2012. Available at: https://www.techstreet.com/standards/din-22123?product_id=1841776 (accessed: 09.11.2021).
4. Overmeyer L. Test Rig for Determination of Indentation. Rolling Resistance of Conveyor Belts according to DIN 22123. 2012.
5. Galkin V. I., Sheshko E. E, Sazankova E.S. The influence of the types and characteristics of belts on the operational parameters of special belt conveyors. *Gornyi Zhurnal*. 2015. No. 8. pp. 88–91. DOI: 10.17580/gzh.2015.08.18
6. Reicks A. V., Rudolphi T. J., Wheeler C. A. A Comparison of calculated and measured indentation losses in rubber belt covers. *Bulk Solids Handling*. 2012. Vol. 32, No. 3.
7. Galkin V. I., Sheshko E. E. Belt conveyors at the current stage of development of mining technique. *Gornyi Zhurnal*. 2017. No. 9. pp. 85–90. DOI: 10.17580/gzh.2017.09.15
8. Hintz A. Effect of Belt Design on the Energy Consumption of Belt Conveyor Systems. Dissertation University of Hannover. 1993.
9. Van de Ven H., Beers H., Lodewijks G., Drenkelford S. Aramid in conveyor belts for extended lifetime, energy saving and environmental effects. *Bulk Solids Handling*. 2016. Vol. 36, No. 6. pp. 16–21.
10. Galkin V. I., Shojaatalhosseini A. Establishment of the rational geometrical form rollers linear sections of powerful tape conveyors. *Gornoe oborudovanie i mehanika*. 2009. No. 3. pp. 50–54.
11. GURTEC: HM Series rollers, an intelligent design for heave duty maining applications. Available at: https://news.bulk-online.com/news-english/gurtec-hm-series-rollers-an-intelligent-design-for-heavy-duty-mining-applications.html (accessed: 09.11.2021).
12. He D. Energy saving for belt conveyors by speed control. *TRAIL Research School*. 2017. DOI: 10.4233/uuid:a315301e-6120-48b2-a07b-cabf81ab3279
13. He D., Pang Y., Lodewijks G. Determination of Acceleration for Belt Conveyor Speed Control in Transient Operation. *International Journal of Engineering and Technology*. 2016. Vol. 8, No. 3. pp. 206–211.
14. Minkin A., Borsting P., Becker N. Pipe Conveying the next stage: A new technology for steep incline high capacity open pit conveying. *Bulk solids handling*. 2016. Vol. 36, No. 2(3).
15. Dilefeld M. Gearless belt conveyor drives – new technology for highcapacity systems. *Bulk solids handling*. 2014. Vol. 34, No. 1.
16. Takraf. Gearless drives for high-capacity belt conveyors. *Mining engineering*. 2014. Available at: https://me.smenet.org/docs/Publications/ME/Issue/06_01MIN_WebExclusive_June1.pdf (accessed: 10.11.2021). EM

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ON SOME ASPECTS OF INCREASING THE TARGET PRODUCTIVITY OF UNMANNED MINE DUMP TRUCKS

This article considers one of the approaches to solving the problem of improving the efficiency of the functioning of unmanned open pit transport. The actual data on the movements of robotic dump trucks within the framework of a continuous transport and technological cycle at one of mining sites of a coal mine are analyzed. During the study, the movement times in the loaded and empty states are recorded. In addition, the time of passing by dump trucks of individual sections of the transport route is monitored, in order to empirically determine the speed reserves for each robot. As a result, several options have been obtained to increase the target performance of an autonomous dump truck by changing the speed modes of movement in certain sections. One of the variants is presented in the paper as an illustrative example. The paper also briefly discusses possible approaches to formalizing the procedure for determining the optimal driving modes of robotic dump trucks, depending on the terrain and features of the route as well as the roadbed condition.

