Prospects for application of robotic mechano-hydraulical excavation of
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To cite this article: V N Fryanov and L D Pavlova 2016 *IOP Conf. Ser.: Earth Environ. Sci.* 45 012002

View the *article online* for updates and enhancements.
Prospects for application of robotic mechano-hydraulical excavation of gas-bearing coal layers at great depths

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Abstract. In the paper the scientific basis for robotic technology of excavation prone to gas-dynamic phenomena of a coal layer with high gas-bearing capacity at great depths is developed. The constructive scheme of automated remote-controlled mining robot, that fractures coal by high-pressure hydraulic jets in the gas polluted environment, is proposed.

1. Introduction
The increased competition on the international market of energy resources due to falling prices for oil and natural gas has led to a reduction in production volumes and consumption of coal. Therefore, to compensate for the declining revenues of the oil and gas industry in the world markets the consumers of oil and gas are searched for on the domestic markets. To create an appropriate niche in the energy system of Russia the oil and gas business in the country proposes to introduce a “carbon tax” with a starting rate of $ 15 per ton of CO$_2$ emissions. One of the directions for formation of the specified niche is a reduction in the proportion of consumption of coal and production of thermal and electric energy using alternative energy sources.

Supporters of creating “carbon-free zones” by reducing coal production and its replacement by alternative energy sources have strong argument:

- the resolution of the climate summit 2015 in Paris on compulsory reduction of emissions of harmful gases, including in Russia in the next 15 years by 30% compared to emissions in 1990 to reduce the rate of warming of the planet;
- high accident rate at coal mines of Russia – for the last 12 years there have been 10 major accidents and the death toll reached 391.

These factors have led to a reduction in the share of coal in the country’s fuel and energy balance to 11-12%. However, the share of coal is significantly higher in developed countries: USA – 18%, UK – 21%, Japan – 30%, which provides greater security to coal-fired power industry to nuclear and hydropower.

In the current competition the first step of the Russian Government on the path of coal mining reduction is to liquidate vary gassy mines. The main cause for conservation and liquidation of mines is an increased risk of gas-dynamic phenomena and endogenous fires in case of spontaneous combustion of coal layers. The nature of these events is poorly understood especially in areas of high seismic activity [1, 2].

One of the variants for increasing industrial safety of coal mines and reducing the risk of incidents dangerous for the staff is to reduce the number of employees by replacing them with machines-robots in hazardous areas. In this regard, it is relevant to develop scientific basis of underground
geotechnology providing an increased efficiency of underground coal mining and industrial safety through the use of robotic excavation of gas-bearing coal layers at greater depths.

The purpose of the paper is to scientifically justify the technological system of robotic mines, including remote coal excavation by hydraulic method, hydraulic transportation of the mined rock, underground dewatering of coal slurry.

2. Description of the technological and technical solutions for the design of robotic mine
The authors developed and proposed the main provisions of robotic technology for underground coal extraction which can be used in the design of a new type of mines [3-4, 13-14]. Justification of the structure and elements of robotic technology of underground coal mining was carried out through the realization of the basic principle: the absence of a person in hazardous areas and the implementation of the functions of the operator in a comfortable environment, remote control of the robot during the excavation, coal excavation, the rock mass transportation to the main workings.

The methods and schemes of opening and preparation of a mine field of robotic mine are accepted conventional recommended by normative and methodological documents, e.g., [1, 7]. The need to develop new methods and schemes of opening and preparation of mine fields within the technological system of robotic mine in the first stage of its creation does not arise, since the safety of work in the performance of these processes is provided by the mines with traditional technology within the level of acceptable risk. As the largest risk to personnel present mining operations within the extraction area, the proposed technological solutions in the robotic structure of the mine must ensure the safety of mining operations during preparatory workings, stope excavation of coal and transportation of rock mass.

The following technical and technological solutions are incorporated in the proposed robotic technology mine system [1, 7]:

1) Exclusion of staff presence in clearing and preparatory coal faces by means of a remote control of robotic coal mining from operator stations located outside the areas hazardous for humans.
2) Performance of basic coal extraction operations in the methane-air environment with an active dust control and water supply on the mechanism of coal fracture.
3) Hydrotransportation of ROM with an underground dehydration cycle of rock mass, clarification of water and waste management in the goaf.
4) Performance of development workings on the pre-drilled wells of large diameter with ventilation of shaft faces due to the mine depression, seam degassing and unloading of the array of rock from pressure to prevent rock bursts and sudden coal and gas outbursts.

