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The challenges of Industry 4.0 and the need for new answers in the mining industry

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Abstract

Relevance of the work is due to the need for further modernization of the economy of the Russian Federation, which involves solving both basic theoretical and applied problems of the domestic mining industry. This circumstance largely determines not only the state of the state's production resources, but also its scientific and technical potential. The global trend in the development of mining operations in the world is mainly determined by open pit mining of raw material resources. Open pit mining is characterized by an increase in the volume of processed rock mass, improved production processes through the use of advanced technologies, which entails the use of high-capacity mining machines. The main problems of open-cut mining are the following: complex mining and geological and mining-technical conditions; depletion of the mineral resource base; and constantly changing environmental conditions. All this leads to an increase in the cost of mining and a decrease in the competitiveness of the products of mining companies.

Objective of the work. To establish the need to modernize traditional technologies in open pit mining with the possibility of integrating the main ideas of Industry 4.0.

Research methodology. When solving the set tasks a complex approach was used, including: scientific analysis and synthesis of previously published research, analytical studies, laboratory experiment and observations of the work of open-pit excavators in real operating conditions. The methods of mathematical statistics include system analysis and modeling with the use of information technologies form the methodological basis of the research.

Results. This paper deals with the issues of modelling the cab of a quarry crawler excavator to meet the technical requirements for the excavator cab in protecting against tipping and rock impacts. Model setup and analysis of simulation results after loading are performed using Autodesk Inventor software. An optimal finite-element model of an excavator operator's cabin has been developed to assess the effectiveness of its structural protection.

Conclusions. Implementing the core ideas of Industry 4.0 is a complex scientific and technical challenge. Its solution is connected with significant economic costs, including modernization of mining equipment, infrastructure, as well as changes in the technology of open-cast mining. The implementation of complex automated control systems and practical application of the latest information and geoinformation technologies will unambiguously give high estimated figures and have high applied potential, and ultimately ensure safety of open pit mining, increase of efficiency and productivity, possibility of mining in regions with complex mining and geological and mining-technical conditions.

Keywords: robotised mining equipment, open-pit excavator, quarry, technology, mobile control room.

Introduction

One of the most current and interesting trends in industrial development and modern technology is the introduction of the concept of Industry 4.0. The term "Industry 4.0" is generally used to describe new, advanced and potentially breakthrough technologies, including full digitalization and artificial intelligence.

The concept of modern manufacturing, Industry 4.0, involves the widespread adoption of information technology in manufacturing, as well as the creation of a new generation of equipment, all integrated into the same digital ecosystem. The defining part of Industry 4.0 is the human being. Human beings must remain the

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“conductor” of the value chain and be able to draw on a full arsenal of highly efficient aids to master complex processes. Modernization and digital transformation of manufacturing operations to ensure efficient operation of equipment are basic components of management [1–8].

In 2018, the national programme “Digital Economy of the Russian Federation” was approved; the aim of the programme is system-wide development and implementation of digital technologies in all areas of life.

Digital transformation in mining is primarily aimed at increasing productivity, so, for example, the approved long-term programme for the development of the coal industry of the Russian Federation until 2030 sets the goal of a fivefold increase in productivity and an increase of at least 2–3 times in the main indicators of the level of industrial and environmental safety.

At the same time, in order to realize Industry 4.0's forward-looking forecasts, the following is noted in foreign analytical reports:

Figure 1. The four industrial revolutions in mining (realized from the German Research Centre for Artificial Intelligence, in translation)

Рисунок 1. Четыре промышленные революции в горном деле (реализовано на основе материалов Немецкого исследовательского центра искусственного интеллекта, в переводе)

– 28% of mining companies globally are planning to increase their IT budgets, despite the current challenges in the industry;

– digital technology is playing a defining role in investment: 70% of companies are considering investing in mine automation, 69% plan to invest in centralized management and control, and over a quarter are exploring the role that robotics could play;

– mining companies will continue to develop transparency, responsiveness and control through data analytics. The number of mining companies using in-depth analytics is projected to increase by 30 per cent in the next few years [8].

The World Economic Forum (2015) has published several reports on the future of work that reflect some of the implications of Industry 4.0. In general terms, the outcome is reflected in an analysis by the German Research Centre for Artificial Intelligence – DFKI (fig. 1).

Review of literature

The main problem with open pit mining is the increasing complexity of the mining and geological and technical conditions caused by the depletion of the mineral resource base, as well as constantly changing environmental conditions. These circumstances lead to an increase in the cost of production of minerals and a decrease in the competitiveness of products of mining enterprises. For example, in a number of works it is indicated that selling prices for certain types of solid minerals have changed significantly over the past decade (about 2

to 10 times), at the same time it should be noted that demand for certain types of minerals is steadily increasing [9–13].

