# Simulation modeling and tracing optimal trajectory of robotic mining machine effector

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**Abstract**. Within the framework of the robotic coal mine design for deep-level coal beds with the high gas content in the seismically active areas in the southern Kuzbass, the motion path parameters for an effector of a robotic mining machine are evaluated. The simulation model is meant for selection of minimum energy-based optimum trajectory for the robot effector, calculation of stresses and strains in a coal bed in a variable perimeter shortwall in the course of coal extraction, determination of coordinates of a coal bed edge area with the maximum disintegration of coal, and for choice of direction of the robot effector to get in contact with the mentioned area and to break coal at the minimum energy input. It is suggested to use the model in the engineering of the robot intelligence.

Reaching of economic efficiency and environmental safety of underground coal mining will condition the role of coal in the energy strategy of Russia in 5–10 years to come. The relevance of this objective is conditioned by the competition on the market of alternative energy sources, fall in oil and gas prices and anticipated imposition of a “carbon” tax for $CO_2$ emissions.

The reasons for abridging underground coal mining include [1]:

—introduction of alternative ecology-friendly sources of energy;

—decision of the Climate Change Summit in Paris in 2015 on the mandatory reduction in toxic gases, including in Russia, in the years immediately ahead by 30% as against emissions in 1990 with a view to decelerating the rate of warming of the Earth’s climate;

—complication of natural conditions of underground mining: greater depths down to 900 m below ground surface, higher gas content of coal beds over 13 $m^3/t$, elevated risk of gas-dynamic events;

—high accident rate in Russian mines: 11 large accidents for the latest 12 years, with more than 350 workers died.

For the first turn, as in the coal industry restructuring in 1992–2000 in Russia, it is planned to close coal mines with the super high methane content, prone to spontaneous firing and gas-dynamic events.

One of the ways of enhancing efficiency and safety of underground geotechnology in complicated natural environment is replacement of mine personnel with robotic machines.

With this end in view, the Siberian State Industrial University has developed the scientific basis for the robotics technology for deeper level mining of coal beds having high gas content [1–3].

The essentials of the proposed robotics geotechnology are:

—traditional methods of getting access to coal and mine field preparation;

—room-and-pillar method, with ventilation, parallel and accumulating drifts driven around a panel (see Figure 1);

—hydraulic mining of coal broken by high pressure water jets, hydraulic transport of coal slurry to underground dewatering chamber and traditional elevation of coal to ground surface.

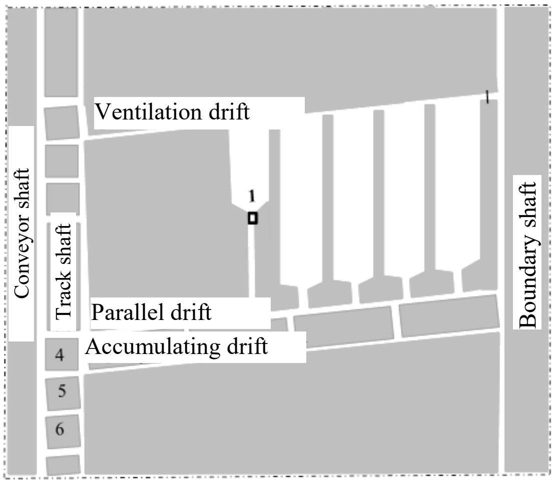


**Figure 1.** Automated coal mining with short rooms.

The designed robot-machine system is capable of:

—forward driving with hydraulic breakage of coal and gravity handling of coal into accumulating drift;

—backward widening of the stall, with turn of a jet generating box with nozzles in perpendicular to the room axis and with gravity handling of coal into accumulating drift;

—support of roof rocks at the stall and face junction with a remote canopy;

—remote and computer-aided control of the processes and operations from operator's panel.

Hydraulic breakage of coal eliminates such processes and operations involved in the conventional geotechnology as:

—mine ventilation as coal extraction is implemented without mine personnel present in the face area;

—precaution of inflammation and explosions of methane in the production face area, as mine air is phlegmatized by water vapors;

—hand control of mining machines due to remote monitoring of state of the production face area and owing to computer-aided control of the robot-machine system from operator's panel located in safe area, including ground surface;

—conveyors and locomotives within the limits of an extraction area owing to gravity hydraulic handling of coal slurry to a dewatering chamber;

—roof rock support as stability of sidewalls is ensured by minimized round-shaped cross section.

