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AUTOMATION OF THE CONTROL PROCESS OF THE MINING MACHINES BASED ON FUZZY LOGIC

Purpose. To improve the efficiency of mining equipment functioning through the introduction of fuzzy inference algorithms into the control of mining facilities being complex objects with dynamic, randomly varied operation modes.

Methodology. A stage to determine nonfuzzy input variable systems as statistic indices has been added to universally accepted algorithm of a fuzzy interference. The indices make it possible to identify operation mode of mining equipment or operation mode transitions. Each input nonfuzzy variable of the system is a result of statistic processing of information signals from the sensors to find unique regularities within the signal; the regularities should correspond to one or several operation modes of the machine, or transitions between them. Additional linguistic input variables of "Previously, their operation mode was..." are introduced to trace temporally varied operation modes of the mining machine. Taking into consideration features of input nonfuzzy variables formation, the system performs fuzzy inference discretely in time; in this context, fuzzy inference interference algorithm is added by the conditions for data accumulation, variations, and zero variations in the machine operation mode.

Findings. A technique to integrate a behavioural model of a mining machine, considered as a control object, into a fuzzy inference algorithm has been proposed. Moreover, recommendations, concerning determination of both nonfuzzy and linguistic input variables of the system, formation of a basis of fuzzy products, and determination of conditions for data accumulation have been formulated.

Originality. Originality of the proposed technique is to use a behavioural model of a mining machine, considered as a control object, for the fuzzy inference algorithm in the form of a set of operation modes of a machine and in the form of a scheme of time-dependent changes in operation modes.

Practical value. The proposed technique is theoretical basis to solve topical scientific and application problem as well as to use nonfuzzy algorithms to control mining machines to improve their efficiency.

Keywords: *mining machines, fuzzy inference algorithm, operation modes of the machines*

Introduction. Mining industry applies a great number of equipment and facilities developing significant mechanical forces resulting from the branch specific nature [1]. Moreover, a tendency toward constant intensification of mining operations along with simultaneous increase in power intensity of the equipment should be mentioned. As a result, mining enterprises are among the largest Ukrainian electrical energy consumers. At the same time, in Ukraine, consumption index of energy resources to mine a ton of coal is one of the world highest values. Improvement of the techniques and algorithms to control mining machines is one of the tendencies to decrease the index.

The problem to be solved. Currently, mining machines are the objects under control involving high information and electronic component. Mining facilities involve dozens of electronic sensors making it possible to measure dozens of physical values. However, the information is used only to provide the operation mode of the machine, predetermined by an operator; or it is stored to an information carrier and screened online for operators. Thus, nonavailability of adequate algorithms to analyze information from sensors in the process of a mining machine operation as well as algorithms to make decisions relying upon the online information processing is the reason why control of equipment in the context of mining industry is not efficient due to human factor (since a decision concerning the efficiency of a machine performance is made by an operator on the basis of his/her experience and visual information).

Literature review. Currently, Europe is introducing changes in a concept of a mining enterprise development to improve market competitiveness of energy carriers. This measure will help improve the efficiency of the mining enterprise, reduce prime cost of its product as well as environmental impact. General idea of a "smart mine" concept is maximum coverage of all production processes at the mine by high-level intelligent systems with their integrating into intelligent structure to control the mining enterprise [2]. Papers [3, 4] explain foundations to introduce high-level systems for intelligent control of coal mining in Ukraine. In the context of the new concept, concerning their design, control, and diagnostics, mining machines and complexes are represented as mechatronic systems [5, 6]. The fact stipulates changes in the approach as for the developing a system to control mining facilities when it is impossible to generate the informative component or informative-electronic one without taking into consideration interdependences between other components. Papers [7, 8] contain examples of control of certain structural assemblies of an object when it is considered as a mechatronic system. However, the solution is for local control problems at the level of informative-electronic component while mining equipment needs an approach as for the development of a control system at the level of the informative component.

Currently, under the conditions of intelligent systems of control and diagnostics developing, a technique, combining several available methodological approaches, is often applied. For instance, in the context of paper [9], the development of intelligent system to control preparation technological complex is performed basing upon the combination of principles of neural control, intelligent classification, and global optimization. In the context of paper [10], decision is made relying upon intelligent cognition of situations with the help of adaptive expert system when fuzzy classification matrix is used for learning. For intelligent control of well drilling, paper [11] proposes to apply a system of adaptive control along with an identifier of a control object being of a neuro-fuzzy structure.