Keywords: *robotic dump truck, digital transformation, optimization models, open-pit mining, Industry 4.0, quarry, route segments, unmanned mining transport systems, robot target productivity, autonomous haulage systems*
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Introduction

At present, the development and implementation of technologies for rock mass haulage using robotic open pit mine equipment is a steady industrial trend in a number of leading countries in the open-cast field, such as Australia, Canada, South African Republic [1–3]. The leaders in the development of robotic and autonomous large dump trucks are such well-known companies as Komatsu (Japan), Caterpillar (USA), Euclid-Hitachi (Japan), BELAZ (Byelorussia) [4-6].

In comparison with the existing technologies of mining and carrying of minerals, robot dump trucks can potentially provide higher efficiency of mining under the condition of rational organizational management, as they allows to reduce operating costs by cutting-down the equipment downtime due to human factors [4, 7–9]. In the last 5–7 years, a number of engineering companies, such as Modular Mining Systems, Wenco MiningSystems, Vist Robotics, ASI

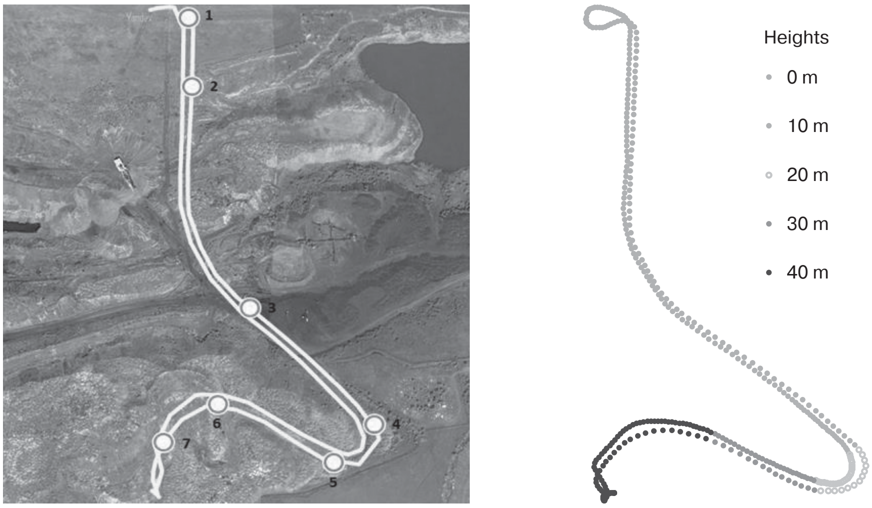

Fig. 1. The route division into segments with a uniform nature of movement

Mining [10–13], in cooperation with manufacturers of mining machinery, have been developing in this area and are starting to launch system pilot projects for autonomous transportation of mined rock.

In Russia in recent years, most mining companies have shown interest in robotic mine dump trucks, but only one domestic pilot project based on the BELAZ-7513R model has been implemented yet – by SUEK-Khakassia LLC at the Chernogorsky pit (Abakansky open pit mine, Chernogorsk, Khakassia, Russia) [5, 13]. It is obvious that the key issue determining the economic efficiency and feasibility of the application of robotics in mining and mine transport operations is productivity [7, 8, 14, 15]. The caution of potential customers relates to the lack of valuable statistical data (including foreign ones) confirming the intensity growth of transportation by robots compared to human drivers [10, 16].

It should be noted that the efficiency of robotic large dump trucks when carrying out haulage operations in autonomous, partially autonomous or mixed (when robots and driver-controlled dump trucks operate simultaneously) depends on the solution of a number of tasks:

1. It is necessary to ensure optimal routing, that is, such a distribution of dump trucks between excavators that allows minimizing transport downtime in queues and ensuring maximum productivity of excavators.

2. It is required to determine the most economical and safe maneuvering schemes for handling operations (including that with the use of reverse gear) in order to reduce the time and increase the safety of maneuvers.

3. Finally, it is necessary to calculate the sequence of coordinates within the framework of a given route between loading and unloading depots, that is, the route of the robot's movement [17] and determine such speed modes for individual sections of the route that would optimize the time of the route while minimizing both emergency risks and consumption of fuels and lubricants.

