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THE ALGORITHM FOR DETERMINING AN OPTIMAL SYSTEM OF ROUTES FOR THE MINE VENTILATION AND SAFETY ENGINEERING MASTERS FOR THE PURPOSE OF MONITORING AERODYNAMIC PARAMETERS OF THE VENTILATION NETWORK IN MINES

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АЛГОРИТМ ВИЗНАЧЕННЯ ОПТИМАЛЬНОЇ СИСТЕМИ МАРШРУТІВ ГІРНИЧИХ МАЙСТРІВ ДІЛЬНИЦІ ВЕНТИЛЯЦІЇ І ТЕХНІКИ БЕЗПЕКИ З МЕТОЮ МОНІТОРИНГУ АЕРОДИНАМІЧНИХ ПАРАМЕТРІВ ВЕНТИЛЯЦІЙНОЇ МЕРЕЖІ ШАХТИ

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АЛГОРИТМ ОПРЕДЕЛЕНИЯ ОПТИМАЛЬНОЙ СИСТЕМЫ МАРШРУТОВ ГОРНЫХ МАСТЕРОВ УЧАСТКА ВЕНТИЛЯЦИИ И ТЕХНИКИ БЕЗОПАСНОСТИ С ЦЕЛЬЮ МОНИТОРИНГА АЭРОДИНАМИЧЕСКИХ ПАРАМЕТРОВ ВЕНТИЛЯЦИОННОЙ СЕТИ ШАХТЫ

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Abstract. Route control of the mine aerogasdynamic parameters is organized in such a way that the obtained information can supplement the information of the unified telecommunication system for dispatch control and automated control of mining machines and technological complexes or another similar system installed in the mine making this information more exact, promptly if possible, without duplications. The route control system is formed from the practical considerations with taking into account the data of the stationary system. Due to the joint functioning of stationary and route control systems with accounting the previous changes of aerogasdynamic parameters, it will be possible to build a predicted trajectory of such a change, which will improve reliability, optimize the control structure and more exactly predict the occurrence of emergency situations. In this article, the authors formulate the main definitions and properties of the route control system and the problem of creating the routes covered the entire mine ventilation network with a given number of control points. An algorithm for constructing a route control system is characterized with taking into account economic and ergonomic conditions, time factor and safety requirements. To solve this problem, it is proposed to use the method of sequential improvement of admissible plan. The essence of the method is that, having received a certain solution (an admissible plan) as an initial approximation, the measures are proposed for improving it till further improvement becomes impossible. The "improvement" here means more complete satisfaction of the proposed criterion for minimizing total time of the master travelling for executing his work on the route. Improvement of the admissible plan is carried out by the Monte Carlo method. The possibility of duplication of data obtained from an automated system and by route control is analyzed, and a reduction of the basis of control stations is grounded. The set of routes for monitoring parameters of the ventilation network elements by mine experts chosen in this way will reduce the risk of obtaining incomplete information about its aerogasdynamic state, and cross-monitoring of measurements within the transversal of the bases of two components of the control system will improve reliability and accuracy of the monitoring.

Keywords: mine ventilation network, aerogasdynamic parameters, monitoring, route control, admissible plan.

A great number of mines in Ukraine are equipped with quite effective unified telecommunication systems of dispatch monitoring and automated control of mining machines and technological complexes (UTAS) [1], which provide control of the main technological processes of coal extraction, including ventilation systems of coal mines.

Nowadays, UTAS operates in more than 15 mines in Ukraine ensuring high socio-economic efficiency of coal extraction.

At the same time, the installation of the UTAS system in the mines encounters certain difficulties. Great volumes of instrumental base, cable facilities and data transmission and feedback systems do not allow to effectively control all dangerous areas of the mine ventilation network (MVN) based on a comprehensive assessment of risk factors. Therefore it is necessary to provide, in addition to the automated control, a route control of aerogasdynamic parameters of mine by organizing it so that the received information can supplement the information about UTAS by making this information more exact, promptly if possible, without duplications.