It should be mentioned, that in the context of all the above cases, a mechanism, intended to combine several methodological approaches if intelligent control system is developed, is substantiated on the basis of the detailed analysis of both technological object and the process as the intelligent control objects.

Taking into consideration the available information concerning mining equipment control by operators, it is expedient to introduce expert systems at the level of information component of the mining facilities. The measure is one of the most potential tendencies for the future progress of intelligent system for mining equipment control to improve its efficiency. The current nonavailability of expert system to automate processes of mining equipment, if it is used effectively in other fields, can be explained by its increased complexity from the viewpoint of the equipment being the control objects as well as complicated environment of its operation. Specific approach is required to develop expert systems for mining facilities control plus possible combination with other methodological approaches on the basis of the detailed analysis of the mining machines as the intelligent control objects.

Unsolved aspects of the problem. Mining machines belong to such a type of control objects whose operating conditions have been studied thoroughly as well as operation modes from the viewpoint of their control. It is meant that an operator makes a decision relying upon recognition of certain operation modes of a mining machine. The complexity of mining equipment control depends upon dynamic and unexpected nature of temporal changes in the equipment operation mode, on the one hand, and impossibility to identify categorically the modes basing upon short-time analysis of sensor signals, on the other hand. Moreover, joint operation of several different-nature structural units of a mining machine interaction with the external environment is a combination of several physical processes within the machine's structural units resulting from the machine-external environment interaction. In this context, each of the physical process can have simultaneous effect on several physical values, measured with the help of the sensors. Due to complicated nature of a physical process, the effect is demonstrated in the form of origination of a certain complex regularity within the sensor signal.

Hence, if expert systems to control mining machines are developed, it is senseless to use algorithm of system self-learning since all possible situations of machine operation mode are known and well understood with available mathematical description of external environment effect on them and physical processes within its structural units [12, 13].

However, analysis of mining facilities as control objects has shown that their expert control systems should be developed relying upon fuzzy inference algorithms since it is impossible to determine definitely what operation mode is taking place right now. Moreover, preliminary processing of sensor signals should be involved to determine certain regularities reflecting specific physical processes within the mining machine structural units or on condition that the machine interacts with external environment. Papers [14, 15] contain such an example of sensor signal processing use to identify operation mode of a shearer.

Purpose. The purpose is to improve the efficiency of mining equipment functioning at the expense of fuzzy inference algorithms implementation in the processes of control of mining machines with dynamically and unexpectedly varied operation modes.

Results. A method to develop the system of fuzzy control is proposed for mining machines with dynamically and unexpectedly varied operation modes being thoroughly studied and constant, yet being problematic as for their identification due to complicated operating conditions. The task of the fuzzy control of a mining machine is to form insertions for controllers of local systems of automated control at lower level to provide economic, technical, and technological indices of operation efficiency of a machine proximal to optimum ones. Thus, fuzzy system to control a mining machine is an upper-level system operating autonomously; besides, it forms tasks for controllers (instead of an operator) in the process of a mining machine functioning. That is to say, a problem of automation of a process to control a mining machine is being solved in practice. Fig. 1 demonstrates structural scheme of a system of fuzzy control of a mining machine.

As it is understood from Fig. 1, a controller is a final element for fuzzy system to control a mining machine; sensors are sources of information signals. In Fig. 1, gray colour indicates the elements, pointing at distinctive features of the system of fuzzy control of mining facilities, being developed according to the proposed technique to compare with traditional system of fuzzy control.

The first distinctive feature of the system of fuzzy control of a mining machine is as follows: the results of statistic processing of sensor signals in the form of clear information criteria are pure input variables rather than the signals; they are projections of indicative events on a mathematical plane making it possible to identify operation mode of a mining machine. Hence, fuzzification should be preceded by a preparation stage of a fuzzy inference algorithm being a preliminary processing of signals from sensors to identify certain substantiated regularities within information signals to be unique representation of one or another operation mode of a mining machine (‘Determining informative features of operation mode’ unit in Fig. 1). At the output of the ‘Determining informative features of operation mode’ unit in Fig. 1, we have several informative criteria of operation modes of a mining machine as clear input variables for a fuzzy control of a machine.