In this paper, the main attention was paid to solving the latter problem; the solution has been based on the results of experimental studies aimed at investigating various movement modes of autonomous vehicles (robotic dump trucks) at the experimental section of the Chernogorsky pit in order to analyze and optimize target performance characteristics, as well as to develop possible formal mechanisms for on-line determining the optimal movement modes for autonomous dump trucks.

Description of experiments

The operation of dump truck robots at the experimental site was carried out during the standard technological cycle "Loading-Transportation-Unloading-Return-Setting up for loading". The cycle time in this case is obviously equal to:

$$T_{haul} = T_{face} + T_1 + T_{dump} + T_2,$$

where T_1 and T_2 is a time of a dump truck movement in loaded and empty state; T_{face} and T_{dump} is a time of operations in the face and on the dump, including loading and unloading stages.

During the experiments, the robotic section performance was first recorded at 25% below the production rate performed by drivers. The subsequent analysis has showed that the rhythmic and calculated execution of technological cycle elements – equally, both by a robot and a human - requires more time than that with professional drivers, when significant part of the actions is performed without step-by-step comprehension, but based on skill, or creatively. Nevertheless, it should be noted that the losses on the measured-type action of robots could be covered by savings on the actions imperative for drivers, including some safety measures that no longer need to be performed in an unmanned mode.

It is rather difficult to evaluate and compare the efficiency of loading and unloading processes, since other equipment is involved in these processes, and the speed of movement and possible downtime of dump trucks are determined more likely by external factors, such as the size and shape of maneuvering platforms, operating modes of an excavator, routing of dump trucks [18]. Nevertheless, this is possible when working on a specific site, and T_{face} and T_{dump} are amenable to improvement. However, these improvements are difficult to formalize, since they are determined by the choice of unique movement trajectories (turns, reverse, etc.) for each specific technological site.

The route of robotic dump trucks was conditionally divided into segments with similar movement characteristics (straight line, turn, ascent, descent, etc., **Fig. 1**) in order to achieve more consistent improvements in transport and technological

Fig. 2. The probable trajectory of leaving the route

cycles. The following hypothesis has been put forward and tested: "due to the uniform movement characteristics within the segment, the measures for increasing intensity will have an effect immediately throughout such a segment."

In these terms, in accordance with Fig.1, the time of one haul by a dump truck is determined by the following formula:

$$T_{haul} = T_{face} + \Sigma_{(1-2)\ldots(6-7)} T_i + T_{dump} + \Sigma_{(7-6)\ldots(2-1)} T_j, \qquad (1)$$

where T_i, T_j – is the passage time of each segment in the loaded and empty directions.

The space behind boundary points 1 and 7 is reserved for maneuvering zones on loading and unloading; they change shape as the site works and, thus, as we noted earlier, a comparison of work speed in them for different time periods cannot be performed.

Non-terminal segments of the route, taking into account the directions (loaded modes) of movement in relation to improvements, are divided into 3 groups. Segments whose performance is limited by the power of the dump truck chassis ($T_{(4-5)}$, $T_{(5-6)}$), cannot be accelerated: on them, the robotic complex uses the maximum driving speed within 25 km/h limits without risk of incidents. The dynamics of check passes under control of drivers on this part of the route was the same.

Segments whose acceleration is limited by the danger of uncontrolled exit beyond the target motion path ($T_{(7-6)}$ ... $T_{(5-4)}$) are mainly associated with empty descent from the dump. On these segments, with worsening weather conditions (rain, snow, ice), road adherence in turns may be lost, which determines the risk of an incident (taking into account the dynamics of traffic and the mass of cars, **Fig. 2**) [19–21]. For such segments, acceleration was carried out in stages with a focus on the dynamics of check passes performed under control of drivers, as well as with testing an increase in the target speed at each step.

As a result, the passage on these segments was accelerated by 40–60% to the level of 18–30 km/h. Taking into account the duration of the segments, a gain in passing time of about 0.5 minutes per haul was achieved.