The route control system is formed for practical reasons with taking into account the data of the stationary system. However, the latter are not fully used. Statistics on changes in the gas situation, which come from the sensors of the stationary system, will update the route control system, more effectively localize areas in the MVN most dangerous by methane emissions by arranging their rational monitoring. On the other hand, the use of results of mine control performed_by portable devices will improve the stationary control system in terms of changing its topological structure and dimensions and will help to develop recommendations for designing stationary control systems for mining facilities with similar conditions of coal extraction.

This relationship of stationary and route systems of aerogasdynamic control makes it possible to consider their joint work promising for achieving both social and economic results.

Based on the joint operation of stationary and route control systems with taking into account previous changes of aerogasdynamic parameters, it is possible to build a forecast trajectory of such a change which will improve reliability, optimize the control structure and more exactly predict the occurrence of emergency situations.

Since it is hardly possible to achieve full adequacy of the simulation model of MVN operation to its real analogue (there are always factors that are not taken or cannot be taken into account), the issues of structural-parametric identification of MVN by insufficiently complete measurement information remain relevant.

Since it is difficult to set and solve this multifactorial problem by existing methods, it is necessary to use the principles of SMART technologies and SMART criteria.

In order to unify further presentation, it is necessary to formulate some definitions and properties.

Definition 1. The basis of stationary sensors for controlling aerogasdynamic parameters (in our case it is the location of the corresponding UTAS sensors) is set according to the requirements [2] and is displayed by a set of branches $D^i \in V \subset F(U,V)$, where $F(U,V)$ is a graph of the MVN.

Definition 2. The measurement points of aerodynamic monitoring by portable control devices are determined by the methods described in [3] and are displayed by a set of branches $D^p \in V \subset F(U,V)$.

Obviously, if there is no UTAS or other system of automated aerogasdynamic monitoring in the mine, the full basis of measuring stations will be $D=D^P$.

Control of the condition of equipment and devices in the mine, as well as monitoring of aerogasdynamic parameters of mine workings with subsequent introduction of the received information into the simulation model of MVN (aerogasdynamic identification) is carried out by the mine masters of ventilation and safety engineering (VSE). They travel along the predefined routes. In practice, the assignment of routes is carried out, as a rule, only on the basis of existing experience of a man who walk along the MVN, and the result of this is that the routes are loaded unevenly, and time of travelling the route significantly exceeds the total duration of performing works in the areas included in this route. In order to reduce unproductive loss of time for travelling between the control and monitoring stations, it is necessary to use mathematical methods and algorithms which will allow to lay optimal or at least close to optimal routes, which can meet certain criterion.

Definition 3. Each working, which is displayed by a branch (or by set of branches) of the MVN, has its own weight, which is determined by the amount of labor costs for measuring aerodynamic parameters in this working and for travelling along it from its initial node to the final one.

Definition 4. The aerodynamic monitoring route M_i is a set of branches, where final node of the previous branch is the initial node of the next one, and which includes at least one control point of the stationary control device, or a control point for portable devices.

Property 1. In some cases, initial node of the route of mine master travelling coincides with the final.

Property 2. The weight of the route is defined as the total weight of all mine workings included in it.

Property 3. Different routes can have the same branches.

Property 4. In case of multiple checks of a control point by both stationary and portable devices, when determining the weight of this branch, these checks are taken into account only once. In case of repeated check of the branch, its weight will be equal only to the weight of its cheack without taking into account the weight of the measured works.

Property 5. Routes should not be laid through the impassable workings and zones of downfalls. There, of course, should not be any stationary control stations.

Formally, the task of finding routes covered the MVN with a given number of control points (CP) can be represented as follows. On the graph of MVN $F(U,V)$, where $|U| = N$ - the number of nodes of the MVN (it is assumed that the CP are located in the initial node of the branch-working), $|V| = M$ - the number of branches (paths from one CP to another, which are not laid through any other CP. Branch, in the general sense, it is not only the element which connects the neighboring nodes (a special case), but also as a sequential set of elements of the MVN), one needs to find a certain number of routes.