The use of traditional technologies in open pit mining determines a number of specific features, namely: incomplete extraction of minerals at lower levels of the open pit; reduction in operational productivity of mining transport equipment, due to the complication of the organization of work related to the execution of technological operations directly by the machine operator.

Statistics of events and accidents at technological facilities show that more than 50% of the cases are related to human factor. Some of them are related to human-operator errors for various reasons. A promising direction in the development of open-pit geotechnology in the area of quality development of reserves, safety and efficiency of mining operations is the complete elimination of technological personnel through an increased level of automation and the possibility of using robotic mining equipment.

There are four levels of automation for mining equipment. Remote control (RC) can be achieved in two ways. The simpler method is for the operator to control the machine from a relatively short distance away. Communication is hand-held by RC. In the second method, the operators are located at a RC room, and workstations are set up for them, duplicating the controls. Special monitors replace the cab windows, and video cameras transmit real-time images of the machines in operation to these screens (fig. 2) [14–18].

The first, simplest level is remote control; used to control the operation of equipment such as excavators and bulldozers. The operator is relatively close to the machine - so that it is in his field of vision - and uses the remote control to perform process operations.

The second level involves telemetric control - the use of mining equipment that is controlled by an operator who is at a considerable distance, using video cameras, sensor signals and possibly additional location software. Telemetry control allows removing a person from a hazardous location for a considerable distance to control the equipment from a safe location.

On the third level, a single operator regulates the activities of several machines, and they move according to the algorithm laid down by the software. The operator controls the process and makes adjustments if necessary.

The fourth and highest level is full automation, where the machine works completely independently, with no human involvement. With full automation, robotic systems take over full control of ignition, gearshift, steering, braking, dumping, dozer blade position, etc., - without any intervention by the operator.

Full automation increases the productivity of mining machines and the use of machine control software enables the operator to "steer" the machine, monitor efficiency and intervene when problems arise.

Figure 2. Automation levels of mining equipment

Рисунок 2. Уровни автоматизации горнодобывающего оборудования

Figure 3. Automation of mining processes in underground mining operations [19]
Рисунок 3. Автоматизация добычных процессов на подземных горных предприятиях [19]

Table 1. Implementation of automated and remote control systems on main types of mining machines

Таблица 1. Реализация автоматизированных и дистанционных систем управления на основных типах горных машин

Year	Company	Development
1993	R. A. Hanson (Rahco)	The company has pioneered the use of GPS-based remote control of loading machines. An autonomous rock transport vehicle was developed. Created a GPS-based storage and loading system
1995	Trimble and Aquila Mining Systems	A GPS-based system for the ongoing monitoring and control of drilling rigs and excavators has been developed that includes the ability to automatically control the drilling rig, increasing operator productivity and reducing machine wear and tear
1995	Modular Mining System	Development of an integrated mining system including surveying, control system, excavator control and real-time operating information
1996	Caterpillar and Trimble	Developed new systems by two companies, combining GPS, radio, computers and software into one secure package specifically designed for mining operations. The system is designed to increase the productivity of all types of mining equipment, including bulldozers, hydraulic excavators, loaders and motor graders
1999	Poltava Mining and Processing Plant	An automated system for the dispatching of mining equipment and monitoring of moving objects has been implemented under realistic conditions
1999–2001	JSC “Vist Group”	The management system for the Quarry mining and transport complex was implemented at the Chernigovets open pit mine of SDS Coal
2008	JSC “Vist Group”	Development and widespread industrial implementation at Russian mining enterprises of the automated control system for mining and transport complexes Quarry
2013	JSC “Vist Group”	The Skolkovo Foundation grant committee supported the Intelligent Mining Enterprise project, identified as one of the most important areas of innovative development in the mining sector

Figure 4. Prototype remote control device for use at a hazardous site: 1 – prototype device; 2 – excavator; 3 – hazardous site

Рисунок 4. Прототип устройства дистанционного управления при использовании на опасном объекте: 1 – прототип устройства; 2 – экскаватор; 3 – опасный объект

The intensive development of integrated automated management systems in the mining industry in the Russian Federation falls in the early 1990s. Scientific and methodological support for projects to realize the opportunities for the development and practical application of the latest information and geoinformation technologies was carried out under the leadership of Academician K. N. Trubetskoy (fig. 3).

The table 1 shows the evolution of remote control systems on the main types of mining machines involved in the main mining processes.