Another distinctive feature of the system of a fuzzy control of a mining machine concerns rule database of the system. According to the universally accepted approach as for the developing algorithms of a fuzzy inference, the rule database relies upon fuzzy product being invariable. Taking into consideration thoroughly studied operation modes of mining facilities, each feature, concerning their control, as well as relatively simple algorithm of actions by operators, if they control equipment, representation of a mining machine control in the form of a base of standing rules of fuzzy product is quite reasonable. However, in the context of the proposed technique, a new approach as for the development of a fuzzy product rule database is applied when a mining machine is the control object. According to it, there is a list of operation modes of a mining machine; each of them corresponds to unique combination of physical processes both inside structural units of the machine and on the condition that interaction between structural units and external environment takes place. Hence, a mining machine functioning is represented as successive time variation of operation modes in terms of a certain trajectory; moreover, each of the modes is considered during definite time. In this context, control task is to determine and provide a trajectory of changes in operation mode of a mining machine; if so, we have economic, technical, and technological indices of operation efficiency of a machine proximal to optimum ones.

If the rule database of fuzzy product relying upon the proposed approach is developed, it is convenient to rep-

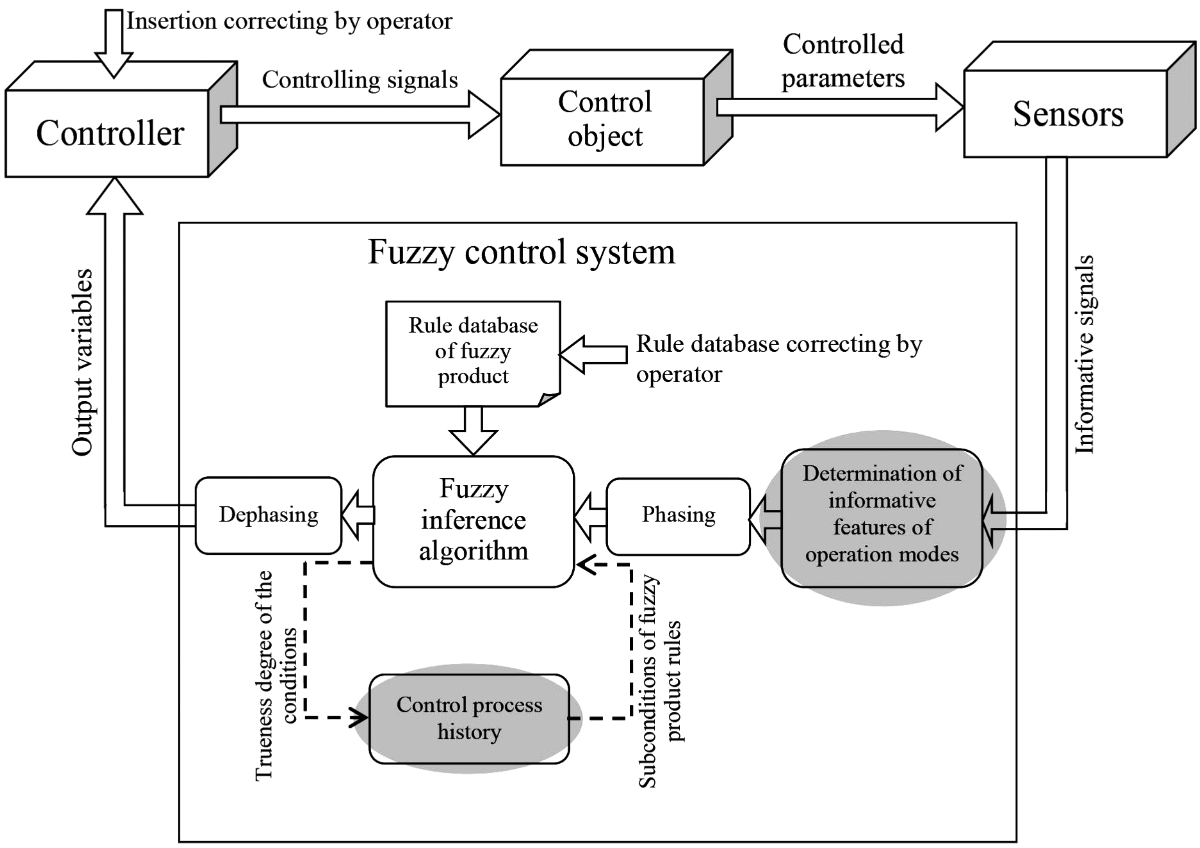

Fig. 1. Structural scheme of a system of fuzzy automated control of a mining machine

resent graphically the control algorithm for a mining machine in the form of a diagram of finite-state automation (i.e. transition graph) on the condition that the operation modes are considered as the graph vertex (Fig. 2). The arches of the graph in Fig. 2 describe transitions from one operation mode of the mining machine to another one; moreover, steadiness of the operation mode is taken as a separate transition with corresponding linguistic meaning.

If the rule database of fuzzy product of the system is developed on the basis of transition graph, represented in Fig. 2, then transition conditions within the graph are conditions of fuzzy product rules in parallel. Transition conditions within the graph in Fig. 2 and conditions of fuzzy product rules respectively are of a complex structure; they consist of subconditions interconnected by means of fuzzy logic operations. The following linguistic variable systems are the subconditions