The basis for the implementation of technical solutions in technological system of a robotic mine is a remote-controlled self-propelled robot. The main robot functions are dredging coal seam according to a given program and monitoring of the following stope elements: shape and size of the edge part of a seam, stability of the roof rocks, the parameters of mine atmosphere, ROM transportation from the stope. All information on the status of these stope parameters is transmitted to the operator to adjust the program.

The possibility for creation of such robot is provided by scientific and technological developments in the field of robotics, development and implementation of remote sensing of geomassif condition and process monitoring. As a counterpart in the design of the robot control system it is proposed to use technical devices and methods proposed in [8, 9].

The main technological element of an excavation robot is a method of coal fracture and transportation. There are many variations of designs of mechanical, hydraulic, pneumatic, vibrating coal fracture [10, 13]. Given the need for a comprehensive solution to the problem of fracture, excavation, loading, ROM transportation, one energy source is adopted – high-pressure water, which will ensure the coal fracture and rock mass jetting, dust control, reduction of the probability of explosion of methane mixture, transportation of coal-water slurry to the underground dewatering chamber [10, 11].
In the course of development of hydraulic underground coal mining a number of methods was proposed and tested in practice, which are fracture of coal by water jets, including: thin jets of water with pressure up to 60 MPa, middle-pressure jets with water pressure up to 12 MPa and a flow rate 300 m$^3$/h.

The latter option was most widely used in hydraulic mines, however, because of the high energy capacity it was not cost-effective compared to the mechanical method of destruction, and was replaced by a combined (mechano-hydraulic) method with a mechanical coal fracture, ROM jetting on the soil of working and the formation of a coal-water flow.

According to the research it was found that the performance of a hydraulic rock fracture greatly depends on the distance from the hydrojet nozzle to the face. In [12] it was proved that as the distance from the nozzle to the surface of the coal seam increases in the range of 30 ÷ 300 mm, the hydraulic fracture productivity decreases almost 50 times. Therefore, continuous and efficient performance of the excavation robot can be achieved by the approximation of its fracturing mechanism to the changing face line at the optimum distance.

The distance from the face to the nozzle is 30 – 50 mm [13], and the possibility of its realization can be achieved by automated robot control. Efficacy of fracture is increased during swings of a cutting mechanism equipped with several nozzles with overlapping jets of water. Another important parameter of the fracturing mechanism of the robot is water pressure, with its increase in the range 10 ÷ 40 MPa the coal fracture rate increases 5 times [13].

Thus, the results of theoretical and experimental research confirm the possibility of a robotic excavation performance of one unit within 50 ÷ 80 tonne/h with program control of cutter motion.

According to the technological scheme of a robotic mine it is necessary to ensure the work of excavation robot in three modes: execution of a mine working with section 1.0 ÷ 1.5 m$^2$ in the direct motion, widening of a mine working up to 6 m in the reverse motion, liquidation of roof rock collapses, rock mass congestion near the robot and other emergencies.

Selection of the required minimal cross-sections of the mine workings was made in accordance with the production experience of application of hydraulic method [10] and result of research of the influence of underground workings form and sizes on rocks stability [5]. Given that the use of robotic technology is possible in difficult geological conditions unfavorable to traditional technology, the round shape of the mine working with small cross-section is adopted. This will allow the mine workings to be conducted without support and the probability of failure of roof rocks to be reduced. In case of local roof rocks fracture in the area of mine working, including behind the excavation unit, the design and the automatic control system provides the possibility for fracture of coal and oversized pieces of rock.

The design of an excavation robot is shown in Figure 1. It consists of the following main components:

1 – body for the assembly and configuration of main components, high-pressure water supply and channels for exchanging information between the operator and the robot;
2 – spacer-chassis for the robot movement, that provides its stability during work and movement in the circular mine working and at the junction with the chamber (Figure 2);
3 – executive mechanism of coal fracture in the form of jet forming box, frame and hoses for water supply and control actions to move the nozzles;
4 – executive mechanisms for the fracture of oversized pieces and accumulations of coal and rock;
5 – controlled overlapping in order to prevent the roof rock fracture;
6 – hoses and connections for transmitting and receiving information;
7 – flexible tube for transmitting power;
8 – system of remote and automatic control.
Besides the offered nodes in the construction process other options of excavation robot configuration are possible. For example, it is recommend to use compact tunneling machines with the developed [6] original constructions of vehicles with the supports into the roof, ground or main workings sides of various shapes, sections and directions using a spacer-stepping-sliding mechanism.

As a basis for the creation of an automated control system solutions of domestic and foreign companies can be used that produce automated remote control mining equipment.
One of the options of opening, preparation and mining of the coal layer area on robotic technology is shown in Figure 3.