Finally, the route segments without significant slopes and dangerous turns are limited in the ability to accelerate their passage only by a length of braking distance ($T_{(1-2)}$ ... $T_{(3-4)}$, $T_{(6-7)}$, $T_{(4-3)}$ ... $T_{(2-1)}$). On the project, the control system of the complex has used "soft" braking, implemented mainly with the help of a dynamic brake and aimed at preventing drift, skidding and other types of loss of control, as well as damaging the road surface and braking system of the dump truck. The length of braking distance for "soft" braking is limited by the obstacle detection horizon on the route by computer vision system. For the equipment and algorithms used, such a horizon is about 60 m, and its provision is possible at operating speeds within 45 km/h.

Generalization of the experiment results

For segments of this type, their passage by robotic dump trucks was accelerated by an amount from 40% to 2.5 times, given that the segments, adjacent to the final ones ($T_{(6-7)}$, $T_{(2-1)}$) are limited by the subsequent transition to maneuvering speed, i.e. it is not possible to perform extreme acceleration throughout them. In total, the improvement measures made it possible to reduce the route time by 2.5 minutes per haul.

Figure 3 shows the total result of the improvements made, taking into account the route decomposition (see Fig. 1). The movement dynamics of dump trucks is shown as before and after the improvements. The movement under driver control is measured in the mode without exceeding the performance norm; besides, the driver in the "creative" driving mode is always able to bit the robot, but this does not ensure stable performance growth due to the required efforts and associated risks [1, 7, 10]. With the haulage arm length 1.8 km (the given distance is 2.9 km), the average dump truck performance was 3 trips per hour, which is 22% higher than the norm calculated using a EKG-8U excavator, with which the project site was equipped. The exact time values

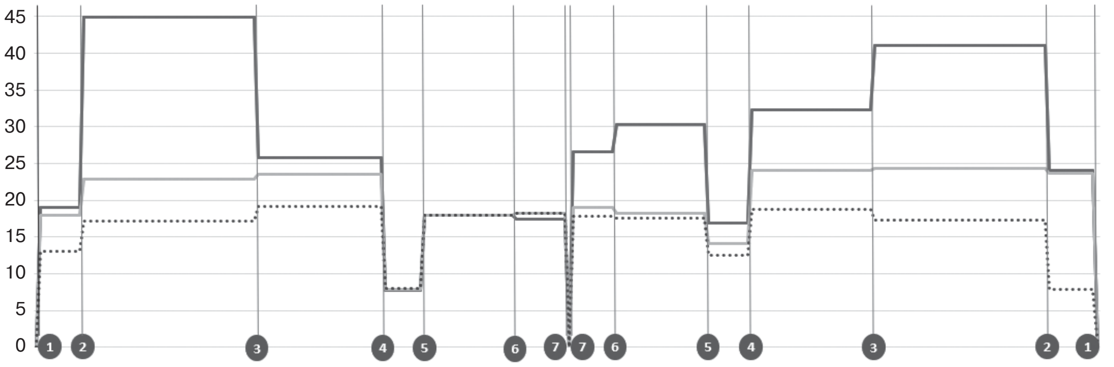

Fig. 3. Profile of the route target speed, km/h (before and after improvements)*

* The graph illustrates average speeds by segments, calculated through path length and passing time. Acceleration and braking curves on achieving the average speed are not taken into account, since they do not affect the graph object – comparison of the total dynamics along the route.

