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A STUDY ON THE EFFECTIVENESS OF IMPLEMENTING REMOTE AND ROBOTIC CONTROL SYSTEMS IN EQUIPMENT MANAGEMENT TO IMPROVE TECHNO-ECONOMIC INDICATORS IN OPEN-PIT MINING

This article discusses key aspects of the efficiency of remote and robotic control systems in mining equipment management, aiming to enhance the techno-economic performance of open-pit mining operations. Costs associated with maintaining suitable (comfortable) working conditions include the use and maintenance of climate control systems (air conditioners, heaters), air purification systems, specialized sealed cabins, and similar measures. Working in poor conditions also increases worker illness rates, leading to higher healthcare costs.

Objective: The article investigates how implementing remote and robotic control systems can improve productivity, reduce downtime, and minimize health risks to operators in deep and hazardous mining conditions.

Methods: The study analyzes case studies and applies statistical methods to quantify the impact of automation on productivity, including assessments of machine speed, downtime reduction, and fuel efficiency. Comparisons between manual and automated operations provide insights into system advantages and areas for potential improvement.

Results: Results show that remote and robotic control systems enhance productivity by 10-40%, depending on route conditions and automation level. The study reveals that the adoption of remote and robotic control systems in mining operations significantly improves productivity and reduces operational costs. Productivity gains reach up to 10-15% on straight transport routes, while optimal conditions with minimal inclines (below 0.3) allow increases of up to 35-40%. Fuel use decreases by approximately 3-5%, driven by optimized load distribution and route planning. Equipment downtime is reduced by up to 20% through minimized idle periods during shift changes. Ore quality is enhanced, with fluctuations in magnetic iron content reduced by 1-3%, leading to improved beneficiation efficiency.

Keywords: remote control, robotic control, mining productivity, automation, safety, open-pit mining, techno-economic indicators.

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ДОСЛІДЖЕННЯ ЕФЕКТИВНОСТІ ВПРОВАДЖЕННЯ СИСТЕМ ДИСТАНЦІЙНОГО ТА РОБОТИЗОВАНОГО КЕРУВАННЯ ОБЛАДНАННЯМ ДЛЯ ПОКРАЩЕННЯ ТЕХНІКО-ЕКОНОМІЧНИХ ПОКАЗНИКІВ ВІДКРИТИХ ГІРНИЧИХ РОБІТ

Метою даного дослідження є оцінка ефективності впровадження систем дистанційного та роботизованого керування технологічним обладнанням для покращення техніко-економічних показників експлуатації родовищ відкритим способом. Для покращення умов праці та безпеки в складних умовах розробки родовищ проведено аналіз теоретичних підходів і досвіду експлуатації існуючих систем керування. Визначено типи дистанційного та автономного управління. Наведено стислі результати їх компаративного аналізу. Визначено потенціал зростання продуктивності та зменшення простоїв технологічного обладнання. Застосовано методи техніко-економічного порівняння для кількісної оцінки впливу на продуктивність у різних умовах експлуатації.

Ключові слова: дистанційне керування, роботизоване керування, відкриті гірничі роботи, техніко-економічні показники, продуктивність.

Introduction

Modern open-pit mines, with their current contours, reach significant depths of up to 500–600 meters. These depths are associated with a corresponding deterioration in working conditions [1]. The challenging environments at deep levels require workers to contend with high dust concentrations due to the fragmentation of rock by explosive or mechanical methods, as well as air contamination from exhaust emissions of fuel-powered mining and transport machinery. Additionally, personnel are exposed to extreme temperatures, strong winds, and radiation, further compounding the hazardous working conditions.

The increase in the stripping ratio with greater open-pit depth occurs in steeply and inclined dipping deposits due to the need to expand pit slopes for access to lower levels. The angles of pit slopes are determined based on safety requirements for personnel, typically not exceeding 47–52°. The rise in operational costs is primarily due to the increased haulage distances, leading to higher consumption of fuel, lubricants, and electricity, as well as the need to expand the fleet of transport machinery and extend conveyor sections.

The reduction in pit productivity is mainly attributed to significant downtime required for air ventilation, heating of work areas in low temperatures, and the inefficient use of transport equipment, which causes idling of loading and excavating machinery. Additionally, worker qualification levels also impact pit productivity.