$$X_i = <Name\_i,\ T_i,\ [0,\ 1],\ G_i,\ L_i>,$$

where *Name_i* is a description of the linguistic input variable (Identification of operation mode of a mining machine in terms of the i^{th} informative criterion); T_i is base term set of the i^{th} input linguistic variable system

$$T_i = \{P_1,\ P_2, \ldots,\ P_n\},$$

where P_i are characteristics of operation mode of a mining machine taken as terms of input linguistic variables of a system of fuzzy control of a mining machine.

G_i element within a formula of linguistic variable X_i definition is some syntactic procedure describing the process when new values for the linguistic variable are being formed from T_i set with the help of certain logic connections and modifiers. L_i element within the linguistic variable X_i definition formula is some semantic procedure making it possible to determine adequate descriptive meaning for each new value of the linguistic variable; the meaning is obtained according to the result of G_i procedure execution helping determine adequate substantial content while fuzzy set forming. If formation of new values for the linguistic variable from T_i set is not involved (i. e. when there is invariable list of characteristics of operation modes of a mining machine with substantiation of the fact which of the characteristics can be identified with the help of one or another informative criterion) then G_i and L_i procedures may not be executed. Within the proposed technique, the above is characteristic feature of all linguistic variables of the system; hence, below formulas will ignore the procedures of their defining.

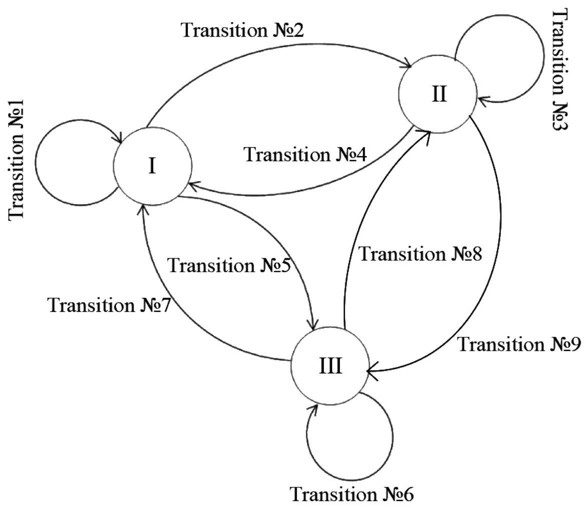

Fig. 2. Graph of transitions between operation modes of mining facilities

In the context of the proposed technique, consideration of a mining machine control history is the distinctive feature of the procedure to form fuzzy product rules i.e. the use of such a linguistic input variable as “Previously, their operation mode was...” is one of the prerequisites of fuzzy product rules. The structural scheme of fuzzy automated control of a mining machine in Fig. 1 shows the feature as a separate element titled “Control process history” and highlighted in grey.

