Simulation Environment for Development of Automated Process Control System in Coal Mining

Victor Okolnishnikov, Sergey Rudometov, and Sergey Zhuravlev

***Abstract*— A set of simulation models was developed with the goal to be used as a quality and reliability assurance tool for new automated process control systems in coal mining. This set of simulation models of various subsystems of a mine was developed with the help of a new visual interactive simulation system. The paper contains a brief description of the simulation system and its characteristics. Main possibilities that are provided by the simulation system are: the quick construction of models from library elements, 3D representation, and the communication of models with actual control systems. These models united to create simulation environment. Simulation environment is visually interactive, include emulation models of technological equipment and allow simulating complex situations in mines and working faces visually as well as to check the response of automated process control system developed for these situations. Simulation environment was used for testing of control programs executed in programmable logic controllers as a part of automated process control systems prior to commissioning. Simulation environment can be used not only for existing coal mining techniques but also for perspective (robotized) techniques. The strategies of underground mines without having actual miners are simulated: replacement of miners by remote-controlled manipulators, robotics-based mining, and control of mobile machines from surface.**

***Keywords*—**Automated process control system, coal mining, emulation, **v**isual interactive simulation.

I. Introduction

A number of Automated Process Control Systems (APCS) for different industries like coal mining and oil mining is being developed at Design Technological Institute of Digital Techniques of Siberian Branch of the Russian Academy of Sciences. Among others the following problems arise during the development of such systems. The complete testing of control system using the programmer's tools prior to commissioning is almost impossible because of inability to connect with real equipment and because of inability to reproduce an operational situation and emergencies.

The most suitable way to solve these problems is simulation. A means for solving these problems is a model integrated with an actual APCS. The model can be run as a part of an actual APCS. On the other hand the model can include software or hardware components of the actual control system, for example, control programs or a programmable logic controller (PLC) in which the control programs executed. This model should also include a model of technological equipment. Such model is known as an emulation model [1].

There are many examples of the use of emulation models for testing automated production lines or automated material handling systems [2]–[4].

This paper describes the use of simulation and emulation models for developing of industrial APCS of underground coal mining (Kemerovo region, Kuzbass, Russia).

Today the technology of coal mining is well developed. But the state of the industry requires and the state of the science permits to make a quality move in tool development for mining. It is now possible to make this branch really safe, and product mined really cheap. One of the ways to reach it is to robotize mining.

In this case robotize means to invent mining and supporting machines that can fully replace a human under the ground. This possibly requires the creation of intellectual machines that can make simple or complicated solution. Such mechanisms are usually called robots.

Robots will allow not only replace humans under the ground but require less supporting background: they can work at very high temperatures, with very high percentage of dangerous gases in atmosphere. The production unit of such robots can the underground gas to get the energy right under the ground, without need to plug them to ground power stations, and loose a significant amount of energy while power transmission deep under the ground. The coal can be separated also under the ground, with rock refuse being placed into empty mine parts.

Today mines use the approaches that can be recognized as robotized (Highwall systems). Main mechanical elements inside the mines are still machines for mining, transportation, and support installation and control.

Also there are a lot of additional machines (generators,

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transporters, etc.) required to organize fully functioning mine.

How exactly will these machines function, what additional machines will they require, what is the cost of machines in stalled in mine, how to organize the delivery of spare parts for these machines? Will big universal machine be more appropriate rather than a lot of small, specialized mechanisms? What will the cost of a final product be? These questions can be answered by the method of computer simulation of coal mining process.

For solution of these problems a set of simulation models of various subsystems of coal mining was developed with the help of the new visual interactive simulation system of technological processes. These models were developed with the goal to be used as a quality and reliability assurance tool for new APCS of coal mining. These models of various subsystems of coal mining were united to create simulation environment of coal mining.

Simulation environment includes also emulation models of technological equipment and allow to simulate complex situations in mines and working faces visually as well as to check the response of APCS developed for these situations. Simulation environment was used for testing of control programs executed in PLC prior to commissioning.