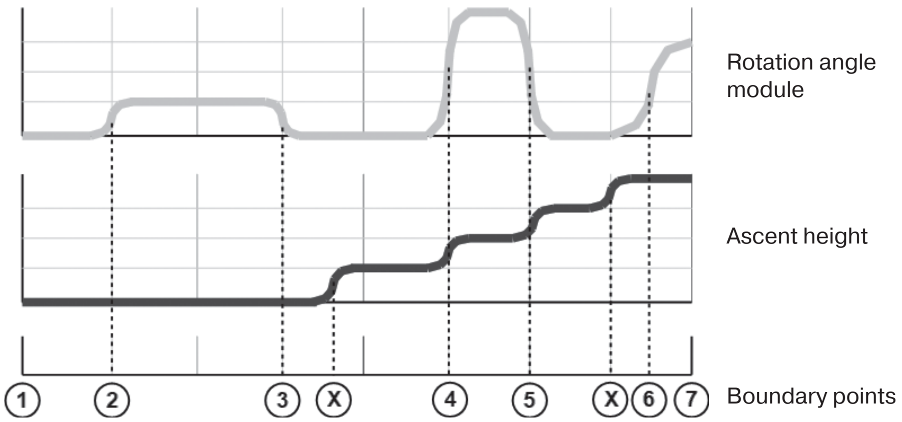

Fig. 4. Boundaries of the route segments on the combined profiles of heights and rotation angles

of individual rides by trucks and route segments have been generalized using median averaging.

Thus, the above described approach makes it possible to extract the target performance of a robotic stripping complex within the reserve limits determined by the movement dynamics of robotic dump trucks. However, the average working time in a shift can also be increased due to additional organizational measures, in particular, by reducing inter-trip downtime (for this section it will amount up to 40 minutes, which is equivalent to 2 additional hauls per dump truck unit).

A formal approach to optimizing the movement modes of robotic dump trucks

The performed optimization of movement modes was carried out in manual mode and has required certain time costs. In the future, it is necessary that this procedure for achieving the effectiveness could be universally applied to any trajectories and areas of operation of robotic complexes without time-consuming additional experimental haulage rounds of dump trucks [4, 9, 17, 22]. Two approaches can be proposed to achieve this goal.

The first approach is connected with the automation of the stage of allocation of segments of a uniform movement nature. With regard to complexes based on robots of BELAZ-7513R, this can be achieved within the following scheme.

The initial state should be characterized by the presence of a route of robot movements between the loading and unloading zones, which would be successfully traversed in autonomous mode at a safe speed – by convention, 5 km/h. The route contiguity points to the maneuvering zones for loading and unloading (the beginning and end of the route) should be determined from the requirements of algorithms for constructing maneuvers.

It is necessary to complete the passage of a route in both directions by a single dump truck with a real-time recording of the readings of the front wheels' turn and accelerometer standard sensors. According to the recorded data, the rotation angle and ascent height profiles are further compiled; when driving, a constant speed have to be maintained so that the profiles have been kept uniform along the length of the route.

Further along the length of the profile, marks should be fixed between intervals passed with a constant wheel rotation angle (with an allowance for a given error). The rotation angle error should be selected experimentally in such a way that the assumption for it does not create segments with increasing curvature of turning; otherwise, in the future this will limit the speed of passage. Similarly, taking into account the specified error on the height profiles, marks between intervals of constant height should be fixed.

When combining the marks of both profiles throughout the route, a certain structuring of the route will be carried out, namely (**Fig. 4**):

1) route segments are obtained in accordance with the intervals of the rotation angle profile;

2) segments of conditionally uniform ascent/descent are highlighted (that is, the elevation profile marks fall inside the angle profile intervals).

In relation to the route shown in Fig. 1, the above described profile bypass allows one to form 6 segments with uniform movement nature in each direction (to highlight 7 boundary marks), including the elevation difference marks will fall on segments 3-4 and 5-6 are "ascent without turning" (similarly, with the reverse bypass – 6-5 and 4-3, "descents"). The remaining segments, respectively, will be determined without a height difference: 1-2 (2-1) – straight, and 2-3 (3-2), 4-5 (5-4) and 6-7 (7-6) are turns.

The second approach presumes determining the optimal set of speeds by segments based on a formal approach to the description of the route and its features. In this case we have to assume:

1. That a digital model of the route (roadbed) is pre-constructed and used [23] and a specific route is selected – that is, a set of macrocoordinates of the centers of basic geometric primitives (for example, hexagons with a face size of 1 m) [17].