Problem formulation

High-speed execution of work operations, especially under challenging conditions and towards the end of shifts, impacts human physical capabilities; consequently, the difference in excavator productivity between operators can reach up to 40%. Costs associated with maintaining suitable (comfortable) working conditions include the use and maintenance of climate control systems (air conditioners, heaters), air purification systems, specialized sealed cabins, and similar measures. Working in poor conditions also increases worker illness rates, leading to higher healthcare costs.

All these factors contribute to the decreased efficiency of open-pit mining as pit depth increases, ultimately leading to the cessation of surface operations and the transition to underground mining for continued deposit exploitation. Reducing the trend of decreasing open-pit efficiency with increasing pit depth is a critical task that could yield additional economic benefits. Lowering mineral extraction costs, considering the aforementioned factors, may be achieved through the following measures:

1. Reducing the stripping ratio.
2. Reducing operational costs.
3. Lowering expenses related to maintaining adequate working conditions.

Reducing the stripping ratio is only feasible by increasing the slope angle of the pit wall; however, this places workers at risk from potential wall collapses, which is unacceptable. Operational costs can be reduced by implementing specialized systems for monitoring and analyzing transportation movements. Decreasing costs associated with worker conditions can only be achieved by removing personnel from hazardous zones.

A unified solution to these challenges lies in the application of remote-control technologies for machinery and open-pit mining processes.

Main material

The application of remote-control systems is advantageous not only in challenging and hazardous environments but also whenever it proves economically beneficial. In North America, remote control using radio communication has gained widespread use in the railway sector. Major Canadian railways, such as Canadian National and Canadian Pacific, extensively implement remote control technology, primarily on switcher locomotives [2].

All switching work is performed by remote-controlled locomotives, while at other stations, remotely operated locomotives complete up to 70% of the switching operations. The cost savings attributed to these systems are estimated at approximately 20 million USD annually. Overall, virtually all sectors of production now utilize remote control systems in one form or another, with annual economic benefits estimated in the millions of USD.

In the mining industry, some major companies are actively pursuing the development of mining and transportation equipment with remote control capabilities. For instance, Komatsu's haul trucks are a notable example. The company places substantial focus on research and development to enhance the technical level of its trucks by equipping them with state-of-the-art electronics and automation technologies.

One of Komatsu's programs is the creation of a fully automated open-pit machine – a 21st-century haul truck. The company has made significant strides in this direction by developing the Komatsu Autonomous Truck, an automated motion control system utilizing the latest advancements in electronics to manage truck movement on quarry roads, including grades of up to 12%.

This system is installed on Komatsu's small and mid-sized haul trucks (HD-785, HD-465, HD-325) with load capacities ranging from 32 to 136 tonnes. In 1993, the company R.A. HANSON (RAHCO) was the first to implement remote control of haulage machines based on GPS technology [3]. Subsequently, they developed autonomous transport for ore mass transportation. Later, using GPS devices, TRIMBLE created a stockpiling and loading system at the El Abra copper mine in Chile.

In 1995, TRIMBLE announced a strategic alliance with Aquila Mining Systems, a developer of real-time monitoring and control systems for drills and excavators using GPS technology [4]. The jointly developed modern drilling system utilizes GPS for navigation (eliminating the need for prior staking) and precise coordinate identification. The system includes automatic drill rig control, enhancing operator productivity and reducing rig wear. By integrating positioning and material recognition capabilities, the system minimizes costs associated with blasting operations. Accurate blasting enhances mine productivity by optimizing excavator efficiency.

A similar GPS-based system on excavators provides quality control, industrial statistics, and productivity indexing, enabling real-time monitoring of blasting efficiency. The installation of GPS systems on excavators also facilitates precise positioning according to project specifications. Notably, GPS-based systems improve quality control and reduce rework.

As of 2020, Hitachi Construction Machinery has been actively working towards the full-scale implementation of this system, with plans to expand its control range to 100 vehicles [5-6]. In May 2020, Sotreq delivered the first remote-control cabin to the Brazilian iron ore mining company, CSN Mineracao's. According to dealers, this equipment, which allows an operator to control a tracked bulldozer located miles away within an open-pit mine, marks a significant milestone for the future of the mining industry, primarily focused on enhancing safety. CSN installed the onboard system on a Cat D11T bulldozer, which is already operational in the open-pit [7].

