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РОБОТОТЕХНИКА В ГОРНОДОБЫВАЮЩЕЙ ПРОМЫШЛЕННОСТИ

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Аннотация: работа в шахтах связана с многочисленными рисками. Современная промышленность требует все больше и больше полезных ископаемых, а богатые месторождения иссякают. Теперь горнодобывающим предприятиям приходится разрабатывать месторождения с более сложными горно-геологическими условиями. Как следствие, риски становятся более опасными и более вероятными. В горнодобывающей промышленности количество несчастных случаев со смертельным исходом в 10 раз выше, чем в среднем по отрасли. Решением этой проблемы может стать промышленная роботизация. Анализ существующих робототехнических систем в горнодобывающей промышленности показал, что их необходимо систематизировать по степени автономности. С аналогичной проблемой уже сталкивались в автомобильной промышленности, и стандарт J3016 был создан маркетинговой группой SAE совместно с Комитетом по техническим стандартам. С учетом существующих примеров систематизации автономных устройств и опыта смежных отраслей мы разработали собственный аналог. По сравнению с существующими систематизациями мы предложили уточнить эту классификацию, чтобы отразить текущие решения. Проанализировав существующие роботизированные комплексы с точки зрения степени их автономности, выяснилось, что открытая добыча полезных ископаемых уже хорошо подходит для внедрения концепции «безлюдного карьера». Однако подземные горные работы могут роботизировать только некоторые процессы. В основном это связано с отсутствием сигнала GPS и сложностью проведения WI-FI и 5G LTE в горных выработках.

Ключевые слова: горное дело, робототехника, цифровизация, безопасность производства, системы управления, маркшейдерия, лидар.

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Robotics in the mining industry

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Abstract: working in a mining environment is associated with numerous risks. In its turn, modern industry demands more and more minerals, but rich deposits are running out. Now mining enterprises have to develop deposits with more complex mining and geological conditions. As a consequence, the risks become more dangerous and more likely to occur. In the mining industry, the number of fatal accidents is 10 times higher than the industry average. The solution to this problem could be industrial robotization. An analysis of existing robotic installations in the mining industry showed that they need to be systematized according to the degree of their autonomy. A similar challenge was already faced in the automotive industry, and the J3016 standard was created by the SAE Marketing Group in conjunction with the Technical Standards Committee. Taking into account existing examples of systematization of autonomous devices and the experience of related industries, we have developed our own analogue. Compared to existing systematizations, we proposed a refinement of this classification to reflect current solutions. After analyzing the existing robotic systems in terms of their degree of autonomy, it turned out that open-pit mining is already well-positioned for introducing the concept of a “humanless open-pit”. However, underground mining operations can only robotize some processes. This is mainly due to the lack of a GPS signal and the difficulty of conducting WI-FI and 5G LTE in mine workings.

Key words: mining, robotics, digital, production safety, control system, mine surveying, lidar.

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1 Introduction

The development and improvement of the mining industry around the world and in our country in particular continues. Modern industry requires more and more minerals, and rich deposits are drying up. Due to these trends, it is necessary to increase the production of minerals, reducing operating and capital costs, despite the difficult mining conditions of mines and quarries. These factors necessitate the use of more efficient and innovative mining technologies. The previous big stage in the development of the mining industry was the transition from the mechanization of work to its automation. The next important stage is mining the robotization of mining production. At the 7th All-Russian Congress of Mining Industrialists, a clause on the need to switch to intelligent and robotic production technologies was included in the list of «Main areas of activities of mining enterprises until 2024». Such transition will allow to create a «manless mine» in the foreseeable future, which will help to significantly improve the labor safety and production economics. According to Rosstat, the mining industry employs 0.79% of Russia’s population. However, they account for 10.8% of all fatal accidents [1]. Robotization can be a solution to this problem.

2 Purpose and relevance

Before using underground wireless networks, neural networks, autonomous mining robots, or mobile touch scanners, the question about the purpose for which these technologies should be used must be answered. One of the major development in mining over the past 20 years has been «humanless» mining technology. In underground mining, there are now only certain devices thatcan be used to reduce the number of workers in the mine. There are already the first examples of unmanned quarries at open-pit mining companies. The main direction of development in the coming years is the optimization of the operation of autonomous equipment and spread of these technologies throughout the industry.