As is known, hydraulic coal mining technology used in the 1960s–90s features some drawbacks [4–6], including:

—accomplishment of basic and auxiliary operations by hand;

—large loss of coal, making 15.4–34.3% in 1988;

—high energy input for mining, hydraulic transport and hydraulic elevation of coal: energy consumption was 410–655 MJ/t of hydraulic coal mines using high-pressure jets and 182–464 MJ/t in water-jet-assisted mining in 1988.

The new proposed robotic mining technology with coal breaking by thin high-pressure jets will allow partly eliminating the above listed drawbacks. This paper presents some data on testing of coal breakage by fine jets with minimized energy input of mining due to optimized trajectory of the effector of the mining robot-machine system pre-set based on points of the maximum energy of rock pressure. The assumed optimization criterion for the coordinates of a current breakage area is given by

$$W_G + W_H \geq W_T, \quad (1)$$

where $W_G$ is the specific energy of coal breakage under integrated influence of natural and mining-induced stresses generated by geological and geotechnical factors; $W_H$ is the specific energy of coal breakage under influence of high-pressure hydraulic jets; $W_T$ is the theoretical specific energy of coal breakage under laboratory conditions, with regard to structural heterogeneity and boundary conditions of a coal specimen to be in conformity with mine conditions.

To find the specific energy of coal breakage under high-pressure hydraulic jets, $W_H$, the data of the laboratory tests from [7] were used, and the relation below was obtained after transformation of coefficients of dimension of values

$$W_H = A\left(\frac{f}{P_j}\right)^2, \quad (2)$$

where *f* is the hardness of coal by Protodyakonov's scale; $P_j$ is the jet pressure on the surface of the edge area of coal bed under breakage, MPa; A is the index of jointing of coal: recommended value is 20 for heavily jointed coal, 40 for medium-jointed coal and 60 for weakly jointed coal.

The theoretical value of the specific energy for coal destruction, $W_T$, was determined with due regard to the uniaxial strength of coal in the edge area from the formula [8]

$$W_T = \frac{(1+v)v\sigma_c^2}{E}, \quad (3)$$

where *v* is Poisson's ratio of coal; *E* is Young's modulus of coal; *V* is the coal volume under breakage, m$^2$; $\sigma_c$ is the compressive strength of coal.

The breakage energy $W_G$ under geological and geotechnical factors was found from numerical modeling of stress state of a coal bed, considering shape and dimension of a panel and a stall.

The modeling used a dedicated application package designed by the authors [9] and ensuring 3D problem solution in rock mechanics. The input data of the geometrical model of coal and rock mass were: depth of mining—900 m, total coal bed thickness—3 m, coal bed dip—12 deg; ultimate compressive strength of coal—10 MPa, extraction panel—200 m along the dip and strike, room was round-shaped with a diameter of 1 m and 6 m wide; rib pillar width was 1 m.

Rocks of immediate roof 14 m thick were represented by alternating argillite and siltstone with the ultimate compression of 20–40 MP; main roof with the thickness of 30 mm was composed of siltstone with the ultimate compression of 40–60 MPa. The shortwall parameters were assumed in conformity with the research results from [10].

The modeling included relocation of the face in the course of expansion of the shortwall relative to the west boundary of the extraction panel with the elongation of the mined-out void and the stall (see Figure 1).

Based on the modeling data, total vectors of stresses, strains and displacements in rocks, ratio of residual strength to natural strength of coal and deformation energy were calculated.

Figures 2 and 3 show the isolines of vertical stresses and specific energy of coal deformation at the juncture of the shortwall and stall. The similar plots were obtained for various locations of the face within the extraction panel.

According to Figure 2, the vertical stresses are extremely unevenly distributed in the immediate roof and, consequently, in the coal bed. The line connecting the points of the maximum abutment pressure goes along the diagonal relative to the stall axis. In conformity with the hypothesis of elastic deformation, a rock burst is expected in the vicinity of the stall. This proves the necessity of remote extraction of coal in shortwalls.

