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OPERATIONAL PLANNING OF ROAD TRAFFIC FOR AUTONOMOUS HEAVY-DUTY DUMP TRUCKS IN OPEN PIT MINES

This article discusses the issues of path planning for movement of an autonomous heavy-duty dump truck along haul roads in an open pit mine. Taking into account the heterogeneity and dynamic nature of the technological environment, the issues of the efficiency and quality of the path planning of are extremely relevant. As a basis for calculations, a digital open pit model is considered, with technological zones and haul roads described as their geometric surfaces fragmented into same-type regular polygons. In this case, the workspace represents a set of discrete points with specified coordinates – the centers of geometric primitives, and the segments connecting them represent the possible directions of travel of an autonomous dump truck. The combinations of these segments, which are assigned certain weights, form a sequence of reference points of a potential route for the robots to move along. Thus, the planning objective in this study is formulated as the search for the optimal value of a certain cost function that takes into account condition of a roadway. The procedure for constructing a graph which acts as a basic model for determining the best route for a mobile robot is briefly discussed. As an algorithm for finding the optimal sequence of points, it is proposed to use a modification of reliable Dijkstra's algorithm, with the running speed being increased owing to the original implementation of parallel computing. In terms of the real-life fragments of haul roads, using the predefined terminal points and the constructed graphs of high dimensionality, the edge weights of which determine the values of the cost function, various routes for dump trucks are constructed and studied. The modeling results confirmed the efficiency of the proposed approach while limiting the use of standard computing resources.

Keywords: *parallel Dijkstra's algorithm, planning objective, autonomous vehicles, dump trucks, open-pit mining, Digital Twin, Industry 4.0, OpenMP*

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Introduction

Autonomous vehicles, in particular, wheeled robots, relish increasingly wider application in different industries such as metallurgy, construction engineering and mineral mining [1]. As a rule, these machines help solving different logistical tasks associated with production. In the mining industry which produces more than 80% of minerals and energy resources using the open-pit method, transportation is a critical component of a production cycle, which exerts a determining influence on the integral indicators of production efficiency. This fact is a small wonder as the studies into robotic and partly or totally unmanned transportation facilities have been carried out for more than 20 years [2–5]. Although mining technologies have certain specific features governed by types of minerals, the transport technologies and processes, as objects of management in open pit mines, possess some invariant characteristics, namely:

— cyclicity of a production process which follows an invariable flow sheet: rock excavation – rock loading/haulage – rock unloading – travel of empty dump trucks – loading of dump trucks;

— dynamic nature of technological infrastructure due to continuous relocation of zones of loading and unloading (or transshipment), which results in periodical transformation of topology of haul roads;

— continuous change of condition of roadway under weight of heavy mining machines, especially in adverse weather;

— unpredictable sudden apparition of technical obstacles which limit actual "travel way" [6, 7].

In the problem of planning autonomous or partially autonomous transport operation, it is possible to discriminate a static component (routing of dump trucks during a shift) and a dynamic component (real-time re-routing) [2, 5, 8–10]. Implementation of this approach involves certain functions:

1. Planning of paths of dump trucks between excavators and unloading zones within a certain time interval (for example, a work shift) to ensure maximal volumes of rock to be hauled. In this case, using various modeling tools, theoretically optimal velocities of dump trucks are determined with a view to minimize downtime of dump trucks and excavators.

2. Determination of motion trajectories of dump trucks within a route and dump truck velocities per sections of a route with regard to a certain integrated optimization criterion including traffic safety, fuel consumption and wear of basic assemblies and units of dump trucks.

3. Control of dump truck travel at preset velocity by means of navigation systems and on-board automation.

When using autonomous dump trucks in open pit mines in real life, the listed tasks should be handled at the same time, i.e., the criteria in use should take into account both macro factors of planning (volume of rock being shipped, travel time) and micro factors (road path, specific trajectory, velocity modes). The second task is the most important as its solution is promotive of general safety and efficiency of transportation as a more uniform process at a minimum number of emergency stops. This study focuses on an algorithm of calculating reference points required to construct a path of travel of an autonomous dump truck using a digital model of haul roads and an empirical cost function. The proposed modification of Dijkstra's algorithm both includes the functional component of the problem and ensures effective and on-the-fly routing at limited time and computational resources.