The advantages of using an autonomous type of equipment are a significant increase in the safety of miners. If machines can be dispatched to potentially dangerous areas without people, this avoids numerous threats to human life and health. In addition to the risk of roof collapses, explosions, fires, or flooding, it the risk of toxic gas poisoning or «dead air» asphyxiation. In addition, people can be avoided in places with inadequate ventilation or high temperatures. The creation of an automatically updated map facilitates operational work planning, optimal placement of equipment and is the basis for modeling the ventilation system. In an emergency situation, the tracking system shows the position of people underground and, if necessary, the direction of their movement. This makes it possible to more effectively coordinate the entire technological chain of mining operations, and in the event of an accident, rescue operations.

3 Market of robotics

Until recently, the global robotics market was growing rapidly. In 2010, 120,000 robotic units were sold. From 2014 to 2019, the growth was 11% annually. In 2019, 370,000 installations were sold. But now the growth has been replaced by a decline. This is due to the beginning of economic wars between the United States and China, as well as the COVID-19 pandemic. According to forecasts, from 2022, the industry will begin to grow actively again. Robotization is becoming necessary in those industries where the cost of production is increasing, there is a large shortage of qualified personnel and high safety is required. According to a report from the International Federation of Robotics, the global robotics market will receive $147.26 billion in revenues by 2025 [2].

The most promising areas for the application of robotics include healthcare, defense industry, rescue operations, manufacturing, and mining industries.

4 Robotics in mining

Mining operations are run in harsh, dusty, environments with high humidity and stagnant water at low pH values, causing premature equipment failure due to corrosion. Temperatures range from low to very high (typically -40°C to 50°C). This determines the high requirements for the strength of the materials from which the equipment is constructed. If methane is released during underground mining, the equipment must be explosion-proof.

Miners' skepticism of IoT and robotics technologies is usually very high. The performance of the equipment must be adapted to the level of training and capabilities of workers [3].

Currently, there are still difficulties in answering the legal questions regarding the use of autonomous vehicles with people. It is necessary to constantly position the equipment with an accuracy of several centimeters, otherwise, an accident may occur, leading to equipment failure and injuries to people.

Robotization is most successful in open-pit mining. The main processes are loading and transportation of waste rock and minerals. Robotic dump trucks appeared on the market in 1996, pioneered by Caterpillar. But while unmanned dump trucks have become commonplace in the world, unmanned loaders and excavators are only now beginning to be actively introduced into production. An example of an advanced robotic excavator is the largest robot in the world working in a coal mine in Queensland, demonstrating how the quarries of the future might work. The 3,500-ton excavator, described on NASA's Cool Robot of the Week website, is a 75-meter dragline that requires 80% less operator involvement [4].

In underground conditions, robotic devices are widely represented by mobile supports, LHDs, and drilling rigs.

Semi-autonomous caterpillar supports began operating in coal deposits in the 20th century. Innovation in this direction is a prototype of a walking robotic support, created by engineers of the REC Kuzbass. The mobile support allows increasing the speed of mining by more than two times [5].

Semi-autonomous drilling rigs have become widespread, which can eliminate the influence of the human factor on the incomplete filling of holes. These systems have significantly increased the efficiency of mining [6].

Underground and open-pit mining is all about the coordinated work of mining equipment and workers. If mining machines could be fully automated to operate without humans, the mining industry would increase productivity and improve employee safety from adverse conditions: dust, noise, gas, water, moving equipment and roof collapses.

5 Levels of autonomy in the mining industry

An urgent task is to systematize all robotic technologies in the mining industry according to their level of autonomy. In the automotive industry, to clarify and simplify the levels of driving automation, the SAE Marketing Group, together with the Technical Standards Committee, has presented a summary table of driving automation levels from zero to five in accordance with the J3016 standard [7].

We propose to develop a similar systematization by the level of autonomy for the mining industry. To do this, we will analyze the existing robotic devices, dividing them into 5 levels according to their autonomy criteria.