2. There are data obtained using on-board inclinometers and accelerometers that allow determining two fundamentally important parameters for any segments of the route:

α is a percentage of the longitudinal slope of the route;

β is a rotation angle module;

η is the third necessary parameter that characterizes the roadbed condition (slippery surface, presence of significant imperfections, etc.). It should be noted that this parameter should be constantly updated (in bad weather conditions, almost after passing of each dump truck), however, the issues of this parameter calculation are not considered in this paper.

Based on a digital model of the route or, which gives less accurate results, using, as in the previous approach, the

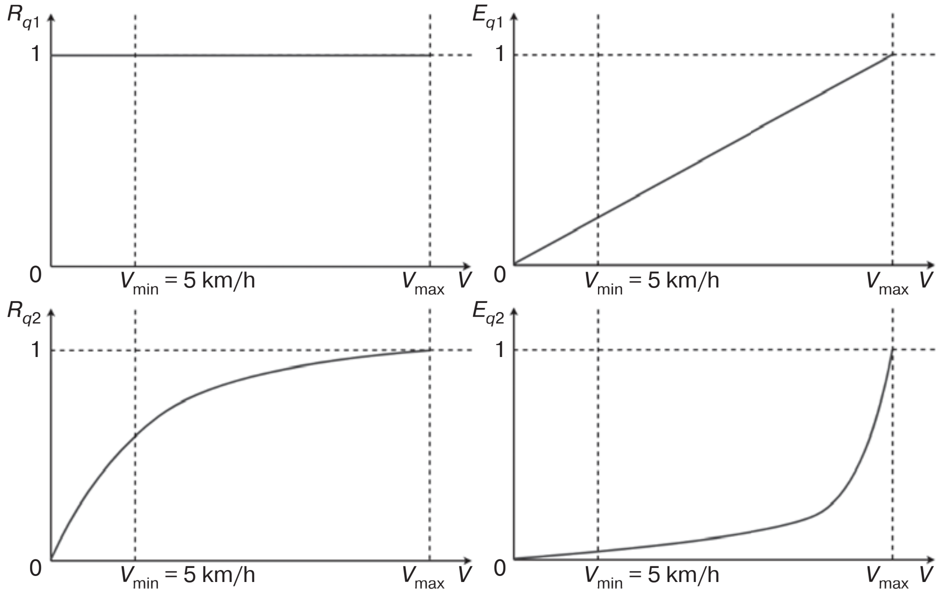

Fig. 5. Examples of *R* and *E* dependencies on speed for different types of segments

operational data of GPS sensors, we divide the entire route $\{S_0, S_f\}$, where S_0 and S_f are the coordinates of the starting and ending points of the route, into $n - 1$ partial interval (segment) of a fixed length, that should be selected in the range from 50 to 100 m based on the size and dynamic characteristics of overweight dump trucks. In this case, the route is a sequence of several reference points $\{S_0, S_1, S_2, \dots S_{n-1}, S_n\}$, while each segment ΔS_i, of course, can have different characteristics {α, β, η} and, consequently, different ranges of possible speeds, which depend on the movement profile: descent, ascent, turn; the presence of cargo on board; the road condition: slippery, broken.

The range of speed modes for each segment can vary and depends on a specific combination of {α, β, η} parameter values. These parameters may be set in various interval-categorical scales, as well as using terms of fuzzy sets. Based on practical common sense, it is logical to assert that 3 to 5 terms are sufficient for a complete description of a possible combination of parameter values, for example: $\alpha = \{\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5\}$; $\beta = \{\beta_1, \beta_2, \beta_3\}$; $\eta = \{\eta_1, \eta_2, \eta_3\}$. This means that in the extreme case we have about 125 (practically, 45 is quite enough) types of segments, the movement modes for which may differ. In that way, for a particular route we have $\{\Delta S_1^j, \Delta S_2^j, \dots, \Delta S_{n-1}^j\}$, where $j \in [1, 2, \dots, k]$; k – is the total number of different segments ($k \le 45$).

