Mechatronic systems in mining roadheaders – examples of solutions

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Abstract: In the process of control of mining machines the problems with development of a classical mathematical model describing phenomena that accompany operation of these machines are presented. These problems are the result of specificity of the process of driving the roadways and the direct reason to undertake trials to use artificial intelligence technologies in modelling of phenomena, which occur during rock-drivage of roadways.

The following problems are presented in the paper:
- state-of-the-art control systems used in roadheaders,
- possibilities of use of artificial neural networks in control systems of mining machines (on the example of a roadheader),
- model tests with use of data recorded during drivage of roadway with use of a roadheader,
- determination of cutting resistance with use of an artificial neural network to determine the value of set angular speed of a roadheader's cutter jib in the plane parallel to the roadway floor.

Presented model tests are the result of R&D projects associated with designing of an intelligent control system of the roadheader, which are realized at the KOMAG Institute of Mining Technology and at the Faculty of Mechanical Engineering of the Silesian University of Technology.

Keywords: mechatronic systems, mining roadheaders, numerical techniques, control system, neural network

1. Introduction

In the Polish mining industry over 92 % of roadways are currently driven by a selective mechanical cutting method using jib roadheaders. Forecasts for coming years anticipate the necessity of driving from 500 km to 700 km of roadways per year [7]. Necessity of opening coal seams on more deep levels causes an increase of driving problems due to:

requirement of driving roadways of greater cross-sections, what is indispensable to ensure a proper ventilation at increasing temperatures and at production rate increase,

increase of rocks compactness and their strength to uniaxial compression.

Implementation of new solutions as regards control systems is associated with a necessity of conducting long and expensive tests. New approach in implementation of the system consisting in using the virtual prototyping method enables to reduce maximally costs and time.

2. Roadheaders control systems used in the Polish mining industry

Rock cutting by a roadheader is the most frequently used technology for drivage of roadways in the Polish hard coal mining industry. Natural hazards (e.g. potentially explosive atmosphere) significantly limit a possibility of use of typical control systems. These systems have to meet certain requirements, which make using a typical industrial automation equipment impossible.

Development of roadheader control systems is possible due to bigger portfolio of sensors available for use in the areas threatened by the explosion hazard. Absolute and incremental encoders, which make monitoring of the cutter head position easier, appeared on the market in the last few years. Currently used solutions of roadheaders control systems give, to a different degree, a possibility of automation of drivage by use of a remote control system or by recording of operational data and sending them to external applications of SCADA type. However, these systems do not ensure a possibility of adjustment of jib circumferential speed to the mining-and-geological conditions of the roadway.

REMAG, JSC [13] is one of manufacturers of roadheaders in Poland, which specializes in manufacturing of light-weight and medium-weight roadheaders. Roadheaders made by this manufacturer are equipped with highly advanced electro-hydraulic control systems, among others with a load sensing system. However, these are not automatic control systems. The whole cutting process is realized manually by the operator, who controls operation of the machine from the desk. The desk of R-130 roadheader

Fig. 1. Desk of operator of R-130 roadheader [own source – Mining Expo 2008]

Rys. 1. Pulpit operatora kombajnu R-130 [materiały własne – Mining Expo 2008]

Fig. 2. Operator's stand of MR340K roadheader manufactured by SANDVIK [own source – Mining Expo 2008]
Rys. 2. Stanowisko operatora kombajnu MR340K firmy SANDVIK [materiały własne – Mining Expo 2008]

is presented in fig. 1. Roadheaders of light-weight of AM-50 or R-130 type have simplified the control system, because the users expect the machine, which is cheap, reliable and simple in operation and servicing, what does not favour implementation of advanced electronic systems. Implementation of a new type of control is associated with trainings, aim of which is to change mentality of users and to persuade them that a better control system will improve work safety and increase effectiveness of roadway drivage. Use of automatic control in roadheaders manufactured in Poland is very significant due to improvement of their competitiveness in relation to foreign solutions, and it will secure work safety.

SANDVIK [14] roadheaders are also used in the Polish hard coal mines. Roadheaders of this manufacturer have developed automatic control systems. Operator's stand of MR340K roadheader manufactured by SANDVIK is presented in fig. 2.

Fig. 3. KTW-200 roadheader manufactured by WAMAG [12]
Rys. 3. Kombajn KTW-200 firmy WAMAG [12]

The operator has a large graphic display unit at his disposal, on which a position of the cutter head in a roadway face and messages associated with the machine operation are displayed. SANDIVK also offers the solutions, which enable remote control – the visualization system is located at some distance from the roadheader.