5.1 First level

The machine is controlled by remote control in the human field of view. The main criterion is that the human is constantly in control of the machine, directly observing its operation. Examples in the mining industry are shown in Table 1.

Table 1
Examples of the first level of autonomy

Type of equipment	Model	Company
Powered roof support [5]	–	SEC Kuzbass
Load-haul-dumper [8]	XLPD	DOK-ING
Mine Surveying Robot [9]	Julius	TUBAF (university)

5.2 Second level

The equipment is controlled by remote control. The person controlling the robot exercises control via a monitor. The main criterion is that the person constantly controls the machine without directly observing its operation. Examples in the mining industry are shown in Table 2.

5.3 Third level

The machine is capable of performing certain operations autonomously. The main criterion is that the machine's ability

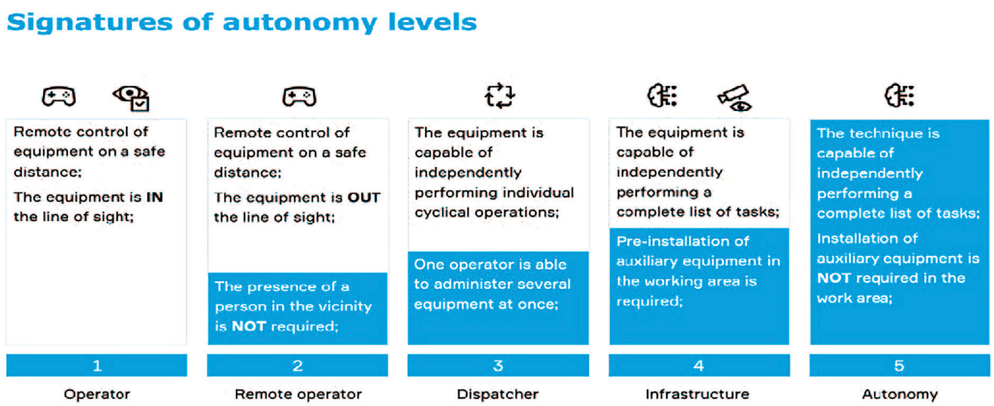

Fig. 1. Signatures of autonomy levels in the mining industry

to perform certain tasks independently, without the need for supervision.

5.4 Fourth level

The equipment is able to perform all necessary operations fully autonomously, but requires the installation of additional sensors. The main criterion is that the dispatcher can control and set tasks to several machines at the same time; the equipment is capable of performing its tasks continuously.

5.5 Fifth level

The equipment is able to perform all necessary operations fully autonomously, no additional sensors need to be installed. The main criterion is that the dispatcher can control and set tasks to several machines simultaneously; the machinery is able to perform its tasks continuously.

A similar systematization was described by A. G. Zhuravlev in his work «Trends in the development of quarry transportation systems using robotic machines» [19]. We proposed a refinement of this classification, taking into account the robotization solutions from Nerospec SK, where the equipment can work fully autonomously, provided the prior installation of WiFi-antennas (neroPOYNT) and radio-frequency identification tags (neroPIN, neroDUST). It is necessary to add the 5th level of automation, in which the main criterion will be that the machine will not only work autonomously but also will not require the installation of additional devices in the working area [14].

As a result of this analysis, we can see that in underground mining, the solutions mainly refer to the third level of autonomy. Consequently, it is worth analyzing the experience of companies that have already been able to create complete solutions for autonomous mining operations. For example, Caterpillar's autonomous dump trucks have the Cat MineStar Terrain, a guidance tool for loading, drilling, and profiling, as the

Table 2

Examples of the second level of autonomy

Type of equipment	Model	Company
Excavator [10]	XE950DA	XCMG
Bulldozer [11]	CHERTA T15	VIST Robotics

Table 3

Examples of the third level of autonomy

Type of equipment	Model	Company
Drilling rig [12]	Robofore	Monrarbert
Dump truck [13]	BelAZ-78250	BelAZ
Remote control for load-haul-dumper [14]	T-RX100J	GHH Group; Nerospec SK
Drilling rig [15]	Simba M6C	Epiroc