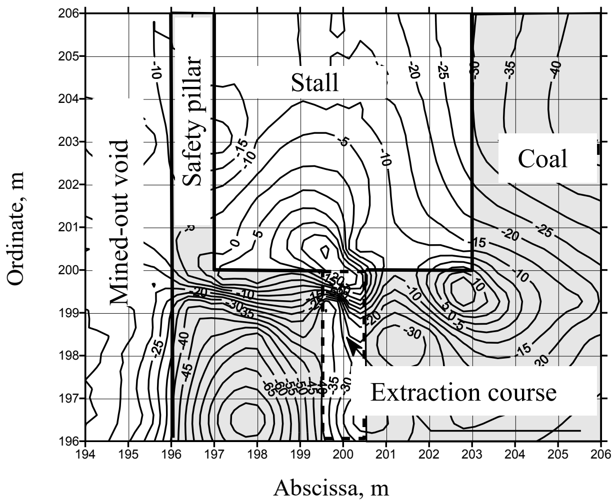


**Figure 2.** Isolines of vertical stresses (MPa) in the immediate roof rocks at the juncture of the shortwall and stall.

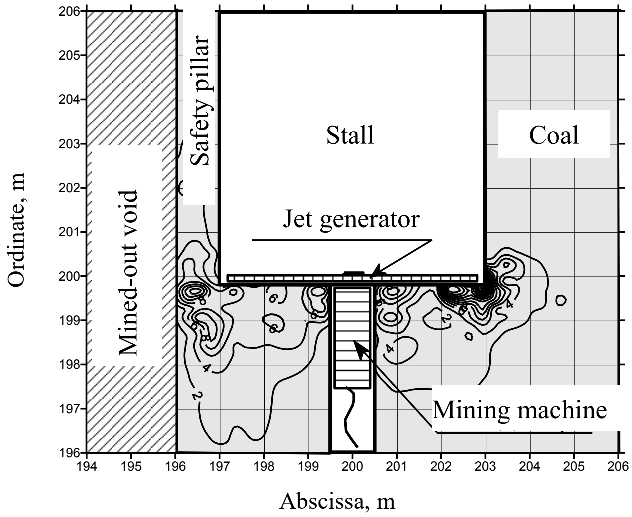


**Figure 3.** Isolines of the deformation energy (MJ) in coal bed at the juncture of the shortwall and stall.

At the shortwall and stall juncture, in the immediate roof rocks, tension stresses can induce rock falls and roof caving. This is also a fact in favor of the robotic coal extraction.

The deformation energy is also extremely unevenly distributed (Figure 3), which requires coal extraction with the minimized energy input with the prediction of the coordinates of the maximum energy deformation points in the production face area.

The modeling allowed finding that stresses in coal–rock mass and the deformation energy in edge are of coal greatly depended on:

—mining depth and coal bed thickness;
—shape and dimension of mined-out area;
—location of the production face area relative to the boundaries of the extraction panel;
—width of the coal pillar between neighbor stalls;
—coordinates of hydraulic mining zone on the surface of the coal bed.

The flow scheme of the coal mining control system is shown in Figure 4. The system operation optimization criterion is the minimum breakage energy $W_H$ under the action of high-pressure jets.

In accordance with (1), the objective function of the specified optimization criterion is

$$W_H = W_G - W_T \to 0. \quad (3)$$

The system of the remote control of coal shortwall mining includes:

Block 1: Object of control, which is a shortwall equipped with a robotic machine system as is shown in Figure 2.

Block 2: Subsystem of continuous remote monitoring of the shortwalling parameters (breakage efficiency, hydraulic transport of water and coal slurry, varied coordinates of the production face surface and jet nozzles in the course of mining, roof rock deformation, mine air parameters, etc.);

Block 3: Bundled software to estimate current conditions and predict optimal trajectory of the mining robotic machine effector, considering the objective function (4), including:

—calculation of stress state of coal bed with regard to the change in the production face coordinates;

—selection of the production face coordinates towards the maximum energy of coal breakage under integrated natural and mining-induced stresses;

—calculation of the coordinates of nozzles of high-pressure jets in accordance with (3) and (4);

—calculation of high-pressure jet parameters (pressure, number of nozzles, water flow rate).