KTW-200 roadheader (fig. 3) presented at the MINING EXPO fair in 2008 and KTW-150 roadheader presented at Mining Fair in 2011 by WAMAG [12], which is a part of the Kopex Group, are the novelties on the Polish market. Remote control system and automation system, which includes among others monitor, on which a position of cutter head in a roadway cross-section and data as regards position of roadheader in relation to roadway axis are displayed, are used in both roadheaders (fig. 4).

Control system of KTW-200 roadheader, which is made by BARTEC Company, can be optionally equipped with data base with information about roadway geometry and module for limitation of cutter head trajectory to not exceed the roadway outline (fig. 5).

Fig. 4. Desk of KTW 150 roadheader [own source – Mining Fair 2011]
Rys. 4. Pulpit kombajnu KTW 150 [materiały własne – Targi Górnictwa 2011]

Fig. 5. Laser system for positioning of KTW 150 roadheader [own source – Mining Fair 2011]
Rys. 5. Laserowy system pozycjonowania kombajnu KTW 150 [materiały własne – Targi Górnictwa 2011]

Transmission of data to the dispatcher room on the surface is a significant function of the control system. Company SANDVIK collaborates with manufacturer of SMOK data transmission system – SOMAR Company [15]. Data from roadheader are transferred to the surface by telephone modems or light pipe.

Work realized within European projects aims at a development of the system for automatic drivage of roadways. These problems are being solved, among others, in the ADRIS project financed by the European Fund for Coal and Steel and in the NEMAEQ project. They refer to use of radar sensors, coal-rock sensors, infrared cameras, systems for analysis of vibrations, systems for wireless data transmission and visualization systems.

3. Possibility of use of artificial intelligence methods in the roadheader control system

Artificial neural networks are more and more frequently used in different branches of industry, including mining industry. A possibility of use of neural networks in studies on rock cutting process by conical rotary bits should be especially emphasized [1–3, 5, 6, 8].

The system controlling the angular speed of roadheader jib which takes into account the mining-and-geological conditions in a roadway face, suggested by the authors, is the example of use of an artificial neural network in automation systems of mining machines.

Identification of resistance of rock cutting is a key function of the control system. A simplified diagram of the system for control of angular speed is presented in fig. 6. It is a modification of the control system with model identification. It was assumed that the maximal angular speed $\omega \Rightarrow$ max of roadheader jib is the input to the control system. A module of neural identification of cutting resistance coupled with the module of determination of speed generates signal ω_1, which is a correction of a set value. Control of speed is realized in a feedback loop (fig. 6).

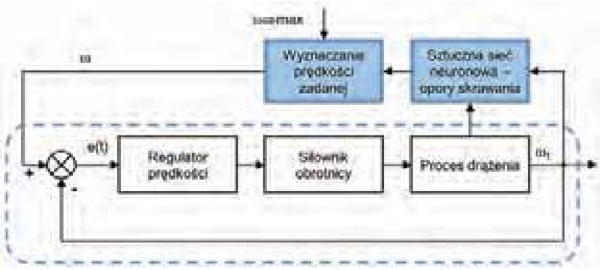

Fig. 6. Simplified diagram of the system for control of jib angular speed by use of Artificial Neural Network [4]
Rys. 6. Uproszczony schemat systemu sterowania prędkością kątową wysięgnika z zastosowaniem Sztucznej Sieci Neuronowej [4]

Module for identification of model parameters was made using an artificial neural network. The network was prepared in the MATLAB software programme with the Neural Network module. Process of neural network learning was realized with use of data collected during tests on parameters of the process of roadway drivage with use of the roadheader. Input data had to be initially processed [10, 9] because it was necessary to filter out the unimportant values or to make changes in their presentation.

All input amounts were initially processed in the neural network, which corrects a given speed of the jib. Selection of the method for data processing was made on the basis of literature analysis [10] and initial numerical analyses.

3.1. Testing of parameters of roadway drivage with use of roadheader

Results of initial tests (fig. 7) and results of tests carried out in real conditions during drivage of a roadway with use of R-130 roadheader manufactured by REMAG, were used in the project. The tests were realized within the R&D project entitled "Integral control system of roadheader" by the specialists from KOMAG and P.U.P. SOMAR, Ltd.