Graph $F=F(U,V)$ has the following characteristics:

a) it is weakly connected, disoriented (travelling by its elements does not depend on their spatial orientation), finite;

b) each of the nodes $u_i \in U$ has a weight $T_i \geq 0$, where $i=1,2,...,N$, T_i - the duration of work performed in the CP with the number u_i;

c) each of the branches $v_j \in V$ has a weight $t_j>0$, where t_j determines the time spent for the transition along the branch v_j;

d) topology of the graph is given by a conditional matrix of incidents $D = \left\| d_{ij} \right\|, i = 1,2,...,M, j = 1,2.3,$ where d_{i3} is the weight of the branch, d_{i1} , d_{i2} are the numbers of the nodes incident to it;

e) the graph shows an uninsulated node b, the weight of which is $T_b = 0$. This node is a point in the MVN, which is the beginning and end of any route.

On the graph $F(U,V)$, it is necessary to construct a system of routes $m_1,m_2,...,m_k$, which have the following properties:

a) each node u_i with weight $T_i \neq 0$, $i = 1,2,...,N$ should be included at least into one of the routes $m_1,m_2,...,m_k$;

b) each of the routes is a contour on the graph with the included uninsulated node b;

c) the weight of the route is defined as the total weight of all branches $v_j \in V$, included in it, and the weight of those nodes for which $T_i \neq 0$;

d) the weight of each route $\tau \leq T^*$, where T^* is the allowable time spent on the route (duration of a shift);

e) routes m_i and m_j, $i \neq j$ may have common branches;

f) the total number of k routes covered the graph should be minimal.

The problem of finding a system of routes close to optimal will be solved under the following assumptions:

1. If more than one route is laid through the node i, for which $T_i \neq 0$, the work in the corresponding i-th CP is performed by the mine master who traveles along only one route.

2. The sequence of works performed on the route is arbitrary.

3. If for nodes i and j, more than one arc is incident (parallel connection of the branches), then the arc with the lowest weight is chosen as the arc incident to nodes i and j , i.e. the initial graph $F=F(U,V)$ is not a multigraph.

The solution of the problem is divided into three stages:

a) formation of an intermediate graph $L (A, W)$;

b) choosing on it of the routes close to optimal;

c) returning to the initial graph $F=F(U,V)$.

The intermediate graph $L(A, W)$ has $A = \{\overline{U}, u_i(T_i \neq 0) \in \overline{U}\} \cup b$, as nodes, where $i = 1,2,..., N$, i.e. the initial node b and those nodes of the initial graph whose weights are nonzero. The number of nodes of the intermediate graph is $|A| = p + 1$, where p is the number of nodes of the initial graph with nonzero weights. The number of arcs of the intermediate graph $|W| = \frac{1}{2} p(p+1)$, and each of the arcs of the graph L incident to nodes i and j, is obtained as the shortest chain connecting the corresponding nodes of the initial graph *F*. The feasibility of transition to the intermediate graph *L (A, W)*, is obvious.

The algorithm for the problem solution is as follows:

I. The formation of the intermediate graph *L (A, W)* on the initial *F (U, V)* is reduced to the search for the shortest chains for different pairs of nodes (a_i, f_j), ($в, a_i$), $i \neq j$, $i=1,2,...,p$, and can be performed by the methods [4,5].

In order to implement on the PC the proposed algorithm for finding the routes for mine masters, the Floyd method [5] can be used for the construction of an intermediate graph *L (A, W)*. This method can be used for both oriented and non-oriented and partially oriented graphs, i.e. to take into account the direction of motion of the methane-air mixture or (in case of an aerological accident) the direction of motion of harmful impurities in the MVN workings. The latter is especially important, because in real conditions the MVN is a graph with one or another degree of orientation of the branches. At the stage of formation of the intermediate graph *L (A, W)* it is necessary not only to obtain the lengths of the shortest chains for various pairs of nodes of the set *A*, but also to memorize the shortest chains. The Floyd's method used at the first stage of solving the problem, allows, in addition to the matrix of lengths of the shortest chains *T1*, to obtain a reference table *T2*. The latter is a matrix of the same dimension, with which one can find the numbers of all intermediate nodes of the shortest chain for any pair of nodes of the graph *F (U, V)*. In the general case, the elements t_{ij}, $i = 1,2,..., p$ of the matrix *T1* are not integers, if the weights of the arcs of the graph *F (U, V)* are not integers. In practice, the weights of the arcs of the graph *F (U, V),* which correspond to the time costs of the MVN working, it is sufficient to have an accuracy of one minute (it is difficult to imagine a situation where this time can be estimated to the nearest second, given the ergonomic characteristics of a particular person). The elements of the matrix *T2* are also integers, because they are the numbers of nodes in the shortest chains. Thus, the matrices *T1* and *T2* can be stored together as one matrix *T3*. This technique has previously been used to store materials that are formed in matrix form, in order to facilitate calculations on a computer with a small volume of memory and low speed. For the modern PC, this is not essential, but simplifies the perception of the computational process. Due to the fact that there are no analytical methods for solving some problems, the heuristic algorithms are widely used in practice to obtain a solution close to the optimal one. To solve the problem of finding an effective system of routes for mine masters is possible by using the method of sequential improvement of the admissible plan (AP) [4]. The essence of the method is that, having received as an initial approximation some acceptable solution (the AP), one tries to improve it till further improvement becomes impossible. "Improvement" here means a fuller satisfaction of a certain criterion. In our case, as a criterion for the effectiveness of the route is used indicator *Δ*, which characterizes the share of time spent for transitions in the total time spent on the route, i.e.