II. Visual Interactive Simulation System of Technological Processes

Computer-based simulation was invented as a way to solve problems that was unable to solve analytically (mostly mathematically). Original problem must be decomposed to the form that allows it to be solved by some existing approach (queuing theory, Petri nets, etc.).

Systems for computer simulation can be divided to classes:

1) Simulation languages and libraries.
2) Systems for visual composition of simulation models.

This classification is not exact: simulation languages can have a visual graphical environment, or systems for visual composition will translate simulation models to some existing simulation language.

But most important is that all these systems can be used just by specialists in simulation. Computer-based simulation is complex. Only specialists in simulation able to make a decomposition of original problem, create simulation experiments, validate and verify models, and most important to make a backward decomposition and analysis of simulation results to final users (subject matter experts).

In the latest 10 years a number of simulation systems appeared that subject matter experts can use (ProModel, WITNESS). But these systems are built based on existing, previous versions of the same products that are only for specialists in simulation. As a rule, interface of such system is untouched, only some subject-oriented components added. And these systems still relies on decomposition of original technological systems like in a raw simulation. But today computers are not limited in memory and processor resources, they are very good with user interfaces, and they allow creating simulation experiments with very detailed simulation models, with detailed and informative graphical representation.

Another disadvantage of such systems is that they try to be universal. This leads to overloaded interfaces and knowledge area of simulation system itself.

Indeed, the simulation of some technological systems is usually complex. It is unexpectedly complex to define it "from scratch", and the simulation science itself is complex.

A subject matter expert does not need anything of this. They just need a tool with elements they are familiar with, that will allow building simulation models immediately, without any preparation like decomposition or data preparation. They even do not need to know if this is a simulation model. Such systems (and our experience shows this) subject matter expert likes and understands most.

At present simulation tools are required for rapid development of models for various industrial applications [5]. Such models can be used as parts of actual APCS for developing, testing, optimization, and operator training [6]–[8]. They can be also used in marketing to present some industry solutions to the customers.

One of the requirements is to reduce or to exclude the participation of specialists in simulation in the process of the simulation model contraction. It is required to ensure transparent access to simulation environment for the specialists from application area having minimal knowledge in information technologies [9].

Non-formalized requirements for the development of state-of-the-art simulation systems are:

1) To create the simulation models by subject matter experts who are not a specialists in simulation.
2) To create the simulation models of complex technological systems by combining simulation models of technological objects in these systems.
3) To hide any aspects of simulation from a final user. Only the possibility to tune parameters must be presented. These parameters must be clearly understandable for final user.
4) To create the simulation models fast, allowing users to focus on problem solving but not on development of simulation itself (and then on a simulation model).
5) To control simulation run visually, with ability to pause simulation at any time and to examine or change simulation parameters.
6) To examine statistical parameters at any time during simulation, in a form that is clearly understandable for final user.

These requirements are given below in a more formal definition that can be applied for realization:

1) Visual interactive interface for simulation creation and execution.
2) Usage of graphical tools for model creation.
3) Support for fast model creation.
4) Simulation model is created from existing, ready-to-use

simulation models.
5) Simulation model creation by final users.
6) Simulation model and simulation system must be able to be connected to any external systems.
7) Simulation model works in two-dimension (2D) and possibly in 3-dimension views.
8) Simulation results are presented as complete analysis, without necessity of any additional analysis.
9) Any statistical data can be exported and analyzed externally.

These requirements were taken into account while designing a new visual interactive simulation system of technological processes MTSS (Manufacturing and Transportation Simulation System) [10]–[14]. It allows building simulation models, using simulation models of technological equipment and a coal layer. The simulation model for coal mining can be created from simulation models of technological equipment, connected with each other and with simulation model of the coal layer. The coal layer can be set with its linear sizes, placed into the geographical coordinates. Various zones in a layer model can have different properties (amount of coal, quality of coal, etc.).

The key point in MTSS is an Equipment Model (EM). EM is a simulation model of a technological object in a technological system. It consists of the following parts:
1) Two-dimensional and three-dimensional graphic images.
2) Input and output parameters.
3) Functionality algorithm describing dependence between parameters.
4) States which EM can reach during the simulation process.
5) Control commands defining switching process between EM states.
6) Some service functions.