Measuring instruments were installed on R-130 roadheader used in "Marcel" Colliery, in the M-6 testing ramp, in $707/_2$ seam. The ramp was driven in the ŁP9/V29/A support of frame spacing 0.75 m. The roadway width was equal to 5.0 m and its height 3.5 m. The cross-section area was 14.8 m^2.

Fig. 7. R-130 roadheader during initial tests at REMAG's testing facility [4]
Rys. 7. Kombajn R-130 w trakcie badań wstępnych na stanowisku badawczym REMAGu [4]

In the lower part of the roadway there was coal of thickness of 1.4–1.6 m and of strength to uniaxial compression equal to R_c = 18.6 MPa. Above there was clay slate of thickness of about 0.3 m and of strength to uniaxial compression equal to R_c = 30.9 MPa. In the near-roof part there was arenaceous shale of thickness of 1.6–1.8 m and of strength to uniaxial compression equal to R_c = 37.5 MPa. The roadway floor was arenaceous shale of strength to uniaxial compression equal to R_c = 37.5 MPa.

Results of visual observation and the events, which were not included in data recorded by sensors (such as e.g.

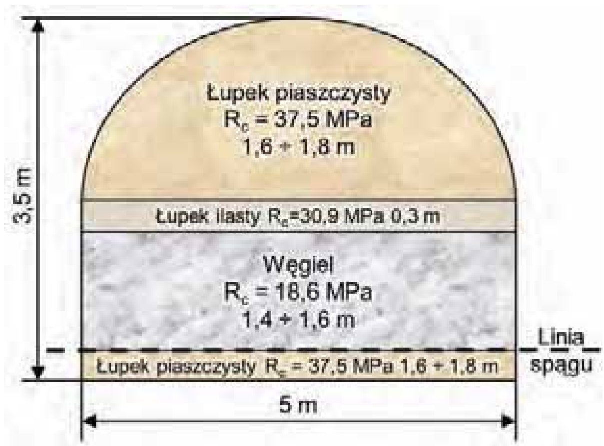

Fig. 8. Geological cross-section of a roadway, in which the tests were carried out [4]
Rys. 8. Przekrój geologiczny wyrobiska, w którym prowadzono badania [4]

downtime caused by the necessity of manual breaking of coal block on a conveyor), were recorded.

A measuring recorder enabled to record data every 100 ms. The information was recorded on memory cards, which were periodically replaced [11]. Geological cross-section of the roadway, in which the tests were carried out, is presented in fig. 8.

Fig. 9. Installation of jib position sensor [4]
Rys. 9. Instalacja czujnika pozycji wysięgnika [4]

Fig. 10. Installation of loading table position sensor [4]
Rys. 10. Instalacja czujnika pozycji stołu ładowarki [4]

The roadheader has been equipped, among others, with sensors of cutter jib vertical and horizontal position (fig. 9), a sensor of loading table position (fig. 10), vibration sensors installed on the cutter head, an inclinometer to determine the position of the whole machine (inclination in x and y axes), as well as with pressure sensors in the hydraulic system.

3.2. Tests of cutter head trajectory

Analysis of the results of roadway drivage tests, which were carried out in the mine, was started from visualization of cutter head trajectory in the roadway area, which was obtained in each cutting cycle.

Despite relatively small changes in a position of rock layers within few days of recording the recorded trajectories significantly differed from each other. It resulted from the fact that cutting was realized by different operators. Selection of trajectories, which meet the assumptions (in which movement in a plane parallel to the floor is an operational movement) from a group of recorded trajectories, was the first step of the analysis. Three groups of data recorded during drivage (which are marked with a cycle number, i.e. 18, 20 and 28) were selected. Exemplary the cutting trajectory of cycle 18, during which 0.75 m of roadway was developed, is presented in fig. 11. Cutting time was equal to 55 minutes and it was longer than average cutting time, i.e. 46 minutes.

The machine changed its position many times during the cycle 18. These were both forward movements, which were associated with cut-in, and movements aiming at displacement of the whole machine in relation to the roadway axis. Due to lack of recording of the roadheader absolute position in a roadway, manual correction of a trajectory, – shift of the graph of realized roadheader manoeuvres, was necessary. Determination of the moment, in which a displacement of the roadheader in relation to roadway axis occurred, was possible due to recording of current of drive motors and due to notes made by observers present during the test.