$$\Delta = \frac{\sum_i t}{\sum_i t + \sum_i T}, \quad i = 1,2,...,k, \qquad (1)$$

where $\sum_i t$, $\sum_i T$ is, respectively, the total time spent for transitions and work on the route. The overall efficiency of the route system is characterized by the value of the functionality $\Phi = k\sum_{i=1}^{k}\sum_i t$.

To build a AP, the nodes with nonzero weights are sequentially included into the route as long as the condition is satisfied

$$\tau = \sum_i t + \sum_i T \le T^*, \tag{2}$$

where τ - is the length of the route.

The best way to include a node into the route is calculated as follows

$$\Theta_{ij} = \begin{cases} \dfrac{t_{ij}}{T_j}, & i \ne j, i \ne 0, j \ne 0 \\ \dfrac{t_{0i}}{T_j}, & i = j \ne 0 \end{cases},$$

where t_{ij} - are the elements of the matrix of lengths of the shortest chains *T1*; t_{0i} - is weights of the shortest chains connected the initial node *b* with all nodes of the graph *L (A, W)*. The set of elements $\{\Theta_{ij}\}$ creates an estimator matrix $\Theta = \|\Theta_{ij}\|$, the order of which coincides with the order of the matrices *T1* and *T2* and is equal to p^2. When being in the node *i* of the route, the transition is made to the node j_1 with the performance of work T_{j_1}, and not to the node j_2 with the performance of work T_{j_2}, if $\Theta_{i,j_1} \le \Theta_{i,j_2}$. Inclusion of the next node into the route is carried out only when the following condition is satisfied

$$R_{k-1} - \left(t_{i_{r-1},i_k} + T_{i_k}\right) - t_{i_k,0} \ge 0, \tag{3}$$

where R_{k-1} - is the time reserve for the node i_{k-1} included into the route and the previous node in relation to the node i_k; t_{i_{r-1},i_k} - is weight of the branch $a_{k1,\,k}$, incident to the nodes i_{p-1}, j_k of the graph *L (A, W)*.

During the construction of the AP, the diagonal elements of the matrix Θ are reviewed. The number of the smallest element determines the node which is included into the route. Let it be the node i_1. Further, the time reserve for this node is calculated by the formula $R_{i_1} = T^* - (t_{0,i_1} + T_{i_2})$, after which the next element of the route is found. For this purpose, the elements of the row with the number i_1 are reviewed, but without taking into account the column i_1. Among them, the smallest should be chozen, and if condition (3) satisfies it, it is included into the route. For searching for the next node in the route, the elements of the line i_2 are reviewed, where i_2 is the number of the next node, but without taking into account the columns of the array $I=\{i_1,i_2\}$. After finding the next node of the route, the total time spent on the route is determined with taking into account the total time spent for transitions and performance of works. If it is impossible to include the next node into the route, its record number is recorded in the array *I* and is not considered in the next search. The AP is considered constructed if none of the nodes with nonzero works remaining on the graph can be included into the route because requirement (3) is not satisfied. The efficiency indicator (1) and the route length τ (2) are calculated for the AP. Columns and rows with the numbers of nodes included into the routes are deleted from the matrices *T1*, *T2* and Θ. The system of routes on the graph *L (A, W)* is constructed if the order of the matrices *T1, T2* and Θ is zero.