EM development process consists of creation a conceptual model of a technological object and its automatic translation into Java in accordance with EM structure in MTSS.

Images of different EMs can be connected to each other visually with the help of graphical port mechanism. Such approach allows building models of complex technological systems using models of contained technological objects.

As a rule each mine has a plan of mining. Such plan is usually created after the scientific investigation of a land zone. In simulation model such plan can be described as linear segments connected to each other by their ends. Mining machine can mine the coal only near each linear segment where it is currently placed. So the coal layer can be simulated as a set of connected linear segments, with coal placed around these segments only at the distance reached by mining machines. The amount, density, amount of gas, etc. of the coal in model can be varied.

Changing the "density" property it is possible to define whether the product is coal or rock. Changing the "amount of gas" parameter it is possible to define how fast the amount of gas will increase while mining. This will define moments when mining must be stopped and mines filled with fresh air.

Mining machine (MM) is the main technological equipment for simulation of working face. Existing mining machines as well as perspective robotized mining machines need a possibility to specify various parameters in a model, like the following:
1) Dimensions of MM.
2) Weight of MM.
3) Performance of MM.
4) Type of control.
5) Presence of special tools for coal layer properties measurement.
6) Presence of connected fastener system.
7) Embedded conveyor with machines for its automatic enlargement, etc.

In addition to the model of working face there were developed models of other subsystems of the mine: a model of belt conveyor network, a model of drainage subsystem, and a model of electric power supply.

A fragment of the model of a belt conveyor network is shown in Fig. 1. The model of the belt conveyor network consists of EMs of conveyor links and bunkers, and requires a simulation model of power supply to function.

A fragment of the model of a drainage subsystem is shown in Fig. 2. This subsystem refers to mine safety systems. It averts mine flood. The drainage subsystem model consists of pumps, tubes, tanks, water flows and requires elements of electricity subsystem.

Main possibilities that are provided by MTSS are: rapid visual interactive building of models from EMs, 3D representation, and the communication of models with actual APCS.

III. Simulation Environment

Simulation environment to test control programs executed in PLC is developed. PLC is a part of APCS. Testing control programs executed in PLC prior to commissioning It reduces the time and the cost of testing and optimization APCS.

The structure of this environment is shown in Fig. 3. It consists of:
1) MTSS workstation which allows the users to work with simulation models of technological equipment and technological processes of actual system.
2) SCADA workstation is a place of APCS operator.
3) The communication environment for data transmission is designed to send data between workstations, controllers and (if system is already deployed) technological equipment. If controller has a direct connection with technological equipment (i.e. it has analogous and discrete ports for input and output signals), a special communication convertor is added to allow testing. This convertor will transform notification signals into analogue and discrete signals, and visa versa.
4) APLC is tested equipment.