Digital model of transportation infrastructure at open pit mine

The concept to support the proposed solution is based on the established mining operation planning methodology using 3D block models which describe interaction between mining equipment and geological environment of mineral deposits. The methodology was adapted to the surface infrastructure of an open pit mine and made a framework for modeling transportation processes. The main element of the surface infrastructure of an open pit are the haul roads and various-purpose technological zones. The digital model of a technological surface is a set of regular polyhedral — primitives (for instances, squares or hexagons with sides of variable length) tied to coordinate network, and each primitive is matched with physicotechnical and spatial coordinates. The application of such model to the description of transportation zones in an open pit mine (haul roads, excavation sites, etc.) was discussed earlier [11]. Construction of such models involves integration of survey data, including UAV surveys, and on-board telemetering results. The model represents a set of fragments (primitives) which are geometrically regular polygons defined by

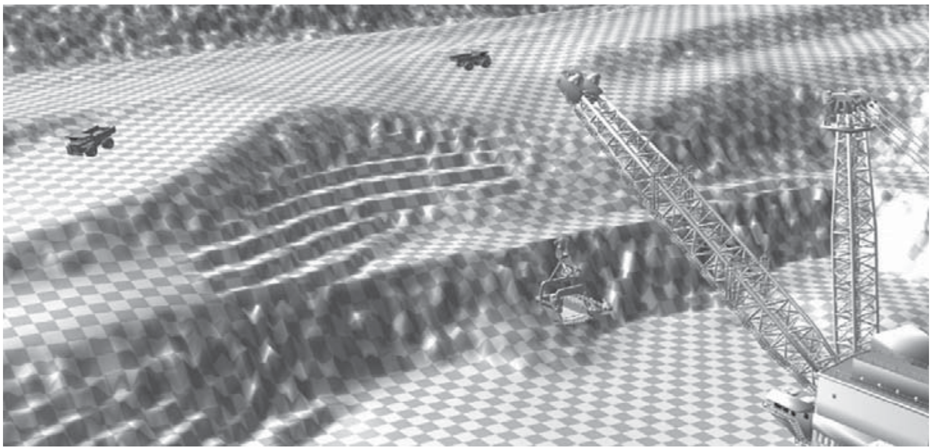


Fig. 1. "Digital model" of mining and transportation environment of open pit mine

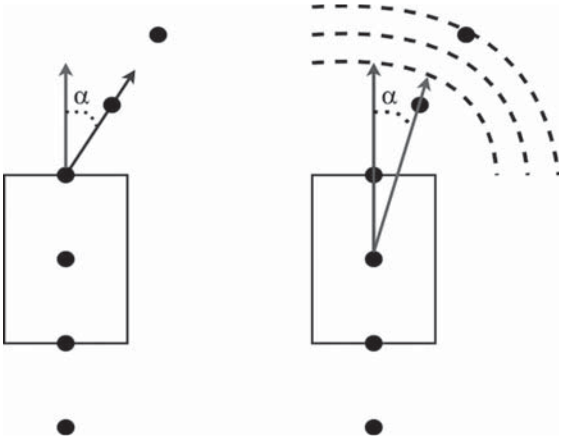
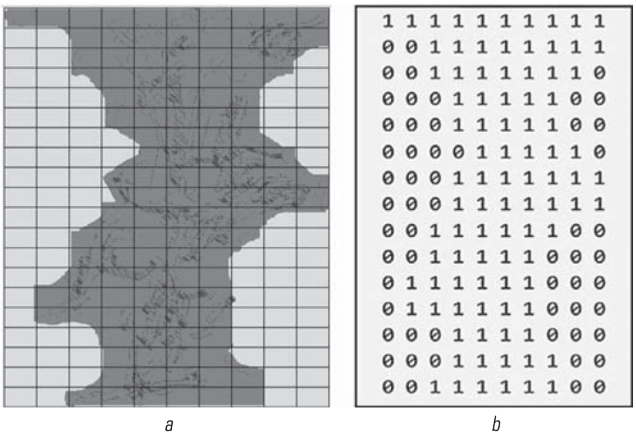


Fig. 2. Paths of autonomous dump truck through reference points



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1 1 1 1 1 1 1 1 1 1
0 0 1 1 1 1 1 1 1 1
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Fig. 3. Two-dimensional projection of a fragment of a quarry road onto a regular grid of primitives in the form of regular quadrangles (*a*); digital representation of a fragment of a road (structural matrix) (*b*)

the coordinates $\left\{x_{ij}, y_{ij}, z_{ij}\right\}, i = 0.1, \ldots, m; j = 0.1, \ldots, n$, where m and n are the dimensions of the fragment adjacency matrix; x_{ij}, y_{ij}, z_{ij} are the center coordinates of the prime elements in the planes *x*, *y* and *z* (**Fig. 1**), which later on act as the reference points of the autonomous dump truck path.