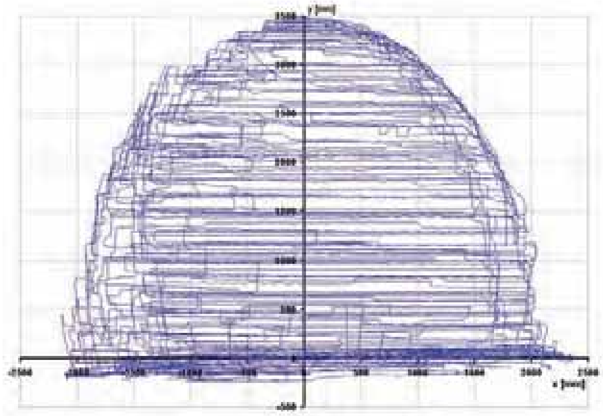

Fig. 11. Cutter head trajectory – cycle No. 18 [4]
Rys. 11. Trajektoria głowicy urabiającej – cykl nr 18 [4]

During one of the cycles (cycle 18) the roadheader cut in the solid coal four times. It was assumed that average web was of about 0.19 m, what was equal to 25 % of cutter head diameter (0.8 m).

3.3. Testing of drive load (current of motor of the cutting drum)

Analysis of changes of drive load (fig. 12) (current of motor of the cutting drum) leads to a conclusion that use of installed power of drive (motor) was insufficient. Rated current of the motor I_{zn} at voltage 1000 V was equal to 90 A [13]. During the cycle the motor was turned off for 11.3 % of time, what was caused by the necessity of manual breaking of a large coal block. The motor operated without load (change of cutting direction, during loading and other auxiliary movements) for 35.9 % of time. Further percentage distribution of current in the range from 45 A to 90 A shows that the machine was not fully loaded; it mainly resulted from the properties of mined rock (R_c from

18 MPa to 38 MPa). Time of overloads was equal to 2.6 % of the time of the whole cycle.

Underload of the machine could also result from the operator's fear of overloading the machine (subjective operator's assessment). A large number of operational movements with ineffective use of technical potential of the cutting machine is the result.

A diagram presenting places, in which overloads occurred (fig. 13) was made on the basis of distribution of current of the cutting drum motor during one cycle

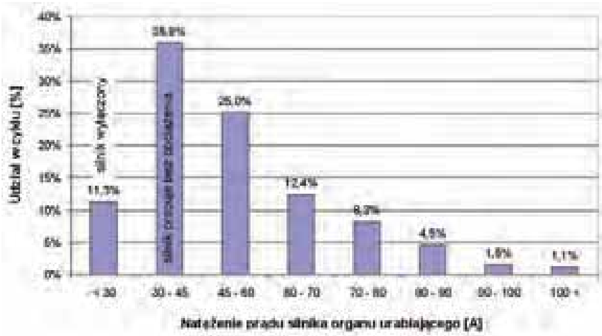

Fig. 12. Percentage share of current of the cutting drum motor in one cycle – statistical analysis [4]
Rys. 12. Procentowy udział natężenia prądu silnika organu urabiającego w czasie jednego cyklu – analiza statystyczna [4]

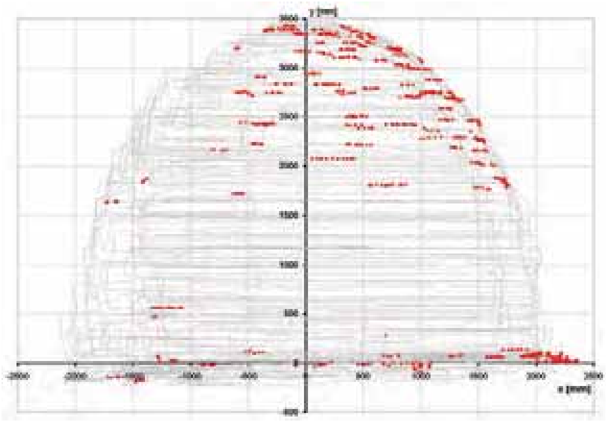

Fig. 13. Places of overloads [4]
Rys. 13. Miejsca występowania przeciążeń [4]

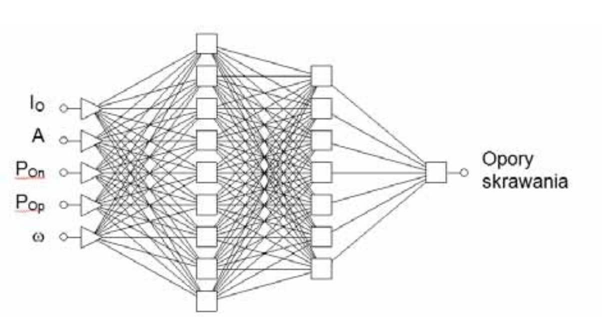

Fig. 14. One-direction, multi-layer artificial neural network [5]
Rys.14. Jednokierunkowa, wielowarstwowa sztuczna sieć neuronowa [5]