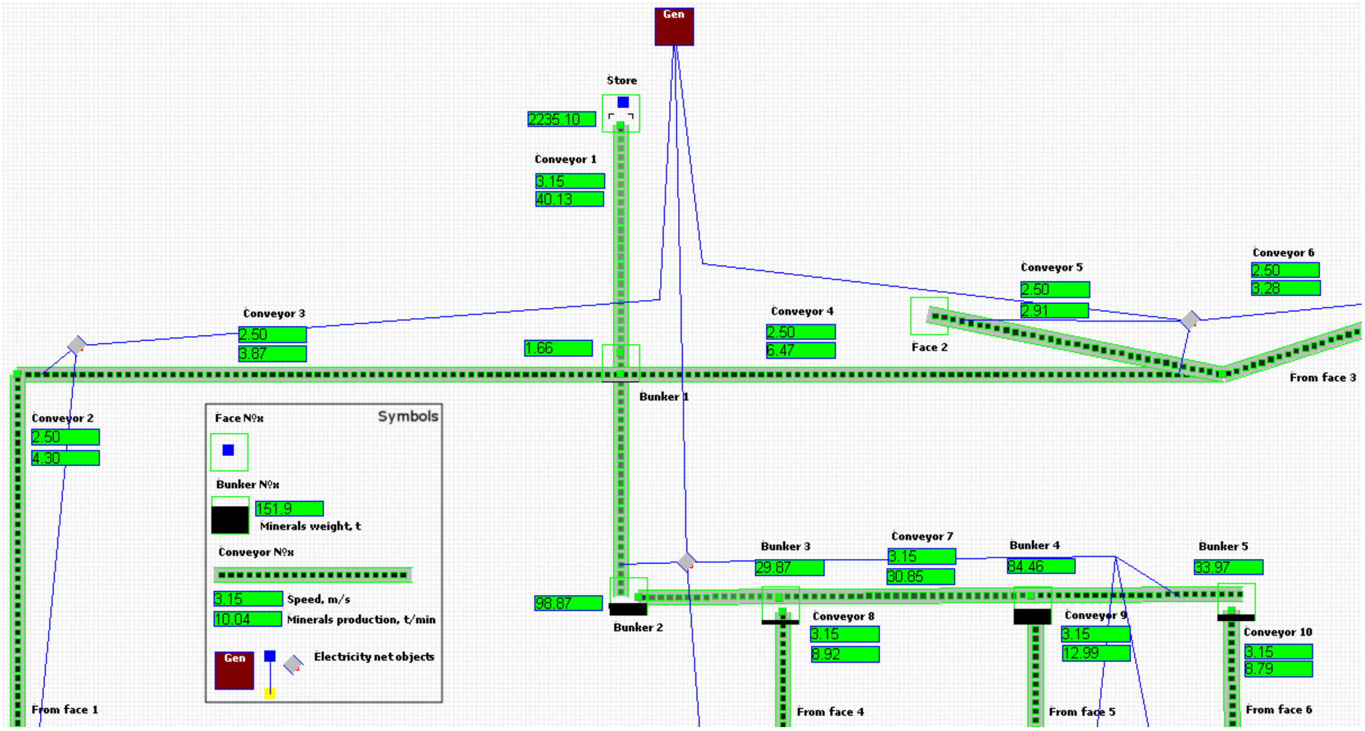

Fig. 1. A fragment of the model of belt conveyor network.

5) Sensors and actuators of technological equipment are the part of simulation environment in case of its usage as a part of a Solution Support System (part of APCS).

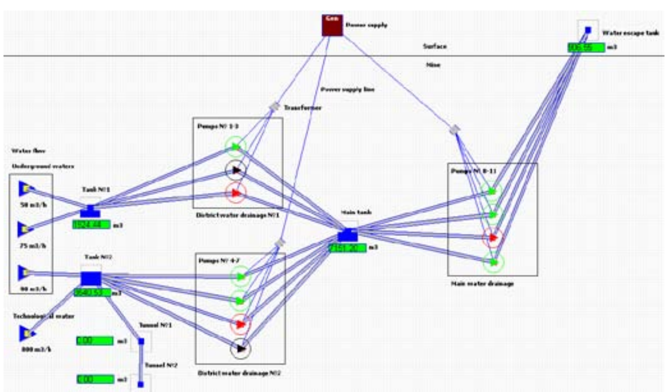

Fig. 2. A fragment of the model of pumping subsystem.

There are a number of simulation models what were developed. They are a part of MTSS workstation and they are used both as a source of control signals and sensor states. Simulation environment can function in the next modes:

1) Testing. This mode is used to check control programs in the frames of APCS.
2) Investigation. The mode is used to research the algorithms of control programs in the frames of APCS. The goal of the mode is to predict the values for various (all) technological parameters predict the consequences of in the case of emergency and develop the operator actions to prevent the cases themselves.
3) Education. The mode can be used to teach and certificate the operators of APCS.
4) Solution support mode. It is used to evaluate various control actions made by an operator of APCS on simulation model before the actual commands are made.

Several modes of operation of the simulation environment are shown in Fig. 4.

There are three modes of operation of the simulation environment: a technological process simulation, a controller testing and real and simulation control program comparing.

Control command starts an execution of a model a technological process in MTSS. Then the command is processed in accordance with the model of the control program. State change is shown in the animation window of MTSS.