After receiving the AP, its improvement is performed. For this purpose, the problem of ordering the nodes should be solved in order to obtain a route with a smaller value of the indicator Δ (1). The Monte Carlo method is used for this purpose [4]. The main principle of this method is the construction of an artificial imitation model, the parameters of which are the sought variables of the problem. In our case, the numbers of the nodes of the graph included into the route are taken as some independent parameters. The function of these parameters is the length of the route τ and the efficiency index Δ, which depend on the sequence of nodes in the route. The sequence of choosing of these nodes can be considered as a random process, as there are no restrictions on the performance of works on the route.

The algorithm for improving the AP is as follows:

a) the number *E* of repetitions of the cycle of AP improving is set;

b) the numbers of nodes included into the AP are recoded into the array G [1: S], where S is the number of nodes on the route with accounting the initial node b$\equiv g_1 \in G$;

c) with the help of a standard subroutine, random numbers α are obtained, which are evenly distributed in the interval [0,1];

d) index of each subsequent element of the array *G* which indicates the number of the next node on the route is determined by the formula [4].

$$r_{j+1} = ENTIER\left[\left(\alpha_j + \frac{1}{s-j}\right)(s-j)\right] + j,$$

where α_j - is a random number from the interval [0,1]; $j = 1,2,..., s-1$.

e) after the construction of the new route, the value of the indicator Δ is calculated for it. If $\Delta' < \Delta$, where Δ' is an indicator of the efficiency of the initial AP, then the latter is accepted as acceptable, and the improvement process is repeated. Otherwise, a new cycle of improving the old AP begins;

f) a check is performed at the end of the AP improvement cycle with specifying: the need to return to paragraph c) of the algorithm or to end the calculations. In the latter case, the array *G* contains the node numbers of the sought route with the efficiency index Δ.

The process of finding the system of routes on the graph *L* ends when at the next stage the dimension of the matrices *T1, T2* and *Θ* becomes zero.

III. The transition to the system of routes on the graph *F* is carried out by using the matrix *T2* obtained by the Floyd method at the first stage of solving the problem.

This system of routes will be close to optimal without taking into account the automated (by the UTAS or other similar systems) control of aerodynamic parameters. At the same time, a significant part of the routes are laid through the workings where the UTAS elements are installed, i.e. there is a risk that the control will be duplicated and its efficiency will decrease. The next part of solving the problem will be the analysis of such duplication and reasonable reduction of the basis of control stations.

When analyzing the ratio of the sets of branches D_i and D_p the following cases should be considered:

a) $Di \equiv D_p$ The case is impossible, because it means that all points which need such control are equipped with stationary control devices. But the installation of stationary control systems is too expensive and this system will obviously be unprofitable;

b) $Di \cap D_p = \varnothing$. This case is also impossible as it means that there are no stationary control devices in the points which need constant monitoring (which should be done by mine masters). Where are they installed then and what are they needed for?!

c) $Di \cap D_p = D^{real}$ is a set of control points, where measurements are duplicated. It needs special attention, because if the automated monitoring system is responsible for the accuracy and reliability of its indicators, and the mine master – for his indicators, then within the specified set, they should coincide, in theoretical terms. The discrepancy indicates either an error of measurement by a portable device, or an inaccurate operation of the system. A measure to eliminate this situation can be: to conduct one more measurement of the route or measurement by another device, or to address the responsible persons to check and re-calibrate a supposedly faulty element of the automated system.

The chosen by this way a set of routes for controlling parameters of the MVN elements by the mine masters will allow to reduce risk of receiving the incomplete information concerning its aerogasdynamic condition (if to increase as much as possible the number of CP, the solution will be close to optimal), and cross control of measurements within the D^{real} will allow to improve reliability and accuracy of monitoring by both components of the control system.