(fig. 12). Analysis of diagrams (fig. 12 and fig. 13) shows a direct relationship between overloads and underload of machine depending on a type of mined rock. It was found that in a rock of higher compression strength R_c load of the motor drive as well as a number of overloads increased at constant set angular speed of jib movement. The method for selection of circumferential speed of the jib movement in a plane parallel to the floor depending on momentary value of parameter R_c (finally on cutting resistance), suggested by the author, can be a solution of this problem.

3.4. Structure of the artificial neural network

The following input parameters of the artificial neural network (fig. 14) were selected on the basis of analysis of measuring data [4] obtained during the tests of roadway development:

current of the cutting drum motor I_O,
efficient value of acceleration of mechanical vibrations A,
under-piston pressure of turning base ram P_{On},
over-piston pressure of turning base ram P_{Op},
angular speed of the cutter jib ω.

Data from a part of the cutting cycle 20 were selected for learning (fig. 15).

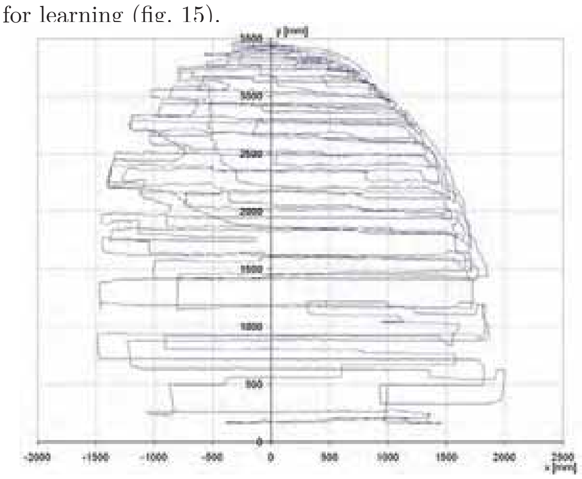

Fig. 15. Trajectory corresponding to learning data (part of cycle No. 20) [4]
Rys. 15. Trajektoria odpowiadająca danym uczącym (fragment cyklu nr 20) [4]

Notes made by observers carrying out the tests were used for selection of input data. Analysis of data visualization revealed the need of:

- removal of data disturbing the process,
- averaging,
- scaling,
- standardization.

Removal of parts disturbing the learning process was the next stage of data preparation. During initial numerical analyses it was found that only data recorded during movement of the jib in a plane parallel to the roadway floor should be further processed. Data recorded during the following situations were removed from the data set:

change of direction of cutter jib movement – on the basis of recorded time process of the jib articulation angle in a plane parallel to the floor, change of a roadway position (manoeuvring pass – drive motors are started) – on the basis of recorded time processes of current of drive motors parts proving that roadheader manoeuvring movements were removed form the set of data.

After selection, a set of learning data included 5767 samples. Averaging and scaling of data were made in the next stages.

3.5. Results of model tests

Results of simulations show that the multi-layer perceptron of 5-9-5-1 structure (5 input neurons – 9 neurons in the first hidden layer – 5 neurons in the second hidden layer – one output) is the network, which recreates cutting resistance in the best way.

The diagram of the network response in the case of set of learning data (blue line – real value of cutting resistance, red line – the value generated by the artificial neural network) is presented in fig. 16.

The diagram of response in the case of another set of real data, which were recorded during tests of the process of roadway drivage, is presented in fig. 17.

Results obtained with use of the artificial neural network were plotted on the cutting trajectory. Cutting resistance corresponding to mining of arenaceous shale, which is present in the upper part of the roadway, is presented in fig. 18.

