukhov@yandex.ru (D. V. Gloukhov)

Please cite this article as: Gloukhov DV, Suchkov DV, Altukhova AP, Smirnov DR. Modeling of Dust Content Control System for Industrial Enterprises in the Mineral Resource Sector. International Journal of Engineering, Transactions B: Applications. 2026;39(08):1802-11.

1. INTRODUCTION

1. 1. Relevance of the Study If we consider in detail the developments published in the last few years in such areas as geotechnology and geomechanics, it becomes evident that they increasingly emphasize the integrated development of underground space (1). This field of research substantially considers the issue of design and construction of underground facilities of the production complex. Construction geotechnology is an integral part of the broader field of mining sciences, with one of its key priorities being mining construction and the post-mining utilization of abandoned underground spaces (2). Rubber technical products (RTPs) are widespread in almost all spheres of human activity. However, the needs of the domestic market in RTP are met by Russian enterprises in volumes of about 45-47%. The relevance of the study is determined by the need to improve the competitiveness (3) of domestic factories by optimizing production, introducing new technologies, taking into account possible legal risks, in particular, the issues of intellectual property rights protection. Such optimization can be achieved, on the one hand, by saving resources, and, on the other hand, by introducing innovative chemical compounds, improving the characteristics of equipment, automation of production lines (1).

Modern scientific research suggests using methods of system analysis for this purpose (4, 5). However, employing such methods necessitates a thorough analysis of the object under study and the development of domain-specific models (6). Therefore, one of the most important tasks in improving the stability of technological processes is the development of a unified approach for identifying input, output, and resultant factors (7).

Mining enterprises are a high-tech (8-10) and multifunctional industrial complex comprising various interconnected units. The main operations are carried out at a different depth (11).

In conditions of intensive operations at enterprises involved in the extraction and processing of materials, the problem of dust generation becomes particularly urgent. Dust has a negative impact on workers' health, reduces product and equipment quality, and contributes to environmental degradation (12-14).

In the context of phosphate rock mining (15), dust generated during extraction and processing poses significant challenges (16). The nature of the mined materials, combined with mechanical processing, leads to the release of fine particulate matter into the air (17). This dust not only impairs visibility but can also cause respiratory issues for workers, necessitating strict organizational, regulatory, and legal measures to ensure occupational safety and health. Furthermore, dust accumulation on equipment can impair functionality and increase maintenance costs, thereby reducing overall operational efficiency (18).

The unique geological and environmental conditions of apatite-nepheline deposits further exacerbate dust-related issues (19, 20). Variations in mineral composition and moisture content can influence dust generation rates, making it essential to develop tailored dust control strategies specific to these mining operations (21). Implementing effective monitoring systems to assess dust levels in real time can facilitate the timely activation of suppression measures, ensuring compliance with both worker safety and environmental standards (22, 23). By addressing these challenges through innovative technologies, mining enterprises can mitigate the adverse effects of dust and promote a safer and healthier workplace.

Enterprises are equipped with powerful ventilation systems that ensure the supply of fresh air and the removal of harmful gases and dust. Ventilation is an integral part of the production cycle. Dust suppression plays a critical role in ensuring safety during various mining operations (24, 25). Over the years, various dust suppression systems and methods have been developed to mitigate the harmful effects of dust on human health, equipment, and the environment. These systems can be broadly categorized into physical and chemical methods, each with specific applications and limitations (26, 27).

Physical dust suppression methods rely on mechanical or aerodynamic principles. Water-based systems—such as sprays, misting, and fogging (28, 29)—are commonly used in open-pit mining and at material transfer points. They capture dust particles using water droplets but are less effective under arid or freezing conditions, and excessive use can lead to slurry formation (30, 31). Mechanical collectors (e.g., cyclones and filters) are employed in enclosed environments and are effective for larger particles but less efficient for fine dust (32). Electrostatic systems use electric fields to charge dust particles, promoting their adhesion or coalescence; electrostatic precipitators are highly effective but relatively costly (33).

Chemical methods involve dust-binding agents, such as calcium or magnesium chloride, which are often applied on haul roads (34, 35). Foam-based systems encapsulate dust particles (36). These methods are particularly useful in water-scarce environments but require frequent reapplication and are less effective for very fine dust.