While the controller testing mode the command goes to a communication manager. The manager realizes that information is transmitted between the controller and the model of the technological equipment with use a module of conversion. This module converts the data which transferred to the controller from the model and vice versa. The data that transmitted from the model is processed in the controller. Controller creates control signals for actuators. These signals entered the communication manager.

Converted control signals are executing in the simulation system. Changing the state of the model is showing in the animation window of MTSS.

There are two independents steps in comparing mode – simulation of the technological process and testing of the controller. First step is simulation of the technological equipment. This step is the same as the simulation mode. Second step consists of execution of the control command in the controller program logic and animation of control actions. Simulation results and the actual results of the execution of the control programs are presented separately.

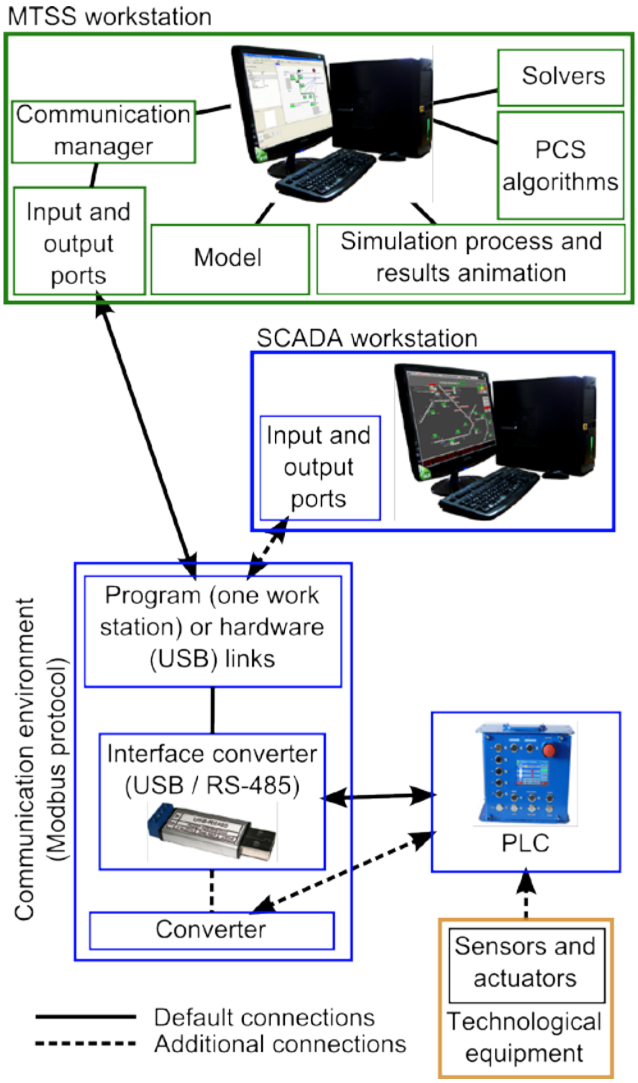

Fig. 3. The structure of the simulation environment.

IV. Simulation of Strategies for Mining

Simulation environment can be used not only for existing coal mining techniques but also for perspective (robotized) techniques.

The strategies of underground mines in the future without having actual miners are simulated: replacement of miners by remote-controlled manipulators, robotics-based mining, and control of mobile machines from surface.

We have simulated possible strategies for underground mining without miners [15]:

1) Solution mining.
2) Protection against underground hazards.
3) Replacement of underground miners by remote controller machines.
4) Robotics-based technologies.
5) Control of underground machines from the surface.
6) Intellectual mining.