An important component of a digital model is the adjacency matrix of the unit fragments. Each fragment is correlated with a set of parameters, including some spatial and technological characteristics.

These parameters are used to calculate a quantitative rating C_{ij} of each fragment and take a key part in calculation of cost functions which conform with the weights of the graph edges that connect potential reference points of a pathway of an autonomous dump truck:

$$C_{ij} = a_1 * D_1 + a_2 * D_2 + \ldots + a_k * D_k, \tag{1}$$

where $D_1, D_2, \ldots, D_k$ is a group of factors which describe suitability of the roadway for the robotic dump truck travel, and are determined using the expert statistical methods at the stage of the model construction. Such factors include, for example:

— weather conditions (rain, snow, no fall-out, ice-slick);
— roadway deformations (pot holes, grooves, ridges);
— position of a fragment relative the roadway boundary;
— $a_1, a_2, \ldots, a_k$ are the weights.

While functioning, the model is periodically updated, and when obstacles appear on a road and make a certain fragment (or fragments) unsuitable for a dump truck to travel, the associated element of the adjacency matrix is nulled.

The neighbor fragments admissible as potential sections of an autonomous dump truck path as in **Fig. 2** are assumed to be as follows:

$$\left(C_{ij} \to C_{i-1,j+1}\right), \left(C_{ij} \to C_{i+1,j+1}\right), \left(C_{ij} \to C_{i,j+1}\right).$$

If a potential route is laid immediately at the boundary of a roadway, as well as in case of twists of the road or obstacles present on it, some neighbor fragments are eliminated from the analysis (the elements in the associate rows and columns are put to zero).

Figure 3*a* shows a digital representation of a roadway section divided into unit fragments using square primitives, and **Fig. 3*b*** offers the adjacency matrix of the fragments without regard to their ratings. The edges of the fragments can vary in a wide range from 1 to 10 m. In the problem under analysis, the primitives are the rectangles 5×10 in size, which approximately agrees with the size of a big dump truck.

Formulation of problem and brief description of its solution

Planning is a key point in robotics. Planning means finding a sequence of feasible situations between indexed positions (start, finish) in the space of search, such that ensures optimal value of a cost function. To explain it more clearly, it is required to determine a route for a robot to travel without obstacles using appropriate dynamic and kinematic models. The search of an optimum way is a difficult problem as it is necessary to take into account a huge number of situations, which leads to the computational complexity. The present day shows a greater respect for the algorithms that work within a paradigm of a continuous robot movement space [12, 13]. These algorithms are highly effective when a robot moves in a high-stress dynamic medium, at potential change in direction of movement every single moment. The problem of traffic planning for heavy-duty dump trucks under analysis is free from the required continual adjustment of their paths. However, should it become necessary, the decision is to be made within the shortest term and for a number of the autonomous dump trucks, which can be hindered by the lack of computational resources of the actual available control systems. In our case, we speak about finding an optimal route (or path) in the high dimensionality graph. The search algorithms, such as A* or Dijkstra's algorithm, can reasonably effectively find an optimal solution (route) if it exists [14–16]. On the other hand, when a graph contains 20.000 and more nodes, the point of the searching time becomes critical. In this study, the main tool of optimized planning is Dijkstra's algorithm, and it is suggested to enhance its capacity by using an original parallel computation scheme and the OpenMP library.

The formal formulation of the problem is as follows. The preset oriented acyclic graph $G(V,E)$ contains no multiple arcs and loops of high dimensionality (a few thousands or tens of thousands points and edges). The set of points and edges, as well as the edge weights w_{ij} are constant at the time of constructing a robotic dump truck plan (or plans for a number of dump trucks). The change in the graph means that the whole computational model is restructured. The weights represent the values of a cost function calculated from the relations of the values of C_{ij}, on the one side, and the values of $C_{i,j+1}, C_{i+1,j}, C_{i-1,j+1}$, on the other side. The computation process takes into account that the cost function is minimum at the straight-line (without change in direction) motion of an autonomous dump truck along the road sections (fragments) most suitable for the dump truck travel by preliminary estimates.