The task is to maximize the total speed of the passage of all segments by the dump truck while fulfilling certain restrictions specific to each segment. Obviously, speed acts as a control parameter, and the criterion for optimal route passage by the robot should be some complex functional that takes into account not only the route passage time, but also safety and resource indicators, for example, fuel consumption. Let us introduce two functions that are determined based on expert analysis and are set in a table or analytically. The first of them determines the relationship between the risk R of running off the route on the segment q and the speed $V_q : F_{R_q} = f(V_q)$ for each of the segment types. The second sets the relationship between the specific resource consumption E and speed $V_q : F_{E_q} = f(V_q)$.

For some segment types, the trends of changes in functions may coincide, and for others they may have the opposite character. Schematic examples are shown in **Fig. 5**, where R and $E \in [0, 1]$, that is, can actually be considered as membership functions of the fuzzy sets "Risks" and "Costs", if such a method of expert assignment of parameter values is chosen, and $V_{\min}(q) \le V \le V_{\max}(q)$.

Thus, the problem of finding optimal sequences of segment-by-segment speeds $V_1, V_2, \dots V_i, \dots V_{n-1}$, can be formulated as a nonlinear programming problem:

$$F = \sum_{i=1}^{n-1}\{f_{Rj}^{i}(V_i) + f_{Ej}^{i}(V_i)\} \to \min, j \in 1, k;$$

$$V_{i_{min}}(j) \le V_i \le V_{i_{max}}(j),\ \Delta V_i \le \text{const}.$$

The last inequality sets an additional restriction on the speed change between segments (in fact, this is a restriction on the possible accelerations when the robot moves).

Since the search space is discrete, in other words, the robot's speed changes with some integer step, then there are two possible effective solution algorithms, namely: one of the algorithms for searching in the state space (for example, the A* algorithm and its modifications) or an evolutionary optimization algorithm, in particular, a quite effective particle swarm optimization method.

Conclusions

1. In this paper, the issues of improving the efficiency of autonomous transport usage in open-pit mining have been considered. Experiments with various modes of robot movement show that the concept of allocating traffic sections with a conditionally constant speed and a gradual increase in this speed, taking into account possible risks, gives a certain gain, including in comparison with an experienced driver.

2. Proposed are a number of approaches that can significantly reduce the time of test hauls by using various expert knowledge, either for rational segmentation of the route, or for the formation of evaluation functions in the implementation of formal segmentation.

3. Since preliminary estimates show that formal approaches are 1.5–2 times less effective for certain types of routs than manual ones, it is proposed to consider this formal procedure as a convenient tool for constructing the initial speed distribution along the route, not excluding subsequent experimental optimization adjustment.