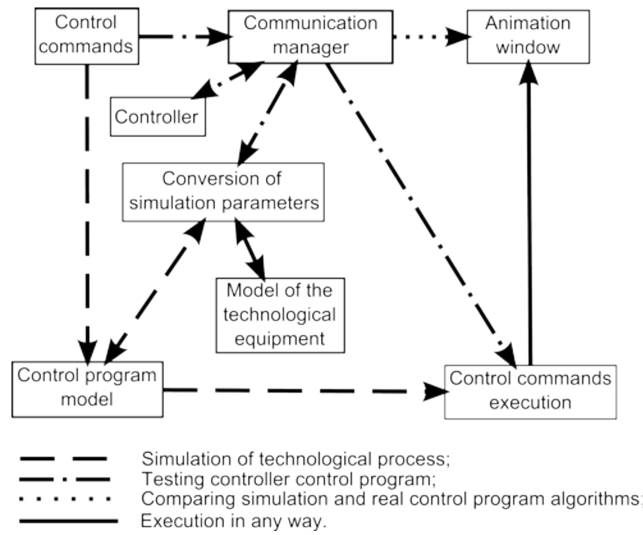

Fig. 4. The operation of the simulation environment.

A. Solution mining

Unfortunately, only a few useful minerals, such as coal or uranium are available for underground solution mining. Transferring semi-processed underground minerals to the surface will result in higher processing costs as well as leaving some minerals in the ground.

B. Protection against underground hazards

The second strategy given above "Future Underground Mine" was considered in the 1970's. Having special protection for miners will reduce their activity while mining. It is for these reasons that the last three strategies are studied by simulation.

C. Replacement of underground miners by remote controlled manipulators

In the early 1990's many experts believed that it was possible to replace miners by robots as are used in manufacturing [16]. Unfortunately, many mining methods make it impossible. An underground manipulator must work with large loads in a constantly changing environment and in a limited space. It is necessary to determine service zones and plans foe the movement of the equipment, ways to avoid collisions during movement of the equipment. Making machines to do the work of miners is difficult because of the high-speed required, work in hidden environments, the rotary and telescopic movements of the machines, etc.

Instead, we will simulate the extraction of the ore extraction for a difficult mining area by using an autonomous bucket loader. The working cycle consists of four actions: scoping of the ore from the stope; movement along a roadway; unloading of the bucket and return to the stope.

Before entry to a potentially dangerous stope, the miner leaves his cabin and controls the scooping via radio.

An operator must select one of two haulage strategies for every haulage action:

1) Turning of scooping with a U-turn of the machine until the bucket is filled (manual circuit).
2) Completion of the loading if an actual filling is to be more than a stated filling; then the additional working cycles are realized.

What a strategy is better for maximum output?

Random filling after a scooping was simulated by random delay. Then, the actual filling of the bucket is measured. If the actual filling is more than a given filling, the haulage is finished and the machine leaves the face and moves to the dumping area. After dumping and U-turn, the machine moves to the haulage road.

If the actual filling is less that a given filling, the machine moves back and reiterates a scooping.

During many simulation experiments the same filling was used for both strategies, the distance of haulage was changed, and output of the shift was evaluated. The results show the shift output is more, if the given filling of a bucket is at least 65% -70% of any rate for haulage length 45 m and scooping time 10 s. This is shown in Fig. 5.

The simulation shows that the output for the second strategy is 17% more than one for the first strategy. The time lost for the reiteration of scooping is more than the time for extra trips. Intellectual sensor of bucket filling can form the signal to finish the loading for the actual haulage length.

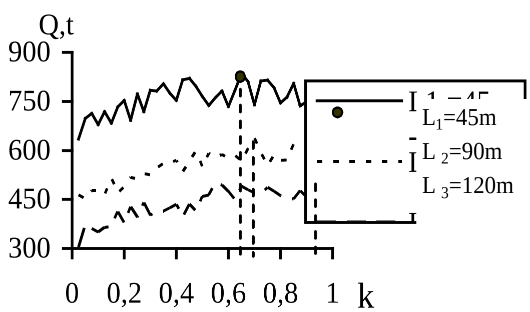

Fig. 5. Shift output Q for various given filling of bucket k and diverse haulage distance L.

D. Development of robotics-based technologies

Certain technologies can not be realized without robotics. This is about the utilization of new opportunities of robotics in mining, such as work in dangerous and narrow zones, actions at high speeds and precise movement, acquisition of data beyond a miner's ability, and data integration. As different from the miners, robots don't require expenses on vital activity, can accumulate information, and measure data exactly.

However, automated equipment is not able to realize the intellectual functions of miner, such as decision making.