These are the cost functions $f_{ij}(L), f_{ij}(R), f_{ij}(S)$, where $i = 0, N$; $j = 1, k_j$; $k_i \leq m$ are the weights of the graph edges, used to shape the path which is a sequence of the graph edges between the terminal points x_0 and x_f, and each edge occurs only once. The optimal route E_{opt} is the sequence of the graph edges, such that ensures minimum of a certain function F:

$$F(E_k) = \sum_{i=0}^{N-1} f_{i,j},(c_{i,j}, c_{i,j+1}); j < k_i,$$

$$F(E_k) = \sum_{i=1}^{N-1} \min\{f_{i,j-1}, f_{i,j}, f_{i,j+1}\}, \quad j \in \overline{1,m} \qquad (2)$$

All weights (cost functions) are rated within a range of [0.1–1], and the total cost depends on the geometry of real-life haul roads and on the size of a unit fragment of a digital model. The distances between the working zones in an open pit can reach 10.000 m and the width of the roadы ranges from 20 to 60 m. Thus, at ф unit fragment 1 m^2 in size, the graph will contain tens of thousands points. At the larger unit fragment, with the size comparable with the dimension of a modern dump truck (approximately 5×10 m), the graph dimensionality remains rather high: 10.000–12.000 edges to select an optimal route. Consequently, reduction in the optimum route searching time is an extremely critical issue.

The authors used well-known Dijkstra's algorithm. The algorithm faces essential difficulty when operating high dimensionality graphs, and the OpenMP library is involved in implementation of parallel computations therefore. Each parallel computation model has its own advantages and disadvantages, and the choice of a model is governed by a specific application and available hardware resources. A shared memory model is a parallel computation model with its memory shared between a number of processors or cores. All processors in the model have access to data in the common memory space and can change them, which allows the processors handle a problem or an algorithm jointly. In the shared memory model, each processor has its own cache to store high-usage data, which reduces time spent to get access to memory, and enhances general productivity [17–19]. This study uses an original methodology of constructing parallel Dijkstra's algorithm, which is free from the parallel algorithm complications through focusing only on parallel implementation of cycles [20]. Such methodology was never used earlier in parallel implementation of Dijkstra's algorithm.

Computational experiment results

The preliminary evaluation of the algorithm efficiency included assignment of the shortest path without regard to the weights, i.e. without regard to the condition of the roadway, and assignment of the best path based on a number of weights (a number of constraints), i.e. with regard to the roadway condition. The parallel implementation of Dijkstra's algorithm using graphs with different number of points (10, 20, 40, 60 and 80 thousand) produced the results described in **Table** and in **Fig. 4**.

Shortest route searching times

Number of points	Shortest route searching time (without regard to weights), s				Shortest route searching time (with regard to weights), s			
	Number of processors (cores)				Number of processors (cores)			
	1	2	4	8	1	2	4	8
10.000	0.470	0.244	0.170	0.109	0.417	0.338	0.154	0.112
20.000	1.569	0.858	0.562	0.394	1.651	1.014	0.676	0.558
40.000	6.306	3.572	2.230	1.664	6.225	3.629	2.320	1.845
60.000	16.485	8.939	6.601	5.004	16.897	9.244	6.421	5.497
80.000	33.543	17.433	11.370	8.934	39.328	19.565	14.432	10.283

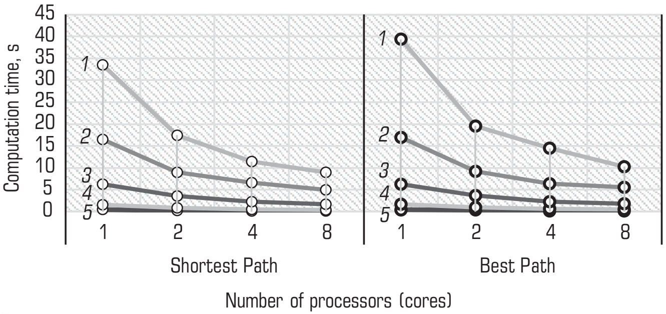

Fig. 4. Visualization of shortest path computation time estimation:
1 – 8000; *2* – 6000; *3* – 4000; *4* – 2000; *5* – 1000

The further evaluation of the efficiency of the proposed solution on parallelizing Dijkstra's algorithm used the haul road section with a length more than 5000 m and a width varied in a range from 25 to 50 m. The digital model of the haul road was constructed using square primitives 5×5 m with the quantitative estimates for each unit fragment.

Figure 5 shows variants of optimum paths for the fragment of the selected road section. In our case, optimality is understood as the minimized total cost of the weights of the edges connecting the reference points of the routes. It is important that the choice of the reference points (graph points) directly depends on approaches to calculating the weights.