This project is part of CSN Mineracao's autonomous mining program [7-8]. The remote-control cabin will provide operators with an ergonomically improved environment free from vibration and noise, reducing fatigue and exposure to risk. System integrators have achieved increased productivity by reducing shift-change times and enhancing work quality through the high-precision operation of the bulldozer.

Literature analysis and synthesis of machine control options indicate that, based on the degree of automation, the following types of remote control can be distinguished, where the main classification criterion is the level of human involvement in the control process:

1. Remote control: this mode replicates in-cabin control but at a safe distance for the operator, thus eliminating exposure to harmful and hazardous working conditions.

2. Semi-autonomous (hybrid or robotic) control: the operator handles the machine remotely during complex operations requiring creative input, while routine tasks, such as navigation to a designated point or unloading, are performed automatically.

3. Autonomous (robotic) control: this mode entails transferring control functions to a hardware-software system installed on the equipment, enabling autonomous operation without direct operator involvement in completing technological cycle tasks.

Let's analyze the main advantages provided by remote and robotic control (Table 1).

It should be noted that robotic control presents two additional drawbacks:

- complete automation of complex processes (such as selective extraction and responses to non-standard situations) is not feasible; therefore, for open-pit mines with numerous such operations, the required personnel may need to be increased.
- maintenance personnel are still needed on-site at the mining enterprise.

The drivers behind the development of unmanned mineral extraction technologies include:

- a shortage of skilled labor and the elimination of the need to construct housing settlements in remote and undeveloped mining areas.
- removal of personnel from hazardous working conditions, allowing operations with mining parameters that would be restricted under safety requirements for human presence.
- enhanced equipment productivity through precise and optimized control.
- cost reductions achieved through productivity gains, elimination of equipment downtime, reduced personnel requirements, optimized management, and so on.

In addition to enhancing operator safety and improving working conditions, "unmanned technologies" can provide several operational advantages by increasing productivity and reducing the energy and resource intensity of production through optimized computer-controlled management [9-10]. However, it is crucial to quantify these benefits against existing literature data: productivity improvements are achieved by increasing machine travel speed and eliminating shift-change times. The increased speed of dump trucks along the haul route can be attributed to:

- optimized computer-based control, eliminating human factors;
- removal of limitations on safe travel speed due to the operator's position in a remote, secure location.

The primary factors determining the potential for productivity gains include:

- the speed achieved by haul trucks on flat segments under manual in-cab operation by drivers;
- the transport distance along a given route;
- the duration of loading and unloading operations (assumed constant when transitioning to robotic control) and their proportion in the total cycle time (although this duration may decrease if excavators are automated);
- the proportion of steeply inclined sections (over 6%) along the route length.

Table 1

Comparative analysis of robotic and remote-control systems for mining equipment.

Type of Control	Advantages	Disadvantages
Common advantages and disadvantages	1. Safe working conditions for operators. 2. Capability for machines to operate in hazardous environments with optimized open-pit parameters.	Additional costs for the acquisition and maintenance of the remote control system
Additional for remote control	1. Ability for operators to coordinate actions while located in the same facility. 2. Capability to operate from several kilometers away, enabling the creation of a centralized control center for a group of closely located open-pit mines.	Potential decrease in machine productivity
Additional for robotic control	1. Increased machine productivity. 2. Extended intervals between maintenance for machines. 3. Operators work in safe and comfortable conditions. 4. Capability for machines to operate in hazardous environments with optimized open-pit parameters. 5. Reduced operational costs through optimal management. 6. Feasibility of establishing a centralized control center for multiple mining and processing complexes located thousands of kilometers away from developed urban areas, with minimal on-site personnel at the open-pits.	1. Extended machine commissioning time. 2. Emergence of a new type of personnel – highly skilled computer operators.