The Scandinavian technology program "Intelligent Mine" is aimed to increase a working time use by information change in real-time, robotization of autonomous mining machines, application of high technologies in mining, forming of mining machinery. One consists of 28 projects such as automatic charging, shotcreting, and drilling, navigation of machines without drivers, high-speed information network, computer control of mining from surface in real-time, and robotized LHD-machines.

We have simulated the robotics-based technology to extract coal from steep coal seams 0.4-0.7 m. This is shown in Fig. 6. Support shift robot 1 rises to roadway and advances by turn support units 2 to face. A shearer 3 moves after support shift robot.

Some support units are in non-standard position and require control from the operator. The more the number of such units is the less control from operator–automat effective is. The conceptual model of the technology consists of two types of control: control from operator-automaton and control from operator.

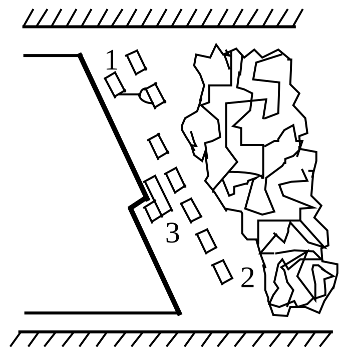

Fig. 6. Robotics-based longwalling of thin steep seams: 1-support shifting robot, 2- support unit, 3- shearer.

Frequency of the non-standard states is simulated at random. The time of failure removal corresponds to random delay. During simulation a total time of support shifting for both types of control has been evaluated. As a result, the line of equal shifting time was constructed. This is shown in Fig. 7.

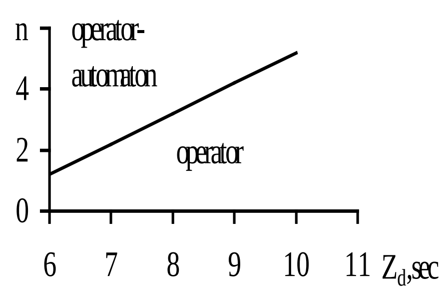

Fig. 7. Border between two types of control.

In addition, the speed of support shifting robot was determined. During simulation experiments the speed Vs was reduced and a relative total labor-intensity I was evaluated. The results showed that the supporting speed must be more than 1.3 meter per minute [17]. This is shown in Fig. 8.

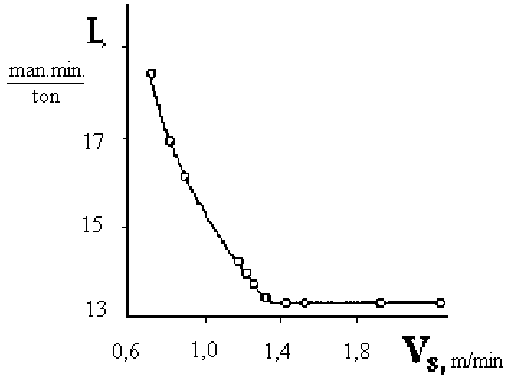

Fig. 8. Influence of support speed V_s on the labor-intensity L for robotics-based extraction of coal.

The problem of underground mining without miners can be solved in two ways:

1) Replacement of miners by manipulators in miner-based technologies.
2) Development of robotics-based mining.

Initially, the uses of automation are limited by the miners' capabilities. The second way was the idea of mine without miners, such as is found in a methane-filled mine. The concept of a robotics-based mining must be one that allows robots specially tailored to the mine. These will result in: reduction of down for the equipment, high speed of work, reduction of labor cost, reduction of driving cost, increased miners' safety, savings of energy and materials, improvement in the social conditions for miners' work, multifunctionality of robotics, stabilization of working actions, flexibility of control, work in places, that were inaccessible for miners, group service of equipment by single robot, and reduce of "know-how"-experience.

Let's compare both strategies. At first, remotely- controlled manipulators (I) and robotics-based technology (II) have the same stages of development. This is shown in Fig. 9.