The paths in Fig. 5 are constructed from calculations of reference points used to plot a smoothed trajectory of the real-life travel of an autonomous dump truck. In the figure, (1) marks the paths constructed at $w = \{0.1\}$. The other paths marked (2) are plotted based on the spatial matrix with the weights in the interval [0–1]. Figures 5*a* and 5*b* depict the paths from the real digital model. Figures 5*c* and 5*d* demonstrate the paths plotted using randomly assigned weights.

All calculations were performed on PC with processor Intel (R) Core (TM) i7-8550U with timing frequency of 1.80 GHz, 8 cores, 8 traffics and 16 GB of operative memory. The programming language was C++ with the OpenMP library controlled by Microsoft Visual Basic 2022 in the Windows 11 environment with 64-bit architecture.

Conclusions

The present research based on using the digital model of haul roads as a multi-fractal representation of transportation infrastructure proves the potential operability and efficiency of the proposed approach. The digital model suggested as an informational framework for the computational procedures is a sufficiently effective ground for the analysis of algorithms aimed at searching optimum paths for autonomous dump trucks.

The proposed modification of parallel Dijkstra's algorithms of searching the shortest path between the fixed graph points also proves to be effective and applicable to handle real-life problems. Dijkstra's algorithm searches for the best paths between all points of a graph since in travel of an autonomous robotic dump truck, it is required to find an optimal trajectory in each section of a road in the context of quality of the road network. The computational

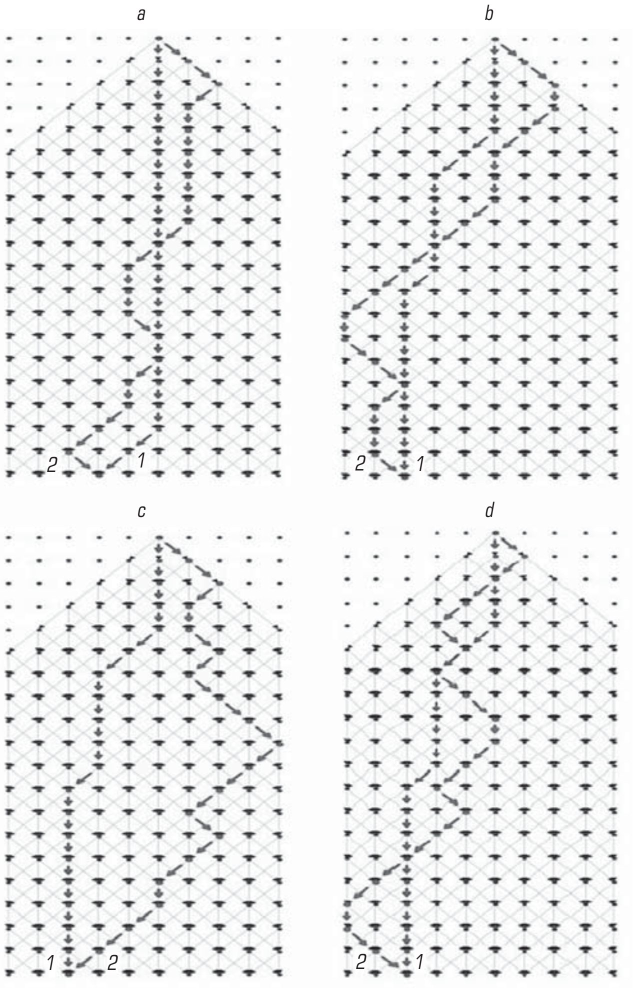

Fig. 5. Examples of optimal paths for different variants of selected weights of graphs:
1 – without regard to weights; *2* – with regard to weights

experiments show that with the proposed approach to calculations using the high dimensionality graphs, the route planning time, even in case of standard computers (tens of seconds), is entirely admissible in terms of real-life technological operations. In this manner, the proposed scheme of parallel computations ensures compensation of computational cost at limited resources within the admissible time of the on-line decision-making.

The further research can be carried out in a number of areas, in particular:

— the use of more complex criteria of the optimal path construction, including condition of the roadway and using the calculation formulas that embrace such weight factors as dynamics of other participants of a technological process, as well as the fuel consumption per different types of work, and the trajectory of the robotic dump truck;

— modification of parallel Dijkstra's algorithm toward calculation of invariably optimal and, consequently, safe routes concurrently for a number of autonomous robots.

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