Modern mining operations increasingly utilize automated systems incorporating real-time monitoring, adaptive control, and data analytics. Dust sensors trigger suppression mechanisms only when necessary, adjusting intensity based on current conditions. Such systems are often integrated with other mining equipment to enable comprehensive dust control. Automatic dust suppression systems are therefore an essential component of modern industrial facilities, playing a key role in maintaining safe dust levels and ensuring worker safety (37).

Currently, global attention is increasingly focused on the transition of mining enterprises toward sustainable development—a shift driven by their critical role in supporting all sectors of the economy (38, 39). In recent years, the global economy has experienced rising prices for many natural resources. It is evident that natural resources are being depleted, and their availability for human consumption is becoming increasingly limited (40). Given the high market demands for industrial products, there is a growing need to develop more innovative and competitive production methods (41, 42), which will ultimately lead to higher-quality products (43).

1. 2. Purpose of the Study A significant role in research aimed at improving the economic efficiency of enterprises (44, 45) is played by the development of modern (46, 47) technological solutions for the operation of existing facilities (48, 49). Central to the development of such solutions is the implementation of measures to reduce the costs associated with the repair and maintenance of mine workings. Equally important are strategies related to asset amortization and process control (50, 51).

1. 3. Problem Statement Relying on earlier studies, it can be noted that modern automatic control systems have several problems related directly to control objects that have spatial coordinates, and there are also difficulties with their analysis and investigation. For example, to realize the monitoring of changes in the stability of an underground structure in the process of its operation, it is necessary to use instrumental measurement of displacements. The above can be realized by studying the deformation processes of the rock mass around the excavation and considering the operation of the excavation support (52). In other words, it is necessary to consider each criterion in detail and apply modern mathematical apparatus, specifically methods of distributed parameter systems. Thus, it is necessary to *develop* a more modern methodology for monitoring and evaluation of the technical condition of different facilities, which is based on ensuring a stable production mode and operational regulation (53, 54).

1. 4. Prerequisites of the Research Problem Methods of systems with distributed parameters have proven themselves in solving various practical problems (55-57). There is a need to develop a system for controlling the temperature field in the tubing during production. As a result, the final cost of field operation and development was reduced (58, 59).

Having analyzed the literature sources, we have identified a significant number of parameters necessary for analysis. The above-mentioned methods were applied in the works of such researchers as Mal'tsev et al. (60), Boronko and Novozhilov (61), Pershin et al. (62), Kalashnikov et al. (63) and Shchirova et al. (64).

Thus, the main task aimed at improving the economic efficiency of enterprises is the development of methods and models (65-67) for assessing their technical condition.

2. MATERIALS AND METHODS

To solve the assigned tasks, a comprehensive research method was applied, including the analysis of global experience in assessing the technical condition of mines and underground structures; methods of system analysis; methods of mathematical modeling; methods of mathematical statistics; methods of control theory; methods of decision theory; mine-based time-lapse observations of dust concentration changes during ventilation; and numerical modeling of dust concentration changes.

The integration of advanced dust suppression methods with automated control systems represents a significant advancement in dust management for the mining and processing industries. By leveraging modern technologies, these systems improve worker safety, reduce environmental impact, and enhance operational efficiency (68).

Automated dust suppression systems consist of several interrelated components that provide an integrated approach to dust control and suppression (69):

1. Controllers and sensors
2. Programmable Logic Controllers (PLC)
3. Visualization and HMI (Human Machine Interface) systems
4. Communication systems and data transmission networks
5. Data analysis and reporting systems

Controllers and sensors are the "eyes" of the system. They provide real-time monitoring of dust levels, measuring dust concentration in the air and transmitting the data to the controllers for analysis.

The transfer function was obtained using the System Identification Toolbox in MATLAB. The identification process was initiated after importing the input and output data into it. The software component constructs the transient response and determines the system's transfer function. An automatic dust suppression system model was developed in Simulink™ R2021b (Figure 1).