Block 4: Subsystem of decision-making by an operator or a robot in accordance with the pre-set program.

Block 5: Subsystem of remote transition of control to a robotic mining machine.

The remote control flow chart for coal shortwalling is proposed to be used in engineering a mining robotic mining machine.

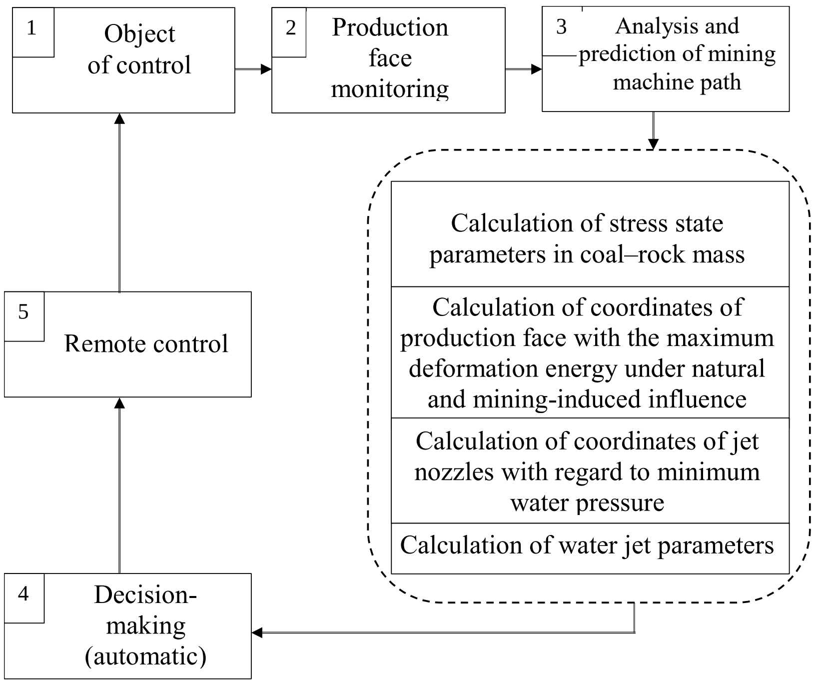


**Figure 4.** Flow chart of remote control of coal shortwalling.

In actual coal mining control, calculation of stresses and energy $W_G$ of coal deformation under influence of geological and geotechnical factors in each cycle of change in the position of the production face and decision-making as per Block 4 (Figure 4) will consume much time. Aiming to enhance operating efficiency of the production face control, it is proposed to carry out simulation modeling at stage of development of an extraction panel specifications and standards and to generate a matrix in the form of 3D digital model of geomechanical parameters of coal–rock mass. A fragment of such matrix is given in the table below with regard to the production face coordinates in Figure 3. The negative values of the deformation energy in the table correspond to the coal disintegration conditions under energy of rock pressure, i.e. no high-pressure jet treatment is required in this case, and only low-pressure water is to be fed to the production area to ensure gravity hydraulic handling of broken coal and rocks.

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Fragment of a digital model of geomechanichal and geotechnical parameters of a production area in coal bed with the ultimate stress limit of 10 MPa.