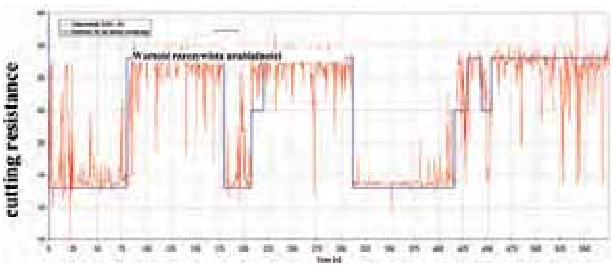

Fig. 16. Results of simulation with use of data – cycle 20 of MLP 5-9-5-1 network [4]
Rys. 16. Wynik symulacji z użyciem danych – cykl 20 sieci MLP 5-9-5-1 [4]

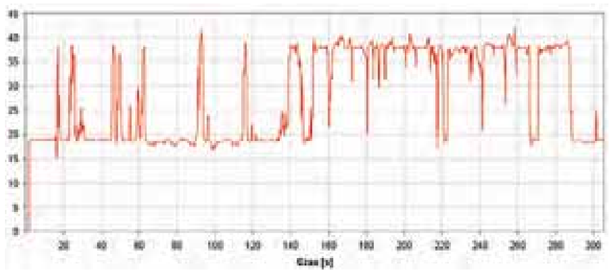

Fig. 17. Results of simulation with use of data – cycle 18 of MLP 5-9-5-1 network [4]
Rys. 17. Wynik symulacji z użyciem danych Cykl18 sieci MLP 5-9-5-1 [4]

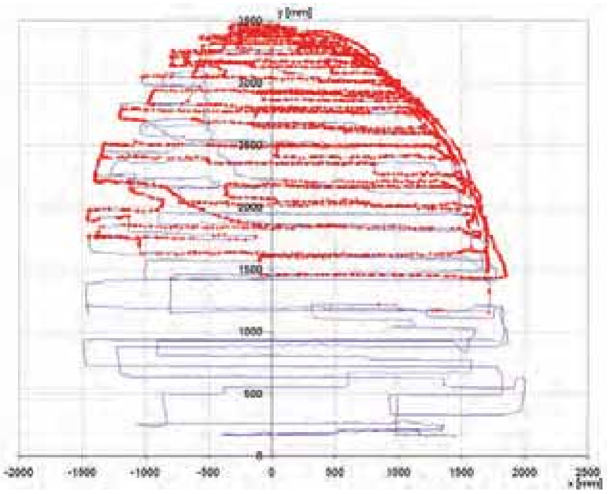

Fig. 18. Cutting resistance corresponding to arenaceous shale [4]
Rys. 18. Opory skrawania odpowiadające urabiania łupka piaszczystego [4]

4. Conclusions

Development of information technologies, electronic systems and automatics enables to use advanced control algorithms, which use the methods of artificial intelligence, e.g. artificial neural networks.

Results of model tests, which are presented in the paper, are the examples of work associated with development of the intelligent control system of the roadheader, realized by the KOMAG Institute of Mining Technology and the Faculty of Mechanical Engineering at the Silesian University of Technology.

The presented method for determination of cutting resistance with use of the artificial neural network is an integral element of determination of set of value of the cutter jib angular speed in a plane parallel to the roadway floor.

Results obtained during implementation of the artificial neural network enable to conclude that the algorithm is able to recognize cutting resistance of mined rock.

Presented tests results were obtained during realization of R&D project associated with development of intelligent system for control of roadheader realized by the KOMAG Intitute of Mining Technology and the Faculty of Mechanical Engineering at the Silesian University of Technology.

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Systemy mechatroniczne w górniczych kombajnach chodnikowych – przykłady rozwiązań

Streszczenie: W procesie sterowania maszyn górniczych występuje wiele czynników, utrudniających przygotowanie klasycznego modelu matematycznego, opisującego zjawiska towarzyszące pracy maszyny. Problemy te, wynikające ze specyfiki procesu drążenia wyrobisk, są bezpośrednią przyczyną podejmowania prób zastosowania technik sztucznej inteligencji w modelowaniu zjawisk występujących w trakcie drążenia wyrobisk korytarzowych (tuneli). W artykule zaprezentowano:

- badanie stanu wiedzy z zakresu systemów sterowania kombajnów chodnikowych,
- możliwości zastosowania sztucznych sieci neuronowych w układach sterowania maszyn górniczych (na przykładzie kombajnu chodnikowego),
- wyniki badań procesu drążenia wyrobiska kombajnem chodnikowym,
- określenie oporów skrawania z wykorzystaniem sztucznej sieci neuronowej do wyznaczenia wartości prędkości kątowej wysięgnika kombajnu chodnikowego.

Słowa kluczowe: systemy mechatroniczne, górniczy kombajn chodnikowy, system sterowania, sztuczna sieć neuronowa

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