It is also worth noting that the speed on inclined descents significantly impacts productivity; however, with an average incline of such sections at 8% and a specific power of modern open-pit haul trucks around 5 kW/ton, the uphill travel speed on these segments is approximately 15 km/h.

$$\Delta\Pi = \frac{(\Delta_v - 1)(2 - \Delta_s)}{\frac{\Delta_v v_1 + \text{p}}{L} + \frac{\Delta_s \Delta_v v_1}{15} + 2 - \Delta_s}, \% \qquad (1)$$

where Δ_v – the speed increase factor when using robotic control;

v_1 – the haul truck speed under in-cab manual operation by the driver, km/h;

L – the transport distance, km;

Δ_s – the proportion of inclined sections along the route length;

T_l – the duration of loading and unloading operations per cycle, hours.

Figure 1a illustrates that a substantial increase in speed is required to enhance hourly productivity. For instance, a 1.5-fold increase in speed (from 30 to 45 km/h) results in only a 14% productivity gain (at a transport distance of 4 km). It is also evident that as the transport distance increases, the effect of transitioning to robotic control becomes more pronounced, owing to the reduced proportion of loading and unloading tasks in the overall cycle duration (Fig. 1b); a similar effect is observed when the duration of loading and unloading operations is directly reduced.

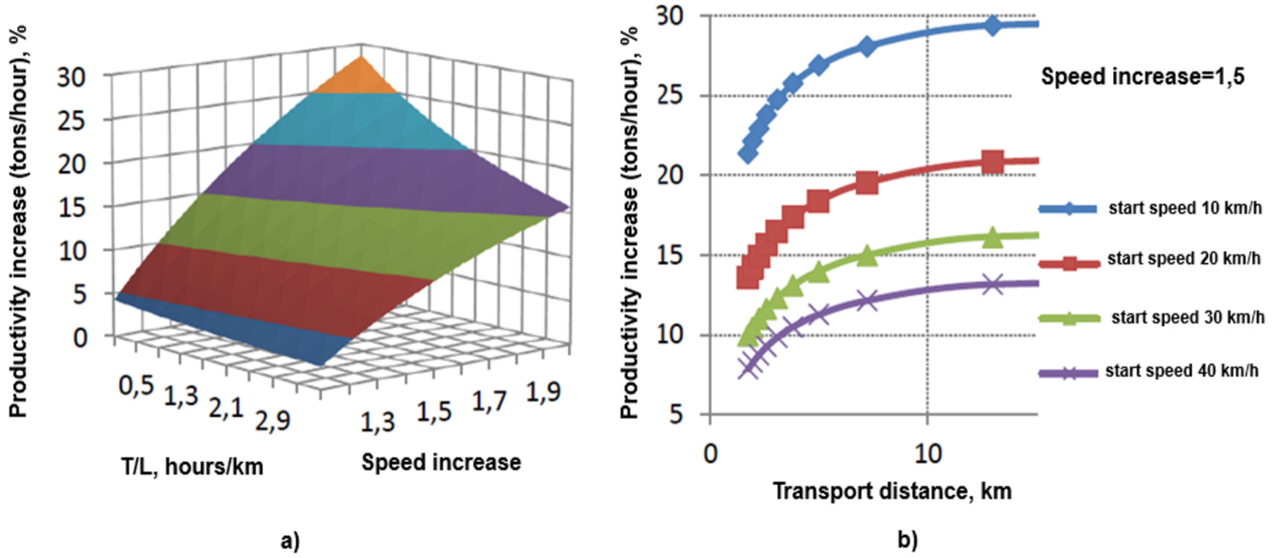

Fig. 1. Increase in hourly productivity of haul trucks depending on key factors: a) the duration of loading and unloading operations relative to transport distance and achievable speed increase when transitioning to robotic control (haul truck speed under manual control at 30 km/h, with inclined sections comprising 75% of the route length); b) transport distance at varying manual control speeds (assuming a 1.5-fold speed increase when transitioning to robotic control).

Thus, the most likely achievable effect from speed increase would be approximately 10-15% on relatively straight routes over 2 km in length, with a limited number of sharp turns and an incline proportion not exceeding 0.75. Under the most favorable conditions—routes with minimal elevation changes and an incline proportion below 0.3 – productivity increases of up to 35-40% are feasible if the maximum speed of haul trucks can be raised from 30 to 50 km/h with the transition to robotic control.