![Diagram of development system](image)

**Figure 3.** Variant of the development system with automated coal extraction.

The coal layer with the angle of incidence of 35° is opened by inclined central and flanking mine shafts, which are executed in a traditional way. The scheme coal layer development is panel. The panel is prepared by parallel and accumulating galleries. Galleries are connected by cross-cuts for airing of the development faces, exit of people in emergency situations and slurry transportation. For gravity hydraulic transportation of coal slurry the galleries are conducted with a slope 0.05-0.07. The panel length is limited by the technical characteristics of the extraction robot and is 150-250 m.

### 3. Results of designing of a technological system for robotic coal layers excavation

To implement robotic underground coal mining technology the variant of system development is offered, which includes both standard technological solutions and original, related to the characteristics of the processes of excavation sites preparation, fracture and transport of coal. Technological scheme of a production area at a robotic mine is developed on the basis of a principle of organization of a complex production and organizational system. For automated control of robotic systems in complex geological conditions it is necessary to create a model of the control object. For this the following steps of a model creation should be performed:

- a comprehensive description of the system;
- study of the problem situation with the list of elements and situations;
- development of the functional schemes of basic processes interaction in the production areas;
- identification of the field for model application;
- formation of a conceptual model;
- algorithmic description of processes and operations;
- preparation of an information description of the model;
- construction of a formal model.

The comprehensive description of the robotic excavation site includes the following main assemblies of subsystems and processes:

- preparation of coal reserves for excavation, including the methods and technical means for workings development, transportation of mined rock, airing of preparatory faces, degassing of
coal layers in the area of preparatory workings, discharge from rock high voltage, industrial safety;
- development of methods for substantiation of clearing faces parameters, methods and means of workings excavation, roof control, robotic coal mining with automation and remote control of technical devices;
- methods and means of rock mass transportation;
- methods and means of servicing the technical equipment and staff life support during repair works;
- energy supply of clearing and preparatory faces;
- communications, signaling, visualization of processes and operations of automated remote control.

Near conjunction of central inclined shafts and accumulation gallery chambers of pumping units are built, the rock mass dehydration and clarification of technological water (4-6 in Figure 2). From the central shafts the parallel and accumulating galleries are located. Airing of these galleries is carried out due to mine depression.

To excavate coal by the robot the workings of circular cross-section are conducted. Since the presence of people is not required in the working face and there are no power sources, it is assumed to use the excavation robot in the dangerous gaseous environment. The operators location on the parallel and accumulating galleries is ventilated due to the mine depression.

After the chamber reaches the upper gallery the executive mechanism of the robot by the operator command turns in accordance with the scheme presented in Figure 2, and coal mining is conducted in a reverse motion. Transportation of the rock mass is carried by water to the dehydration chamber and by conveyor to the Earth’s surface.

Since coal excavation is carried out near the edge of the erodible layer, the flow of the coal slurry will be formed near the conjunction of the working and camera. Under these conditions, the collapsed rock (10 in Figure 2) will not float to the robot, which will reduce the ash content of the rock mass. By operator command the axis position of the fracturing mechanism must be changed depending on the angle of dip, flow rate and capacity of the cross-section under the the robot body.

For the parallel development workings in particularly difficult conditions (gas-bearing layers prone to gas-dynamic phenomena) it is offered to use a robotic excavation complex according to the scheme shown in Figure 4.

![Figure 4. Scheme of the parallel galleries drifting with unloading and degassing of rocks by wells with diameter more than 1 m.](image)

Wells of large diameter are located ahead of the development faces in the coal layer, which help to degas and unload rocks. Simultaneously with the airing of wells due to the mine depression the
heading machine (3 in Figure 4) widens the mine working to a full cross-section with a hydraulic transportation of rock mass. This method decreases dustiness in the development face, coal dust and methane-air mixture are removed by advanced well, restrictions on the gas factor are eliminated. This leads to an increase in the speed of developments and provision of comfortable working conditions.

4. Conclusion
On the basis of the developed technological and technical solutions for design of robotic mines and their discussion the following conclusions and recommendations for the practical use of the results are proved.

1) A promising direction for the increase of industrial safety at coal mines and reduction of the risk of accidents is the development and construction of robotic coal mines.
2) The main differences of the robotic coal mine compared to the traditional one are:
   - exclusion of staff presence in the stopes and development faces by means of a remote control of robotic coal mining from operator stations located outside the areas hazardous for humans;
   - performance of major coal mining operations in the methane-containing atmosphere with active dust control;
   - drifting of mine workings with advanced wells of large diameter and airing of development faces due to the mine depression.
3) The mandatory elements of construction of an excavation robot are the following key components: body, chassis, the executive mechanism of coal fracture, jet forming box, controlled overlap, hoses and connections for transmitting and receiving information, flexible stands for the electricity transmission system and automated remote control.

References
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