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References

1. Oxborrow J. R. Implementation of an Autonomous Haulage System on retrofitted haul trucks at Nevada Gold Mines Goldstrike operations. *SME Annual Conference and Expo2020*. 2020. 159172.
2. Bhattacharyya S. S., Shah Y. Emerging technologies in Indian mining industry: an exploratory empirical investigation regarding the adoption challenges. *Journal of Science and Technology Policy Management*. 2021. DOI: 10.1108/JSTPM-03-2021–0048
3. Lukichev S. V., Nagovitsin O. V. Digital transformation of mining industry: Past, Present and Future. *Gornyi Zhurnal.* 2020. No. 9. pp. 13–18. DOI: 10.17580/gzh.2020.09.01
4. Ishimoto H., Hamada T. Safety Concept and Architecture for Autonomous Haulage System in Mining. *Proceedings of the 37th International Symposium on Automation and Robotics in Construction*. 2020. pp. 377–384. DOI: 10.22260/isarc2020/0054
5. Vladimirov D. Y., Klebanov A. F., Kuznetsov I. V. Digital transformation of surface mining and new generation of open-pit equipment. *Gornaja Promyshlennost*. 2020. No. 6. pp. 10–12.
6. Sobolev A. A. Review of case history of unmanned dump trucks. *Gornyi Zhurnal.* 2020. No. 4. pp. 51–55. DOI: 10.17580/gzh.2020.04.10
7. Gaber T., Jazouli Y. E., Eldesouky E., Ali A. Autonomous haulage systems in the mining industry: cybersecurity, communication and safety issues and challenges. *Electronics*. 2021. Vol. 10(11). DOI: 10.3390/electronics10111357
8. Akbari A., Bernardini S. Informed autonomous exploration of subterranean environments. *IEEE Robotics and Automation Letters*. 2021. Vol. 6(4). pp. 7957–7964.
9. Malavolta I., Lewis G. A., Schmerl B., Lago P., Garlan D. Mining guidelines for architecting robotics software. *Journal of Systems and Software*. 2021. Vol. 178(2). DOI: 10.1016/j.jss.2021.110969
10. Price R., Cornelius M., Burnside L., Miller B. Mine planning and selection of autonomous trucks. *Springer Series in Geomechanics and Geoengineering*. 2020. pp. 203–212. DOI: 10.1007/978-3-030-33954-8_26
11. Ali D., Frimpong S. Artificial intelligence, machine learning and process automation: existing knowledge frontier and way forward for mining sector. *Artificial Intelligence Review*. 2020. Vol. 53(8). pp. 6025–6042.
12. Androulakis V., Sottile J., Schafrik S., Agioutantis Z. Concepts for Development of Autonomous Coal Mine Shuttle Cars. *IEEE Transactions on Industry Applications*. 2020. Vol. 56(3). pp. 3272–3280.
13. Klebanov A. F. Automation and robotization in opencast mining: experience in digital transformation. *Gornaya Promyshlennost.* 2020. No. 1. pp. 8–11.
14. Voronov Y., Voronov A., Makhambayev D. Current State and Development Prospects of Autonomous Haulage at Surface Mines. *E3S Web of Conferences*. 2020. DOI: 10.1051/e3sconf/202017401028
15. Nagovitsyn O. V., Voznyak M. G. Robotic mine management. *GIAB*. 2021. No. 5(1). pp. 326–335.
16. Paredes D., Fleming-Muñoz D. Automation and robotics in mining: Jobs, income and inequality implications. *The Extractive Industries and Society*. 2021. Vol. 8(1). pp. 189–193.
17. Temkin I., Myaskov A., Deryabin S., Konov I., Ivannikov A. Design of a Digital 3D Model of Transport–Technological Environment of Open-Pit Mines Based on the Common Use of Telemetric and Geospatial Information. *Sensors*. 2021. No. 21(18). DOI: 10.3390/s21186277
18. Zinoviev V. V., Starodubov A. N., Nikolaev P. I. Modular system of simulation modeling of conventional and robotic mining technologies. *IOP Conference Series: Earth and Environmental Science*. 2021. No. 773(117). 0120672019. DOI: 10.1088/1755-1315/773/1/012067
19. Ristovski K., Gupta C., Harada K., Tang H. K. Dispatch with confidence: Integration of machine learning, optimization and simulation for open pit mines. *Proceedings of the ACM SIGKDD International Conference on Knowledge Discovery and Data Mining*. 2017. pp. 1981–1989. DOI: 10.1145/3097983.3098178
20. Sun X., Zhang H., Tian F., Yang L. The Use of a Machine Learning Method to Predict the Real-Time Link Travel Time of Open-Pit Trucks. *Mathematical Problems in Engineering*. 2018. pp. 1–14. DOI: 10.1155/2018/4368045
21. Temkin I. O., Klebanov D. A., Deryabin S. A., Konov I. S. Haul road condition determination under controlled interaction of robotic elements in open pit mining and transport system. *Gornyi Zhurnal*. 2018. No. 1. pp. 78–82. DOI: 10.17580/gzh.2018.01.14
22. Ali D., Frimpong S. DeepHaul: a deep learning and reinforcement learning-based smart automation framework for dump trucks. *Progress in Artificial Intelligence*. 2021. No. 10(2). pp. 157–180.
23. Temkin I. O., Myaskov A. V., Deryabin S. A., Rzazade U. A. Digital twins and modeling of the transporting-technological processes for on-line dispatch control in open pit mining. *Eurasian Mining*. 2020. No. 2. pp. 55–58. DOI: 10.17580/em.2020.02.13 EM