This model consists of the transfer function of dust concentration in the mine (the control parameter). The model consists of the following main blocks:

- block "IN" - setting the parameter of dust concentration in the workplace;
- PID-Controller required to implement the steady state of the controlled object;

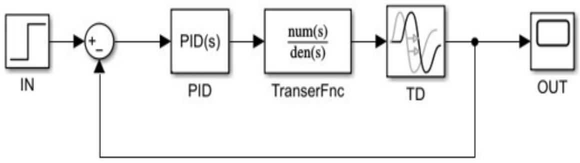


Figure 1. The Simulink™-based algorithmic implementation of the controlled system structure with regulatory components

- "Dust Concentration Transfer Function" is the dust concentration control object of the workplace, which is implemented by the Transfer Function block;
- TD (Transport Delay) - delay of the object;
- Scope block - for displaying the transient process of the system.

In the context of designing a dust suppression system with automatic regulation of dust concentration, the use of adaptive PID controllers enables effective handling of changing operating conditions. A representative example of this methodology is an adaptive PID controller demonstrating stability and rapid adaptation to non-stationary disturbances without requiring precise knowledge of the system model. Properly tuned parameters of an adaptive PID controller ensure reliable suppression of unwanted oscillations and efficient regulation under conditions of uncertainty and noise (70).

3. RESULT AND DISCUSSION

3. 1. The Control System Identification

The use of an automatic dust suppression system in an apatite-nepheline mine is justified by several factors (71, 72) that make it an ideal solution for this task. This system effectively reduces dust levels, which is important for worker safety and health.

In order to address the given problem, in-situ mine observations were conducted, including measurements of dust concentration and the rate of dust generation. The sampling depth is 50 samples, and the sampling period is 1 s. The input signal (Figure 2) and output values (Figure 3) of the system are presented below.

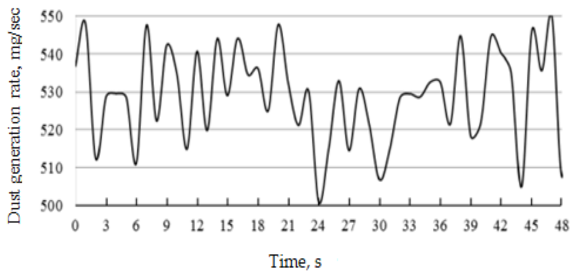


Figure 2. Input experimental data

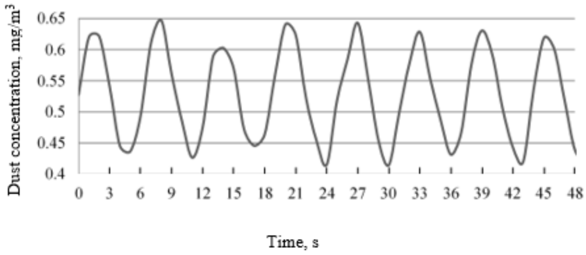


Figure 3. Output experimental data

3. 2. The Mathematical Model Construction

We use the built-in PID Tuner functionality of MATLAB™, which enables automatic tuning of PID controller coefficients to achieve high system performance metrics. The expression for the PID controller after coefficient tuning is given by Equation 1:

$$R(s) = k_{per} + \frac{1}{T_s} + T_D s = 0.3865 + \frac{5.272}{s} + 1.8903 \qquad (1)$$

Figure 4 presents the transient response under high dust concentrations (5 mg/m³ and 4 mg/m³). The results confirm the PID controller's efficacy in industrial dust suppression, achieving both dynamic disturbance rejection and steady-state setpoint tracking.

3. 3. Prototyping of the Model within Framework of Mining Production

The system is initialized when the mining equipment is started or when the shift begins. Figure 5 shows the scheme of interconnection of program components.

The algorithm for processing the state is as follows:

1. Dust concentration controllers measure the level of dust in the air in certain enterprise areas.
2. The measured data are transmitted to the central system controller via wired or wireless communication.
3. The central controller analyzes the received data, calculates the average concentration, determines the dynamics of changes.
4. The system compares the measured dust concentration values with pre-set threshold values that signal unsafe dust levels.