The development of modern remote control systems for mining machines is primarily driven by the need to use them in demanding mining and geological environments. Most developments in remote-controlled machines were originally designed for military purposes, or for operation at potentially hazardous sites. However, due to the fact that the range of their application is quite limited and the operating conditions are difficult to predict, engineering companies do not develop serial samples of remote-controlled mining machines, but instead create machines individually for each required operating condition. The British company JCB created a single-bucket excavator for a demolition and demolition company, with all operations controlled remotely. The excavator is based on two of the company's production models, the lower end being the JCB JS 220Lc and the upper end the JCB JS 190. The excavator has a weight of 2.1 tons and a maximum bucket lift height of 8.7 meters. The use of a remote control on this model allows the operator to carry out the most accurate dismantling of the required elements without risk to the life of the operator, and also without breaking integrity of neighboring structures not subject to demolition.

In a number of works [20–22] the question of the operator's removal from the potentially dangerous area of work has been solved through the use of remote control technologies (fig. 4).

To date, there is a prototype and the prototype of the remotely controlled dump truck BelAZ-75131. Tests and improvement of the robotic dump truck and robotic haulage technologies are carried out in the conditions of BelAZ plant site (fig. 5).

Underground mining applications define specific requirements for control systems. In this case, in order to get the machine operator out of the cab without compromising the overall performance of the machines, the remote control system must be used to control all technological operations, including the movement and implement control of the machine.

Figure 5. Remotely operated dump truck BelAZ-75131

Рисунок 5. Дистанционно управляемый автосамосвал «БелАЗ-75131»

The problem statement

With all the indisputable advantages of robotized mining equipment, which include: minimizing the influence of the human factor, changing the quantitative values of the main parameters of the open pit and the individual elements of the development system, increasing the operating productivity of the unit of equipment, improving the quality of operations, relieving the operator from physically demanding and monotonous work, etc. Scientific discussion on creation of robotic complexes on the basis of traditional mining machinery is still open.

Thus, in a number of scientific publications, namely in the work of D. Ya. Vladimirov “Substantiation of parameters of robotized mining engineering systems in complicated conditions of open-cast mining of mineral deposits” the following is stated: “As every solid minerals deposit has unique quantitative and qualitative parameters and characteristics, implementation of robotized mining transport equipment is connected with a number of difficulties, caused, first of all, by the adjustment of communication systems with the control centre and interconnection between them. Therefore, it is proposed to arrange open pit construction using traditional (mechanized) equipment, if the deposit is not located in the area with complicated natural and climatic conditions, and as the mining works develop, the system is adjusted and geological information is specified, to reequip the operating equipment with appropriate processes in order to convert it to industrial robots. It is suggested to arrange open-cast mining construction with application of traditional (mechanized) equipment, if a deposit is not located in the area with complicated climatic conditions, and in process of development of mining works, system debugging and geological information specification to carry out additional equipment of operating machinery by correspondent processes with the purpose of its transfer to industrial robots. Another point to bear in mind is that users regard the purchase of machines and equipment as a capital investment that forms part of the actual capital stock. The technological and commercial risks are high, the decision takes longer and the price plays less of a role than “technical type and ergonomic features” in the selection condition”.

Methodology for ergonomically designed mobile control stations for quarry excavators

At the same time, this publication is aimed at addressing issues that are well related to modern approaches in the field of creating advanced robotic systems of mining equipment, namely the development of mobile control points of mine excavators, taking into account the requirements of ergonomics. In the operation of modern open-pit excavators the workplace of machinist completely does not provide conditions of isolation from the negative impact, as from the territory of the technological operation, and the constructive elements of excavator [23].

Domestic manufacturers of mine excavators, namely PJSC “Uralmashzavod” (Ekaterinburg) and

IZ-KARTEKS named after P. G. Korobkov (Kolpino, St. Petersburg) use in the manufacture of machines modern complete cabins for mine excavators with different bucket capacity produced by NPF Podemnik LLC and UZGM LLC, in which design solutions corresponding to modern level of mine excavator cabins of foreign analogues in ergonomics and aesthetics of interior, increasing comfort of working conditions and increasing a working area of the excavator operator’s view.

Many technical facilities used in industry require the presence of a human (operator), that’s why it is necessary to constantly improve their design to ensure maximum safety of working conditions [24–28].

The current scientific position in most engineering-psychological and ergonomic research in the creation of new models of machine cabs is an anthropocentric approach. The viewpoint of many developers of machinery, who encounter negative effects of human factor in modern production, is reduced to maximum automation of control systems, i. e. reflects the machine-centric approach [29].

