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

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 allow 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 conveyors, Gornoe oborudovanie i mehanika. 2009. No. 3. pp. 50–54.


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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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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:

$$I_{opt} = I_{ace} + T_1 + I_{dump} + I_2,$$

where $T_1$ and $I_2$ is a time of a dump truck movement in loaded and empty state; $T_{ace}$ 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 $T_{ace}$ and $I_{dump}$ 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
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:

\[ t_{\text{haul}} = t_{\text{accel}} + \sum_{i=1}^{j} t_i + t_{\text{dump}} + \sum_{j=6}^{T-6} t_{j-2} \]  

where \( t_i \) – 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 \( (T_{1-3}, T_{5}) \), 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 \( (T_{7-6}) \) 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 \( (T_{1-2} \ldots T_{3-4}, \ldots \ldots T_{6,7}, T_{4-3} \ldots T_{2,1}) \). 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...
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:

\[ \alpha \] is a percentage of the longitudinal slope of the route;

\[ \beta \] is a rotation angle module;

\[ \eta \] 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
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 $v_{min}(q) \leq V \leq v_{max}(q)$.

Thus, the problem of finding optimal sequences of segment-by-segment speeds $v_1, v_2, ..., v_n$, can be formulated as a nonlinear programming problem:

$$\tau \rightarrow \sum_{i=1}^{n} (\Delta r_i(v) + r_i^*(v)) \rightarrow \min, j \in [1, k];$$

$$v_{min}(j) \leq V \leq v_{max}(j), \Delta V \leq \text{const}.$$
3. Since preliminary estimates show that formal approaches are 1.5–2 times less effective for certain types of routes 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