For robotic systems operating in fully automated mode, eliminating equipment stoppages for operator shift changes can further enhance daily productivity (Fig. 2).

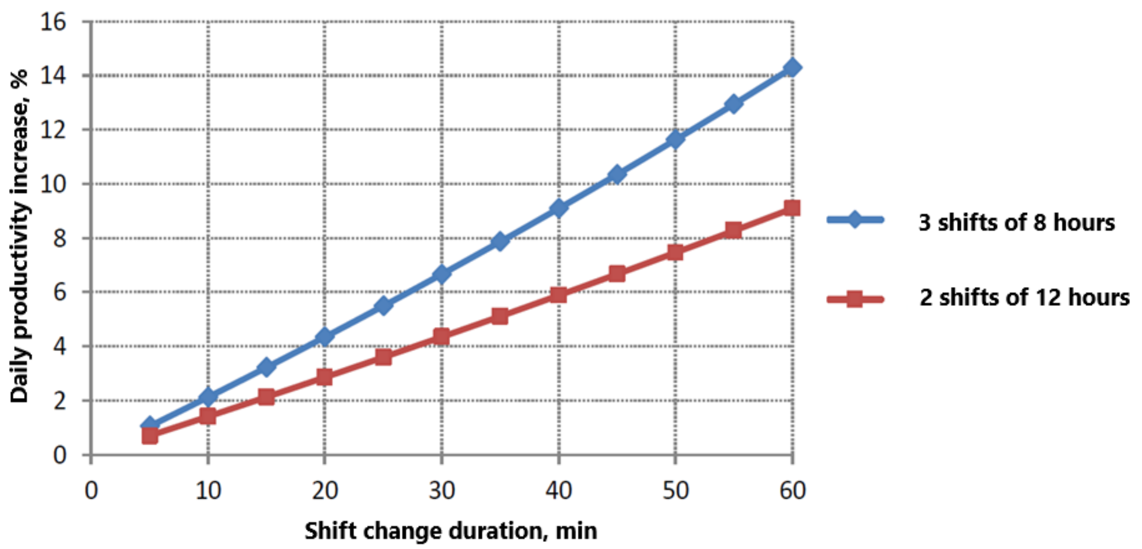

Fig. 2. Relationship between the increase in daily haul truck transport volume and the duration of shift change eliminated with the transition to robotic systems

Conclusions and further research directions

Thus, with the advancement of robotic control systems and the establishment of fully robotic mining complexes, the development phase of "unmanned" ore extraction technologies will likely emerge. These technologies are expected to differ significantly from current methods in terms of parameters and approaches to mining, owing to the absence of hazardous impacts on workers. Specifically, the inclines of transport routes may increase, and transport unit speeds may be enhanced.

As unmanned extraction technologies evolve, mining equipment will also transform, potentially featuring cabin-less designs capable of shuttle, non-reversing movement on steep inclines. The implementation of remotely controlled machinery will drive changes to the technical standards governing mining operations. Further development of unmanned extraction technologies will also prompt improvements to the legal framework for mineral extraction, where equipment operation requirements within mining activities may be relaxed, while stricter standards for mitigating environmental impacts on local populations and ecosystems will be introduced.

Calculations conducted based on the conditions of the MPP "Inhuletskiy" demonstrated that implementing an automated control system for internal-pit transportation achieved the following:

1. Reduction of mining and transportation equipment downtime in the pit due to mine-related delays (by up to 20%) through the use of the "1+1" criterion (one dump truck at loading and no more than one dump truck in queue);
2. Increased productivity of pit operations by extending the use of mining and transportation equipment (by up to 0,5-0,6%);
3. Stabilized ore blend composition (reduced fluctuations in magnetic iron content by 1-3%) through the application of the "quality" criterion;
4. Enhanced quality and yield of concentrate (by 0,3-0,4%) by reducing fluctuations in the blend supplied to beneficiation and minimizing magnetic iron losses in tailings;
5. Decreased fuel consumption (by 3-5%) through independent continuous monitoring, load optimization of dump trucks, and rapid assessment of critical angles in transportation routes;
6. Reduced transportation distance per ton of ore transported to 0,02 – 0,025 km by dynamically identifying optimal transport routes.

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