To this end, methods and tools are applied at the design stage to evaluate future technical developments. At creation of mobile control stations for mine excavators we used virtual prototyping method, which on the one hand reduces the probability of design errors, and on the other hand allows to realize estimation of machine prototypes based on anthropometric criteria using hardware and software capabilities, to automate design process, and also provides an opportunity to compare cabins of similar designs.

Criteria for evaluating the virtual prototype are two main groups: technical and anthrop technical [30–34].

Technical criteria refer only to the evaluation of technical characteristics and allow evaluating its features, such as functionality, durability, reliability, etc. [35].

Anthrop technical criteria are conditioned by the presence of a person inside the machine or equipment. Ergonomic criteria can be distinguished in this group: limb ranges – identification of range and comfort zones, including the need to work in uncomfortable body postures; visual field; muscle-skeletal loads – ability to exert forces and torques on limbs; safety criteria – protection from mechanical hazards; head injury criteria; noise; vibration; risk of slipping, tripping, falling; proper lighting – no shaded areas, glare and strobe effect.

Results

For the implementation of ergonomic development and implementation of the design and schematic solutions in the standard models of excavators, a computer program has been designed to simulate and group the workplace of the excavator operator. The main requirement for such models is probably a more complete reproduction of the excavator structure and control principles, taking into account ergonomic requirements.

For ergonomic design a three-dimensional model of the system “Man–Excavator–Face” was developed, which allows you to choose the rational constructive-technological solutions and to identify the ergonomic parameters of excavators that require improvement. Computer

graphics means are used to solve the problem of spatial and anthropometric compatibility of an excavator operator with the workplace elements. The model allows performing:

- three-dimensional simulation of an operator workplace with the group of elements and assurance of information interaction;
- an excavator operator dummy for ergonomic assessments and design of surfaces to place the body, taking into consideration the diversity of anthropometric characteristics of a person.

When modeling an ergonomic system “Man–Excavator–Face” the formalization of the anthropometric characteristics is required, designed in a mathematical model of “Man–the Excavator Operator”. A simulation model of an operator (dummy) is created according to the anthropometric parameters of the person. The dummy is placed in a simulation excavator cab; the result is evaluated as an ergonomic index – controllability.

On the basis of analysis of existing designs for cabins of mine excavators, in 3D solid and surface parametric designing system Autodesk Inventor we created modernized modular cabin, which can be used for mobile control stations of mine excavators (fig. 6, a, b) [36–42].

The excavator cab frame was tested under different types of loading. The following loads were applied consecutively: lateral and vertical. In accordance with the requirements of Rock Slide Protective Structures (RSPSs) the frame must provide protection of the operator from possible falling of large pieces of rock from above (overhanging “canopies”, blocks and separate large boulders), protection of the operator during overturning the excavator from the ledge, etc. (fig. 6, c) [43, 44–46].

The study made an economic assessment of the measures effectiveness to create a comfortable working environment for a mining excavator operator (tables 2, 3).

Figure 6. Modeling in Autodesk Inventor: a – 3D model of the excavator; b – test of the quarry excavator cabin at application lateral and vertical load; c – dependence of the deformation of the cabin frame on the applied load

Рисунок 6. Моделирование в Autodesk Inventor: а – 3D-модель экскаватора; б – испытание кабины карьерного экскаватора при приложении боковой и вертикальной нагрузок; в – зависимость деформации каркаса кабины от приложенной нагрузки

Table 2. Characterization of the effect sources in the implementation of organizational and technical measures**Таблица 2. Характеристика источников эффекта при реализации организационно-технических мероприятий**

Event	Sources of effect and their characteristics		
	At the micro level (enterprise economics)	At the macro level (country's economy) Social	At the macro level (country's economy) Social
Improving the ergonomics of mining excavators	Increased labour productivity by reducing downtime Savings on investments if you need to replace the excavator 1.5 times longer ECC life	GDP growth (gross domestic product) Solving the problem of deterioration of equipment in the mining industry (the need to update the equipment fleet) (depreciation of 70%)	Creating ergonomic working conditions for operators
Improving the efficiency of in-house training for drivers	Labor productivity growth due to higher operators' qualifications	Solving the problem of labor shortages	Continuing education, reducing staff turnover

Table 3. Indicators for assessing the economic effect of the measures implementation to create a comfortable working environment for a mining excavator operator**Таблица 3. Показатели для оценки экономического эффекта от реализации мероприятий по созданию комфортных условий труда для машинистов карьерных экскаваторов**