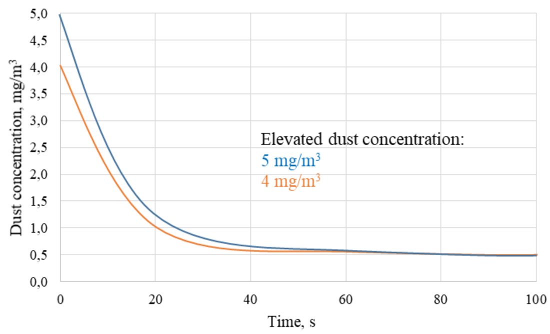


Figure 4. Transient response with PID controller at elevated dust concentration of 5 mg/m^3 and 4 mg/m^3

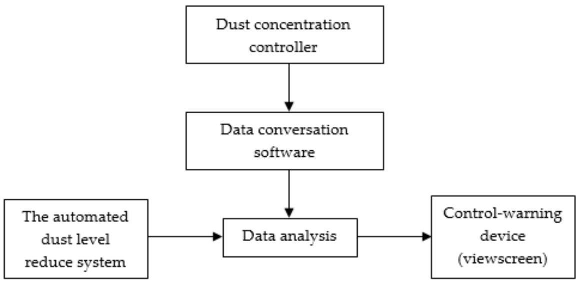


Figure 5. Functional scheme of components interrelation

5. If the dust concentration exceeds the set threshold values, the system determines the need for intervention to reduce the dust level.
6. The system activates appropriate dust suppression mechanisms in areas where thresholds have been detected to be exceeded.
7. The system monitors changes in dust concentration after activation of the suppression system to assess the effectiveness of the measures taken.
8. Dust concentration data are regularly updated, and the cycle of collection, analysis and response is repeated in real time.
9. If a malfunction or fault is detected, the system activates safety measures, including shutting down the dust suppression supply.

The main characteristic of this process is the dust concentration values in the air and on the surface of the equipment. Warning alarms are triggered when dust concentration values in the air are exceeded.

The list and characteristics of signals through which information about the facility is transmitted comply with *GOST 24.104-2023 «Common system of standards for automated control systems. Automated control systems. General requirements»*.

Let us consider the database of dust concentration control in the air implemented at the apatite-nepheline mine. The calculation algorithm is designed for automatic control of dust concentration in the enterprise using a PID controller and sending data to the server. At the beginning of the operation, the user is prompted to enter the machine name, controller name, and their identifiers. Then, the PID controller parameters and the setpoint of dust concentration are set. Variables for the integral component and the previous error are initialized.

The basic function "main" sends the data about machine and controller to the server for registration using the appropriate API URLs. After successful registration, a cycle starts in which random values of dust concentration are generated. These values are used as input for the PID controller, which calculates the correction signal (pid_output).

The correction signal is applied to the measured dust concentration value to obtain the corrected_value. If the corrected value exceeds the dust concentration setpoint, the system is stopped and water irrigation is initiated. If the value is within acceptable limits, it is sent to the server and the operation status is displayed.

Thus, the code automatically adjusts the dust concentration in the mine using a PID controller and sends the data to the server, providing real-time monitoring and control of the system.

3. 4. Economic Efficiency Assessment

In the process of analyzing the current state of dust suppression processes at the enterprise, the required number of personnel was identified to ensure proper monitoring and management of the system. The number and structure of personnel were determined based on the volume and complexity of work required for effective dust suppression.

Based on the volume and complexity of work, an analysis was conducted of the average statistical indicators of the number of personnel in enterprise service companies. Consider that specialists work on a standard five-day working week, then, considering holidays and vacations, the average number of working days is 248 days per year (Table 1).

Due to automation of dust suppression process, the workload of occupational safety specialist was reduced, and his working hours were reduced to 0.5 of the standard 40-hour working per week.

Automation has also reduced the workload of the system operator and mining engineer, as process data now comes from sensors rather than being collected manually. As a result, the company no longer needs to

TABLE 1. Salary fund before system operation

Stages and content of performed works	Performer	Labor intensity of works (man-hours)	Working days	Tariff rate (RUB/hour)	Basic salary (RUB/year)
Supervision of labor protection rules	Occupational safety specialist	14	248	400	198,400
Designing and controlling mining	Engineer	40	248	750	1,488,000
Manual controller readings	Operator	40	248	435	863,040
Total					2,549,440
Social contributions					3,319,370
Total					5,868,810

manually calibrate mine process parameters or walk to equipment locations. Thus, a mining engineer's working hours are reduced to 0.7 of a standard working day. The operator's workload is also reduced to 0.8 hours of the original, as the presence of a specialist is still necessary, but the workload has decreased due to the automation of information collection and analysis tasks (Table 2).