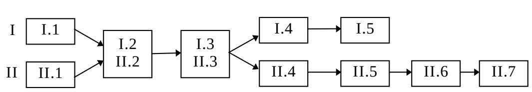

Fig. 9. Development of two strategies for mining in the future. The following designations are shown in the figure.

I – remotely-controlled manipulators: 1 – mechanization of manual work, 2 – remote control under direct visibility, 3 – remote control without direct visibility, 4 – reduce of manual work for traditional mining, and 5 – work in hazardous areas.

II – robotics-based technologies: 1 – indirect control of equipment, 2 – remote control under direct visibility, 3 – remote control without direct visibility, 4 – automation of cyclic actions, 5 – robotics-based technologies, 6 – adaptive interaction of machines, and 7 – flexible technologies of unmanned mining.

The development of remotely-controlled manipulators is finished by work of manipulators in hazardous areas under remote control without direct visibility whereas technological robots will have been developed to robotics-based technologies. Therefore mine technological robots are more perspective for intellectual mining in the future.

E. Control of underground machines from the surface

At present a machine's driver works in a cabin. Idea of mining in the future is: operator controls of machine from surface.

As a rule, on-board system takes routine actions of control such as movement in roadway, whereas operator takes intellectual actions such as scooping of rock mass. Thus an operator can control of many machines.

However, many questions hadn't answer: how many machines is accessible for an operator, when a queue takes place, what an order of service is more effective, what an influence has a correlation between automatic and remote control on downtimes of machines, what an influence on technology has a distribution law of actions time.

Some sub-systems must be created for such strategy. These include an information network to transmit sound, data, and video information in a real-time mode between underground machines and the surface; man-machine interface for the control of underground machines from the surface; on-board control systems for autonomous machines; software for both current and strategic mine planning; navigation and positioning of autonomous machines in the roadways.

The control of machines from the surface has the following advantages: super-deep mining, better safety for the miners, less time for moving between the surface and the working area; mine planning in real time; planning of equipment maintenance based on actual work; changing of mining activities from the surface; acquisition of new knowledge, such as fuel expense, working reserve, current cost in various areas, state of a machine stock; shortening of machines downtimes.

F. Intellectual mining

Let's present some features of intellectual mining:

1) Mobile machines are equipped by on-board control systems instead of a driver.
2) Autonomous mining machines move along guide line.

As a result, any machine can adapt itself to changing working conditions: to change positions of working heads, and direction of movement, step size and speed of extraction and roof support. Such opportunities will make possible to avoid some geological hazards, avoid dangerous rock pressure manifestations, stabilize the quality of mining and increase the utilization of machinery. Existing information networks for distributed sensors for rock pressure or voice exchange are not available for intellectual mining because the control of autonomous machine in real-time requires a limited time delay and video information. It is necessary to form a conceptual plan of intellectual mining before designing it elements. These elements include the information network, sensors for mining planning, sensors for the control of the machines, interface between the operator and the underground equipment, awareness of the placement of the machines, and navigation of movement in the roadways.

The simulation makes it possible to determine the requirements of the mining machinery. These include the working speeds and output. Because it is about non-existing mining, the validation of the models requires a special methodology.

V. Conclusion

The Java and Eclipse RCP is used as a technology and a platform for implementation of MTSS. Such selection allows having portable implementation on many platforms. Also Java technology is good enough to meet all needs, including performance and graphics (2D and 3D).

One of the tasks solved using MTSS is the creation of a simulation model of the underground perspective mining. Current version of this model allows creating investigations of configurations of a working face (amount of mechanisms, energy consumption). It is possible to combine simulation of working face with simulation of other areas of working face and underground mining (electric power supply, drainage, belt conveyors) to create very complex and detailed models of mining industry. These models are visual and interactive. Today the primary goal of these simulations is to provide a source of emergency situations for developing of APCS.

MTSS allows development of simulation environment that makes in possible to create very detailed and reliable simulation models by subject matter experts who are not familiar with computer-based simulation.

MTSS started as a simulation environment for technological systems. But its applications are not limited only by technological systems itself. Specialist in simulation can build libraries of EMs for wider range of systems by using capabilities of MTSS. Example is the library of EMs for computer simulation of complex computational network.

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