| Breakage zone coordinate in the face area, m | | | Deformation energy, MJ | | |
|---|---|---|---|---|---|
| *X* | *Y* | *Z* | $W_T$ | $W_G$ | $W_H$ |
| 1 | 2 | 3 | 4 | 5 | 6 |
| Distance to the face 1.5–2.5 m, ultimate compression strength of coal is 20 MPa | | | | | |
| 196.25 | 197.75 | –2 | 6.68 | 1.39 | 5.29 |
| 196.75 | 196.5 | –2 | 6.68 | 2.02 | 4.66 |
| 197.37 | 195.75 | –1.75 | 6.68 | 1.52 | 5.16 |
| 198.00 | 196.5 | –1.8 | 6.68 | 1.64 | 5.04 |
| 199.00 | 197.25 | –0.88 | 6.68 | 1.38 | 5.3 |
| 201.25 | 198.5 | –0.5 | 6.68 | 5.16 | 1.52 |
| 202.25 | 198.5 | –1.5 | 6.68 | 4.3 | 2.38 |
| 203.25 | 198.25 | –1.3 | 6.68 | 1.71 | 4.97 |
| Distance to the face 0.6–0.9 m, ultimate compression strength of coal is 15 MPa | | | | | |
| 196.25 | 199.12 | –2 | 3.75 | 5.38 | –1.63 |
| 196.75 | 199.25 | –2 | 3.75 | 8.29 | –4.54 |
| 197.37 | 199.25 | –2 | 3.75 | 4.28 | –0.53 |
| 198.00 | 199.37 | –0.88 | 3.75 | 3.72 | 0.03 |
| 1 | 2 | 3 | 4 | 5 | 6 |
| 199.00 | 199.37 | –1.75 | 3.75 | 6.94 | –3.19 |
| 201.25 | 199.37 | –1.8 | 3.75 | 5.5 | –1.75 |
| 202.25 | 199.37 | –1.8 | 3.75 | 7.46 | –3.71 |
| 203.25 | 199.37 | –1.8 | 3.75 | 2.42 | 1.33 |
| Distance to the face 0.1—0.5 m, ultimate compression strength of coal is 10 MPa | | | | | |
| 196.25 | 199.63 | –2 | 1.67 | 7.55 | –5.88 |
| 196.75 | 199.87 | –2 | 1.67 | 3.85 | –2.18 |
| 197.37 | 199.87 | –2 | 1.67 | 3.35 | –1.68 |
| 198.00 | 199.87 | –0.88 | 1.67 | 6.68 | –5.01 |
| 199.00 | 199.87 | –1.75 | 1.67 | 4.67 | –3.00 |
| 201.25 | 199.87 | –1.8 | 1.67 | 10.46 | –8.79 |
| 202.25 | 199.87 | –1.8 | 1.67 | 20.04 | –18.37 |
| 203.25 | 199.87 | –1.8 | 1.67 | 9.34 | –7.67 |

Using the numerical modeling results, the curves of the deformation energy in coal under influence of rock pressure at various distances to a production face are plotted in Figure 5. The dotted and dashed lines show the limit energy required for coal breakage. At the points located above the limit energy values, it is not required to use high-pressure jets.

It is suggested to display such plots on an operator's panel for making control decisions (Figure 4).

It is recommended to use the research findings in development of technical requirements for layout and software support of a robotic mining machine.

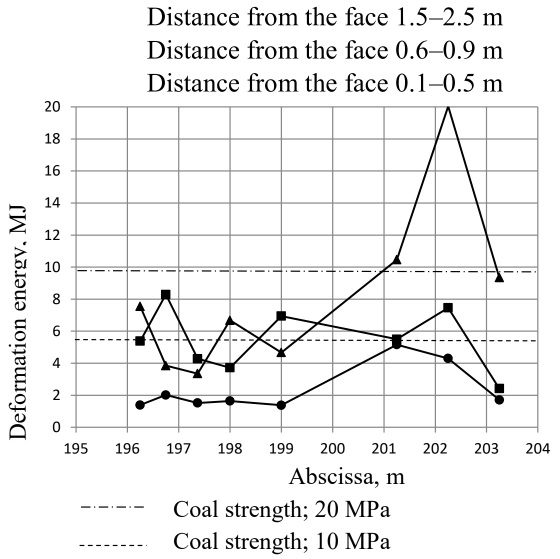


**Figure 5.** Energy deformation of coal under rock pressure.

## Conclusion

The relevance of robotic coal extraction technology to be developed in introduced in mining in complicated natural conditions has been substantiated.

The authors have put forward a process flow chart of coal mining with a robotic machine in gassy area using high-pressure jets and hydraulic transport of broken coal to a dewatering underground chamber.

The procedure to select optimal parameters for high-pressure jet operation is based on the criterion of minimized destruction energy at maximum utilization of energy of rock pressure.

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