Introduction of the information, concerning time variation of operation mode of a mining machine, to fuzzy inference algorithm will help the system make decisions relying upon data of the current operation mode and current changes in operation modes as well as taking into consideration the trajectory of previous changes in operation modes, which will enhance the likelihood that the system will make adequate decisions.

The proposed technique recommends formulating subconditions, conditions, and conclusions of fuzzy product rules of a rule base of fuzzy control of a mining machine relying upon behavioural analysis of a human operator in the context of numerous situations if the mining machine is controlled manually. Moreover, the stage, when conditions and conclusions of fuzzy product rules of a rule base of fuzzy control of a mining machine are being formed, should involve algorithm to search and support trajectory of mining machine operation modes in terms of which economic, technical, and technological indices of the mining machine efficiency are proximal to optimum ones. The algorithm is developed on the basis of simultaneous analysis of a process of the mining machine control by operator as well as the mining machine as a control object.

The proposed technique to develop a system of fuzzy control of a mining machine basing upon identification of its operation modes provides one more addition to fuzzy inference algorithm to compare with traditional approaches. Taking into consideration the fact that during certain period of time any mining machine is functioning in a constant operation mode, the graphs of transitions, demonstrated in Fig. 2, are not continuous but during certain periods when either condition of changes in operation modes or a condition of the operation mode steadiness is met. Taking into account the feature as well as the fact that to determine informative criteria (depending upon the selected algorithm for the analysis of informative signals from sensors), samples should be of definite lengths; if so, then according to the proposed technique, the fuzzy inference algorithm will coincide with that shown in Fig. 3.

According to Fig. 3, the fuzzy inference algorithm starts from accumulation of data to form samples of ade-

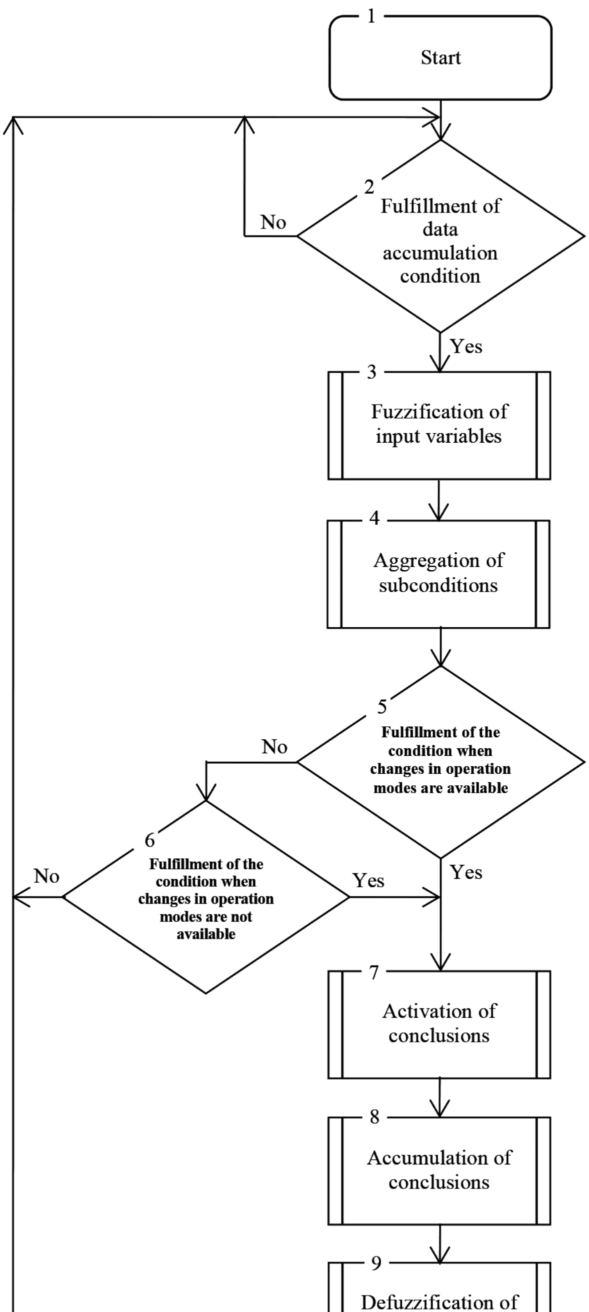

Fig. 3. Scheme of fuzzy inference algorithm within the concept concerning the development of fuzzy system to control a mining machine

quate-length informative signals to determine accurate informative criteria as input correct variables of the system. Unit *2* controls the condition of adequate sample length of the informative signals. If the condition is met according to a certain informative criterion within Unit *2*, fuzzification procedure takes place within Unit *3*. In terms of other informative criteria, corresponding subconditions of the rule base of fuzzy product remain inactive.