To calculate a quantitative assessment of the economic efficiency of the implementation of an automatic dust suppression system at the enterprise, it is necessary to calculate the implementation costs. These include hardware infrastructure costs (equipment, computers, physical infrastructure) and software costs. For continuous and correct operation of the system, it is necessary to purchase and install specialized equipment (Table 3).

Equation 2 can be used to calculate the operating costs:

$$\mathrm{C_T} = \mathrm{M} + \mathrm{Z_{mp}} + \mathrm{A_{exp}} + \mathrm{S_{tc}} + \mathrm{S_{en}} + \mathrm{S_{equip}} + \mathrm{O_{cst}} \tag{2}$$

Let us calculate electricity costs for the year in accordance with the mode of operation of the enterprise (the system performs continuous control at production) (Table 4).

The depreciation charge per month for equipment and expensive tooling with a long service life is calculated using Equation 3:

$$A_{exp} = \frac{K \cdot H_a}{100}, \tag{3}$$

Let us calculate the monthly depreciation rate of the equipment. A personal computer lasts 7 years on average, a server the same number of years. Using Equations 4 and 5, we get:

$$H_a = \frac{1}{T_{tst}} \cdot 100\% = \frac{1}{84} \cdot 100\% = 1.19\% \tag{4}$$

TABLE 2. Salary fund after automation

Stages and content of performed works	Performer	Labor intensity of works (man-hours)	Working days	Tariff rate (RUB/hour)	Basic salary (RUB/year)
Supervision of labor protection rules	Occupational safety specialist	7	248	420	104,160
Designing and controlling mining	Engineer	28	248	750	744,000
Manual controller readings	Operator	40	248	348	690,432
Total					1,538,592
Social contributions					2,003,246
Total					3,541,838

TABLE 3. Calculation of equipment costs

Name	Quantity (units)	Price (RUB/unit)	Amount (RUB)
Server	1	291,000	291,000
Personal computer (specialist's workstation)	1	70,000	70,000
Total			361,000
Equipment delivery			6,500
Equipment installation			6,500
Total			374,000

Then:

$$A_{exp} = \frac{K \cdot H_a}{100} = \frac{37400 \cdot 1{,}19}{100} = 4450 \text{ RUB/month or } 53\,407 \text{ RUB/year} \tag{5}$$

Costs for maintenance and repair of the equipment, which are covered by the warranty contract, are assumed to be 3000 RUB/year. Thus, after implementation of the system, the operating costs amount to 3.70 million RUB/year.

Now, using the obtained data, the economic effect from the introduction of automatic dust suppression

TABLE 4. Calculation of electricity costs for the year

Equipment	Power (kW)	Equipment operating time (hours)	Electricity tariff (RUB/kWh)	Total cost of electricity (RUB)
Personal computer	0.4	8,760	6	21,024
Server	1.3	8,760	6	68,328
Dust concentration controller	0.2	8,760	6	10,512
Total			99,864	

system is calculated. The economic effect is determined by Equation 6:

$$E_{ceff} = C_{st1} - C_{st0} = 5.87 - 3.70 = 2.17 \text{ mln RUB} \quad (6)$$

The payback period of the costs invested in research shall be determined by Equation 7:

$$T_{pb} = \frac{Cst_{res}}{Ec_{eff}}, \quad (7)$$

The results show that the implemented system will pay off in the first year. Thus, the implementation of the automatic dust suppression system not only reduces current costs, but also creates additional economic benefits, providing more stable and efficient operation of the enterprise. This confirms the high economic efficiency and feasibility of the proposed system implementation.

3. 5. Discussion Ventilation control refers to the timely supply of the required air flow to the workplace at any time the necessary air flow to the places of work at any time, providing normal process flow and safe working conditions for workers. Ventilation management can consist of both the development and implementation of long-term (one-time) ventilation control long-term (one-time) measures in topologically and aerogasodynamically stable conditions, as well as the operational redistribution of air flow rates through ventilation workings air flow rates through the ventilation network depending on the deviations of controlled parameters from technological norms, stipulated by the safety rules and rules of technical operation of enterprises (6). In general, the ventilation control system can be structurally regarded as a consisting of a control system and a controlled object. Between them, there is a continuous exchange of information and its processing. At the same time the information should be processed by the system in such a way that the proposed control actions (measures) lead most effectively to the achievement of the management objective under certain limiting conditions (73) imposed by safety regulations. One of the components of the ventilation process is reduction of dustiness of objects and monitoring of dust formation in the mine atmosphere. Therefore, an important task is the implementation of the dust suppression process at the places where works are carried out.