Economic Effect Source	An indicator characterizing the achieved effect quantitatively or qualitatively
<i>Effects at the micro level (enterprise economics)</i>	
Increased labor productivity by reducing downtime	The increase in the volume of work (in percent, in roubles per 1 excavator)
Labor productivity growth due to higher qualifications of drivers	The increase in the volume of work (in percent, in roubles per 1 excavator)
1.5 times longer ECC life	Cost saving (in roubles per year)
1.5–2 times increase in working capacity of hoisting ropes	Cost saving (in roubles per year)
Savings on investments if you need to replace the excavator	Savings on investments (in roubles per year)
<i>Effects at the macro level (national economy)</i>	
GDP growth (gross domestic product)	GDP growth (in percent, in roubles per 100 ECC)
Solving the problem of equipment deterioration in the mining industry (the need to update the equipment fleet – depreciation of 70–80%)	Not quantified
Solving the problem of labor shortages	Not quantified
<i>Social effect</i>	
Creating ergonomic working conditions for workers	Not quantified
Improving professionalism, qualifications of employees, reducing staff turnover	Not quantified

The measures will increase the amount of work performed on one mining excavator by 20%, or 12,528 thousand rubles per year; reduce annual operating costs by 417 thousand rubles per one mining excavator; reduce investment per year and one mining excavator by 1667 thousand rubles.

Conclusion

The development of basic Industry 4.0 approaches is a complex scientific and technical challenge that involves significant capital expenditure, including robotics,

infrastructure, on-board information and diagnostic systems, and changes in surface mining technology and regulations. The implementation of integrated automated control systems and practical application of the latest information and geoinformation technologies will unambiguously give high estimated figures and have high applied potential, and ultimately ensure the safety of open pit mining, increase in efficiency and productivity, and the possibility of mining in regions with complex mining and geological and mining-technical conditions.

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Вызовы Индустрии 4.0 и необходимость новых ответов в горнодобывающей промышленности

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Аннотация

Актуальность работы обусловлена необходимостью дальнейшей модернизации экономики Российской Федерации, которая предполагает решение как основных теоретических, так и прикладных проблем отечественной горнодобывающей промышленности. Данное обстоятельство в значительной степени определяет не только состояние производственных ресурсов государства, но и его научно-технический потенциал. Мировой тренд развития горных работ в основном определяется добычей сырьевых ресурсов открытым способом. Открытая разработка месторождений полезных ископаемых характеризуется увеличением объемов перерабатываемой горной массы, совершенствуются производственные процессы за счет использования передовых технологий, что влечет за собой использование высокопроизводительных горных машин. К основным проблемам добычи полезных ископаемых при открытом способе можно отнести следующие: сложные горно-геологические и горнотехнические условия; истощение минерально-сырьевой базы; постоянно изменяющиеся условия внешней среды. Все это приводит к повышению себестоимости добычи полезных ископаемых и снижению конкурентоспособности продукции горнодобывающих предприятий.

Цель работы. Установление необходимости модернизации традиционных технологий в добыче полезных ископаемых открытым способом с возможностью интеграции основных идей индустрии 4.0.

Методология исследования. При решении поставленных задач использовался комплексный подход, включающий: научный анализ и обобщение ранее опубликованных исследований, аналитические исследования, лабораторный эксперимент и наблюдения за работой карьерных экскаваторов в реальных условиях эксплуатации. Методологическую основу исследований составляют методы математической статистики и системного анализа и моделирование с использованием информационных технологий.

Результаты. В работе решены вопросы моделирования кабины карьерного гусеничного экскаватора на соответствие техническим требованиям, предъявляемым к кабине экскаватора при защите от опрокидывания и ударов кусков породы. Настройка модели и анализ результатов моделирования после нагружения выполнены с применением программного комплекса Autodesk Inventor. Разработана оптимальная конечно-элементная модель кабины машиниста экскаватора, предназначенная для оценки эффективности ее конструктивной защиты.

Выводы. Реализация основных идей индустрии 4.0 – это сложная научно-техническая задача, решение которой связано со значительными экономическими затратами, в том числе на модернизацию горной техники, инфраструктуру, а также изменение технологии открытой добычи полезных ископаемых. Реализация комплексных автоматизированных систем управления и практического применения новейших информационных и геоинформационных технологий дает высокие расчетные показатели и имеет высокий прикладной потенциал, обеспечивает безопасность открытых горных работ, повышение эффективности и производительности труда, возможность добычи полезных ископаемых в регионах со сложными горно-геологическими и горнотехническими условиями.

Ключевые слова: роботизированное горнотранспортное оборудование, карьерный экскаватор, карьер, технология, мобильный пункт управления.

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