Unit *4* (Fig. 3) performs "Aggregation of subconditions" procedure in such a way: trueness degree of rule base of fuzzy product should depend upon trueness degrees of certain prerequisites as well as upon the number of active subconditions.

In such a case, high level of the condition trueness will be available if only high trueness degrees involve the majority of subconditions the condition consists of. The requirement for the procedure to aggregate subconditions depends on the fact that searching for regularities in the informative signals may be performed within different time scales; thus, different time periods may be involved. Actually, the system obtains information, concerning the object, gradually; the fact should be involved in the decision-making algorithm.

Alternatively, "Aggregation of subconditions" procedure can be performed using average-method, where weight coefficients are applied, if informative criterion is required to determine several operation modes of a mining machine simultaneously.

High trueness level of one of the conditions, involving subconditions of changes in the operation mode of a machine, is the condition for changes in operation modes of a mining machine in Unit *5* (Fig. 3). A value of trueness degree of a condition, corresponding to the high one, is determined empirically during physical experiments of computational ones. It is one of the parameters of a mining machine fuzzy control making it possible to adjust the system additionally taking into consideration operational features of a machine in terms of actual conditions which could not be done for various reasons in the process of the system development. Fig. 1 demonstrates the possibility of an operator to correct rule base through parameters of fuzzy control system which were introduced specifically for that. The possibility is shown by means of corresponding external input effect.

The condition, when changes in operation mode of a mining machine are not available (Unit *6*), consists of two subconditions, connected with fuzzy operation "AND". Subcondition one is a high trueness level of corresponding condition of rule base of fuzzy product involving several subconditions of identification of non-availability of changes in operation mode according to certain informative criteria. The subconditions are also aggregated with the help of average-method taking into consideration the number of active subconditions. Subcondition two is to fill up samples of informative signals to determine informative criteria within maximum time scale, provided by signal analysis algorithm. In other words, the subcondition is for data accumulation sufficient for all informative criteria determination.

Procedures of fuzzy inference algorithm in Units *7*, *8*, and *9* (i. e. "Activation of conclusions", "Accumulation of conclusions", and "Defuzzificaztion of output variables") are performed according to the recommendations agreeable to a common traditional approach as for the development of fuzzy inference systems.

Conclusions. Basic principles of the proposed technique as for the development of systems for fuzzy control of mining facilities, making it possible to apply traditional algorithms of fuzzy inference to automate control process of mining machines, are:

- determination of rule base of fuzzy product relying upon a mining machine behaviour as a control object in the form of a diagram of a finite automation states (transition graph). Operation modes of a mining machine are the graph nodes. Each of them corresponds to unique combination of physical processes both inside structural units and on the condition they interact with external environment. Arches of the graph describe operation mode-operation mode transitions;

- implementation of the preparatory stage of fuzzy inference algorithm through preliminary processing of signals from sensors to identify certain substantiated regularities in the informative signals being unique representation of one or another operation mode of a mining machine. As a result, we obtain informative criteria to identify the operation modes;

- the informative criteria, obtained as a result of preparatory stage, are taken as input pure variable systems. Input linguistic variables of the system are fuzzy description of identification results of operation modes of a mining machine according to informative criteria; moreover, they are subconditions of a rule base of fuzzy product;

- introduction of information, concerning the order of temporal variations of operation modes of a mining machines, in the algorithm of fuzzy inference of information while using additional linguistic input variables " Previously, their operation mode was..." as one of the subconditions of fuzzy product rules;

- use of the fuzzy inference algorithm with inference procedure discretization in time relying upon the conditions of data accumulation and nonavailability of changes in operation mode of a mining machine.