This paper proposes a methodology for ventilation control during the monitoring of dust formation under atmospheric conditions, in which the regulated parameter is dust concentration and the input influence is the fan blade rotation speed. Thus, the topic of the paper is relevant.

While this study confirms the operational viability and significant economic benefits (2.17 million RUB annual savings) of our PID-based dust suppression system in the apatite-nepheline mining environment, further research could strengthen its broader applicability. For instance, direct comparisons with conventional dust control methods across diverse mining sections would better quantify performance gains. Though our 50-point dataset validated core functionality under targeted production conditions, expanding validation through longitudinal trials with larger datasets and statistical metrics (e.g., MSE, RMSE) would rigorously assess long-term controller accuracy. Furthermore, scalability challenges—such as integration in complex mine topologies or extreme dust scenarios—warrant dedicated investigation. Addressing these aspects in subsequent research will further solidify the framework's applicability across the mining industry and provide deeper insights into long-term performance optimization.

Nevertheless, the implementation of automated PID systems in industry not only improves the accuracy of process parameter control but also delivers significant cost savings through enhanced efficiency and reduced operational downtime. The proposed system regulating dust concentration via a PID controller can be further substantiated by successful examples from other domains of automatic control (74).

4. CONCLUSION

As a result of the research and synthesis of the automatic dust suppression system at the enterprise, the following key results were achieved.

A detailed analysis of the existing systems in industrial facilities was carried out, their technological and economic advantages and disadvantages were revealed. The possibilities and limitations of current solutions were evaluated, which enabled the justified selection of methods and tools for the development of a new system.

The task of developing a dust suppression control system at the enterprise was formulated. Modeling of control processes was carried out, aiding in the determination of the key parameters of the system and the creation of its architecture.

A system architecture was designed, including data acquisition and processing of dust concentrations in the production facility. A prototype system was developed, which was tested and demonstrated high accuracy and speed.

Implementation of the developed system of automatic dust suppression allows to significantly reduce operating costs by optimizing the system operation and reducing the wear of equipment. Evaluation of economic efficiency showed that the savings for the first year will amount to 2.17 million RUB, with potential for further growth in economic benefits in subsequent years.

The developed system of automatic dust suppression, based on modern sensors and programmable logic controllers is highly accurate, autonomous, and reliable. Its implementation not only improves the safety and efficiency of mining processes, but also brings significant economic benefits. The work has important practical significance for various industries, contributing to its modernization and sustainable development.

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Persian Abstract

چکیده

این مقاله به بررسی مشکل ایجاد یک سیستم مؤثر کنترل گردوغبار می‌پردازد .نویسندگان با استفاده از روش‌های تحلیل سیستم‌ها، مدلسازی ریاضی، تئوری تصمیم‌گیری، اندازه‌گیری‌های زمانی تغییرات غلظت گردوغبار در تهویه معدن و مدلسازی عددی تغییرات غلظت گردوغبار، یک سیستم خودکار کنترل گردوغبار برای کانسار آپاتیت-نفلین توسعه داده‌اند .معماری سیستم طراحی شده است که مراحل دریافت و پردازش داده‌های غلظت گردوغبار تا پاسخ فعال‌سازی سیستم کنترل با تنظیم شدت عملیات بر اساس شرایط را پوشش می‌دهد .یک نمونه اولیه از سیستم ساخته و آزمایش شده است .هستهٔ سیستم مبتنی بر کد توسعه‌یافته‌ای است که به‌طور خودکار غلظت گردوغبار در معدن را با استفاده از یک کنترل‌کننده PID تنظیم کرده و داده‌ها را به سرور ارسال می‌کند که امکان پایش و کنترل بلادرنگ سیستم را فراهم می‌نماید .مزیت اقتصادی سالانه اجرای این سیستم در محل مورد مطالعه، ۲’۱۷۰’۷۰۱ روبل بوده است .افزون بر منافع اقتصادی حاصل، این سیستم بهبود شرایط کاری، افزایش ایمنی و کاهش اثرات مضر بر محیط زیست را در پی خواهد داشت.