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Анотація. Маршрутний контроль аерогазодинамічних параметрів шахти організується таким чином, щоб отримана інформація доповнювала інформацію уніфікованої телекомунікаційної системи диспетчерського контролю і автоматизованого керування гірничими машинами і технологічними комплексами або іншої подібної системи, яку встановлено на шахті, за можливості оперативно уточнюючи, але не дублюючи її. Система маршрутного контролю формується з практичних міркувань з урахуванням даних стаціонарної системи. На основі комплексування стаціонарної і маршрутної систем контролю з урахуванням попередніх змін аерогазодинамічних параметрів можна буде побудувати прогнозну траєкторію такого змінення, що дозволить підвищити надійність, оптимізувати структуру контролю і більш обґрунтовано прогнозувати виникнення аварійних ситуацій. У статті сформульовано основні визначення і властивості системи маршрутного контролю, сформульовано задачу пошуку маршрутів, що охоплюють шахтну вентиляційну мережу з заданою кількістю пунктів контролю. Охарактеризовано алгоритм побудови системи маршрутного контролю з урахуванням економічних, ергономічних умов, часового терміну і вимог безпеки. Для вирішення цієї задачі запропоновано використовувати метод послідовного покращення допустимого плану. Суть методу полягає у тому, що, отримавши у якості початкового наближення деяке рішення (допустимий план), намагаються покращити його доти, поки подальше покращення стає неможливим. Під «покращенням» тут розуміється більш повне задоволення запропонованого критерію мінімізації сумарного часу переходів і виконання робіт на маршруті. Поліпшення допустимого плану здійснюється методом Монте-Карло. Проаналізовано можливість дублювання даних, отриманих з автоматизованої системи і шляхом маршрутного контролю і обґрунтовано скорочення базису станцій контролю. Вибрана таким чином сукупність маршрутів моніторингу параметрів елементів вентиляційної мережі гірничими майстрами дозволить знизити ризик отримання неповної інформації відносно її аерогазодинамічного стану, а перехресний контроль вимірів у межах пересічення базисів обох складових системи контролю дозволить підвищити достовірність і точність моніторингу.

Ключові слова: шахтна вентиляційна мережа, аерогазодинамічні параметри, моніторинг, маршрутний контроль, допустимий план.

Аннотация. Маршрутный контроль аэрогазодинамических параметров шахты организуется таким образом, чтобы полученная информация дополняла информацию унифицированной телекоммуникационной системы диспетчерского контроля и автоматизированного управления горными машинами и технологическими комплексами или другой подобной системы, установленной на шахте, по возможности оперативно уточняя, но не дублируя ее. Система маршрутного контроля формируется из практических соображений с учетом данных стационарной системы. На основе комплексирования стационарной и маршрутной систем контроля с учетом предыдущих изменений аэрогазодинамических параметров можно будет построить прогнозную траекторию такого изменения, что позволит повысить надежность, оптимизировать структуру контроля и более обоснованно прогнозировать возникновение аварийных ситуаций. В статье сформулированы основные определения и свойства системы маршрутного контроля, сформулирована задача поиска маршрутов, охватывающих шахтную вентиляционную сеть с заданным количеством пунктов контроля. Охарактеризованы алгоритм построения системы маршрутного контроля с учетом экономических, эргономических условий, временного фактора и требований безопасности. Для решения этой задачи предложено использовать метод последовательного улучшения допустимого плана. Суть метода заключается в том, что, получив в качестве начального приближения некоторое решение (допустимый план), пытаются улучшить его до тех пор, пока дальнейшее улучшение становится невозможным. Под «улучшением» здесь понимается более полное удовлетворение предложенного критерия минимизации суммарного времени переходов и выполнения работ на маршруте. Улучшение допустимого плана осуществляется методом Монте-Карло. Проанализирована возможность дублирования данных, полученных из автоматизированной системы и путем маршрутного контроля, и обосновано сокращение базиса станций контроля. Выбранная таким образом совокупность маршрутов мониторинга параметров элементов вентиляционной сети горными мастерами позволит снизить риск получения неполной информации о ее аэрогазодинамическом состоянии, а перекрестный контроль измерений в пределах пересечения базисов обеих составляющих системы контроля позволит повысить достоверность и точность мониторинга.

Ключевые слова: шахтная вентиляционная сеть, аэрогазодинамические параметры, мониторинг, маршрутный контроль, допустимый план.

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