Table 4

Examples of the fourth level of autonomy

Type of equipment	Model	Company
Drilling rig [16]	Cat 793	Caterpillar
Dump truck [17]	930E-4AT	Komatsu
Load-haul-dumper [18]	Bobcat	Built Robotics

main unit. By block, Caterpillar means a system consisting of sensors and an IT solution that can handle the task itself. As Michael Murphy, chief engineer at Surface Mining and Technology, who has worked with Caterpillar since the beginning of the autonomous quarry, noted that the main task was to create multiple blocks, which then in combination could provide autonomous operation of equipment [20].

The solution to moving to the fourth level is to accumulate experience in third-level robotization, so that a fully autonomous robot could be assembled from various prefabricated blocks.

6 Small robotic platforms

The main obstacle to the transition to the fourth level of automation is the lack of GPS, GLONASS signal in the mine, which is noted by the developers of existing models of robots for 3D mapping of mines. In the condition of underground mining, t no system can provide accurate positioning, comparable in accuracy to the positioning on the surface [21]. The use of small platforms, no larger than the size of a standard ATV, can greatly increase the speed of building a block-based underground positioning system to move to the third level of autonomy. The business strategy used here is to create an MVP, i.e., the creation of a robot capable of solving one task independently [22]. The positive effect of this strategy will be the rapid accumulation of a system of solution blocks to create an autonomous industrial robot with the lowest development cost per block. Production and testing of one small robot is much cheaper compared to the creation of an off-the-shelfautomated complex. The negative factor is the insufficient passability of the small robot in mine conditions. Of particular interest is the bottom-hole survey, where the permeability requirements are much higher compared with other parts of the mine [23]. Therefore, it is necessary to take into account the experience of application of high-passability small-sized robots in various industries. For example, the agricultural robot Siberian Tiger is an autonomous platform with wheels located on four vertical telescopic and steerable axles, which allows the unit to move omnidirectionally [24].

The first device needed to create this system would be, as on the surface, a positioning device . The pioneers in creating such robots are those described in more detail below.

7 Conclusions

Based on the above, we conclude that in the mining industry there is a demand for the creation of complex machines of 4

Fig. 2. Reviewed robotic platforms

and 5 levels of autonomy. It is impossible to solve this problem in the short term because of the enormous financial costs and scientific and technical efforts. However, it is necessary to solve this problem, despite its complexity, because its solution will significantly increase the safety and efficiency of mining operations.

We propose to solve this complex issue step by step by breaking it down into simple components, creating small autonomous units that solve local mining problems. After accumulating a sufficient number of units solving small problems in autonomous mode, they can be combined to create a complex of autonomous equipment of the 4th or 5th levels. Mining companies will be able to implement the concept of a «manless mine» concept.

There is a wide range of solutions for the use of autonomous machines in the mining industry. However, for mining companies that extract minerals by underground mining, they are not enough, and they cannot provide an autonomous complete technological chain with the existing developments. Creating small-scale robotic systems is an economically feasible step on the way to building a full-scale complex.

The companies are now focused on developing a solution for precise positioning and 3D mapping of the mine, but the research is being conducted in areas in the mines where there are no problems with passability. Once an accurate positioning solution is developed, there will be a need for an undercarriage that can not only move around the mine but also survey with the accuracy of a surveyor [25].

This global concept requires progressive motion and block building. There is already experience in creating surveying robots that can survey mine workings. However, these devices are used in places where high passability is not required, although the main volume of surveying takes place in the bottom-hole areas (where there are problems with this due to the rugged ground). In other words, to survey these areas, the robot must have high cross-country capability and stability. That is why we created the MARC-1 robot, whose task is to move in places where high cross-country capability is required. Unlike existing analogs, we use a running gear based on the Rocker-Bogie concept. In addition to testing the robot's ability to overcome obstacles, we will evaluate the accuracy of surveying. The surveying will be done with LiDAR mounted on a gyroscopic stabilizer. As a result of the study, we will be able to conclude on the feasibility of using this undercarriage to perform surveying work in mountain environments.

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