The technique, proposed by the paper, is the theoretical background to solve the topical scientific and applied problem concerning implementation of fuzzy control algorithms for mining facilities to improve their efficiency.

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Автоматизація процесу керування гірничими машинами на основі нечіткої логіки

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Мета. Підвищення ефективності функціонування гірничих машин за рахунок упровадження алгоритмів нечіткого прийняття рішення у процеси керування гірничими машинами як складними об'єктами з динамічно змінюваними непередбачуваним чином режимами роботи.

Методика. До загальноприйнятого алгоритму нечіткого прийняття рішення доданий етап визначення вхідних чітких змінних системи як статистичних показників, що дозволяють ідентифікувати режими роботи гірничих машин або переходи від одного режиму до іншого. Кожна вхідна чітка змінна системи є результатом статистичної обробки інформаційних сигналів із датчиків з метою пошуку в сигналі унікальних закономірностей, що відповідають одному чи декільком режимам роботи машини, або переходам між ними. Для відстеження траєкторії зміни у часі режимів роботи гірничої машини вводяться додаткові лінгвістичні вхідні змінні системи: „До цього спостерігався режим ...". З урахуванням особливостей формування вхідних чітких змінних система здійснює нечіткий процес прийняття рішення дискретно у часі, при цьому в алгоритм нечіткого прийняття рішення вводяться умови накопичення даних, зміни й відсутності зміни режиму роботи машини.

Результати. Запропонований спосіб інтеграції моделі поведінки гірничої машини як об'єкта керування в алгоритм нечіткого прийняття рішення. При цьому сформовані рекомендації щодо визначення чітких і лінгвістичних вхідних змінних системи, формування бази правил нечітких продукцій та визначення умов накопичення даних.

Наукова новизна. Полягає у використанні в алгоритмі нечіткого прийняття рішення моделі поведінки гірничих машин як об'єктів керування у вигляді сукупності режимів роботи машини та схеми траєкторій зміни режимів у часі.

Практична значимість. Запропонований у роботі метод є теоретичною основою для розв'язання важливої науково-прикладної проблеми розробки та практичного застосування алгоритмів нечіткого керування у процесах керування гірничими машинами з метою підвищення ефективності їх роботи.

Ключові слова: *гірничі машини, алгоритм нечіткого прийняття рішення, режими роботи машин*

Автоматизация процесса управления горными машинами на основе нечеткой логики

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Цель. Повышение эффективности функционирования горных машин за счет внедрения алгоритмов нечеткого принятия решений в процессы управления горными машинами как сложными объектами с динамично меняющимися непредсказуемым образом режимами работы.

Методика. К общепринятому алгоритму нечеткого принятия решений добавлен этап определения входных четких переменных системы как статистических показателей, позволяющих идентифицировать режимы работы горных машин или переходы от одного режима к другому. Каждая входная четкая переменная системы является результатом статистической обработки информационных сигналов от датчиков с целью поиска в сигнале уникальных закономерностей, соответствующих одному или нескольким режимам работы машины, или переходам между ними. Для отслеживания траектории изменения во времени режимов работы горной машины вводятся дополнительные лингвистические входные переменные системы: „До этого наблюдался режим ...". С учетом особенностей формирования входных четких переменных система осуществляет нечеткий процесс принятия решений дискретно во времени, при этом в алгоритм нечеткого принятия решений вводятся условия накопления данных, изменения и отсутствия изменения режима работы машины.

Результаты. Предложен способ интеграции модели поведения горной машины как объекта управления в алгоритм нечеткого принятия решений. При этом сформированы рекомендации по определению четких и лингвистических входных переменных системы, формированию базы правил нечетких продукций и определению условий накопления данных.

Научная новизна. Заключается в использовании в алгоритме нечеткого принятия решений модели поведения горных машин как объектов управления в виде совокупности режимов работы машины и схемы траекторий изменения режимов во времени.

Практическая значимость. Предложенный в работе метод является теоретической основой для решения важной научно-прикладной проблемы разработки и практического применения алгоритмов нечеткого управления в процессах управления горными машинами с целью повышения эффективности их работы.

Ключевые слова: *горные машины, алгоритм нечеткого принятия решений, режим работы машины*

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