Automated loading of fragmented rock in mining: A literature and technology survey

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Synopsis

Increased competition and globalization in the mineral industry has resulted in demands for advanced equipment technology. The automated loading problem entails the design of a system capable of regulating complicated bucket-rock interactions that occur during excavation. A notable amount of previous work has been performed to address this issue, although such work has mainly focused on the excavation of granular material such as soil rather than on rock. Moreover, none has resulted in widespread industry adoption of automated rock loading technologies. Provided is an extensive survey of the state-of-the-art in autonomous excavation, with a focus given to the automation of load-haul-dump (LHD) underground mining machines that operate in fragmented rock.

Due to increased competition and globalization in the mineral industry, mining companies have been attempting to develop and implement new and innovative technologies. Among such efforts has been a move towards automated mobile equipment, including robotic excavation [1]. Although the concept of autonomous excavation has gained some attention in the last decade, few investigations into the development of such technologies have been reported for large and non-homogenous excavation media, such as fragmented rock.

In particular, this survey focuses on the problem of autonomous excavation using hydraulically actuated load-haul-dump (LHD)-style underground mining machines, as in the example of figure 1. The environments in which LHD machines are required to operate tend to be somewhat hazardous in that the loading of ore occurs at underground drawpoints. These drawpoints often pose the danger of falling or shifting broken rock during loading. In order to increase safety during such operations, remote control and tele-operation technologies have already been developed for LHD operators [20]. The obvious next step is the development of a reliable system for autonomous loading of fragmented rock.

![Figure 1: A load-haul-dump (LHD) machine](image)

In addition to increased safety, automation of the loading task has the potential to provide enhanced productivity, through improved machine utilization and superior machine performance. Unlike a human operator, an automated machine could remain steadily productive, irrespective of environmental conditions or prolonged work hours. Furthermore, an automated loader might generate more accurate loading, making up for shortcomings in operator skill. Finally, operator abuse and machine wear would most likely be diminished through automation, possibly resulting in better machine reliability and reduced maintenance costs.

As will be discussed, despite the fact that a notable amount of previous work, both theoretical and experimental, has been conducted to address the autonomous rock excavation problem, widespread adoption of automated loading has yet to occur in the mining industry. Moreover, literature on the subject indicates that there is a surprising lack of knowledge with regards to the fragmented rock excavation process, and more specifically, with regards to the interpretation of dynamic forces that impact the loader’s bucket as it passes through the rock pile. It is perhaps for this reason that effective systematic techniques for excavation control have yet to be invented for this task.

Studies in rock excavation

There exist a number of studies that focus specifically on the problem of autonomous rock excavation. Some are based on experimental observations, while others stem from purely analytical research.
Analytical work

Perhaps the most significant number of contributions in the literature pertaining specifically to the problem of automated loading of rock in underground mining has been by Hemami of the Canadian Centre for Automation and Robotics in Mining (CCARM) at École Polytechnique in Montréal QC, Canada. Among the first of Hemami’s papers was a pioneering exercise in deriving the kinematics and performing a force analysis for a generalized LHD loader mechanism. In this work, Hemami and Daneshmand [16] presented an analytical study of the loader mechanism geometry and the required hydraulic cylinder forces through treatment of the mechanism as a robot manipulator.

Hemami [10] acknowledged that the trajectory control of standard industrial robots (e.g. welding or cutting robots) is different than the control required for loading of an LHD bucket. It was suggested that the trajectory a loader bucket should follow through the rock pile not have priority in the control scheme, since the objective is to effectively fill the bucket, not to follow a strictly specified path. Some conceptual discussion was also provided on the topic of motion control. The forces acting on the bucket were described as potentially stochastic in nature, and the need for trajectory alteration in the event of prematurely high loads on the bucket was stated. Hemami divided the possible bucket-rock interaction forces into five components:

\[ f_1: \text{ the weight of loaded material and material directly above the bucket;} \]

\[ f_2: \text{ the force of compacting material by the bucket;} \]

\[ f_3: \text{ the sum of frictional forces acting between the bucket and excavation media;} \]

\[ f_4: \text{ the digging resistance of excavation media, and;} \]

\[ f_5: \text{ the necessary force to accelerate material in and above the bucket.} \]

Means for analytically determining, or at least approximating, some of these dynamic forces were subsequently presented [11, 13, 17]. Along with a relatively extensive list of suggested future work, Hemami put forth the following as reasons for the complexity of the excavation problem: (i) the shape, size, geometry and composition of the cutting device may vary from machine to machine; (ii) adding teeth to the cutting edge changes the scenario, and; (iii) material properties are determined by many factors, including hardness, cohesion, uniformity, water content, temperature, size, and compactness.

A method for determining an appropriate bucket trajectory was also presented by Hemami [12]. The proposed trajectory generation technique employed the idea that resistance to compaction described by the force \( f_2 \) may be set to zero, so as to minimize the expenditure of energy. However, a method for tailoring the derived loading trajectory was not explained in any detail, and its potential effectiveness at completely filling the bucket was not determined. A mathematical model for the variation of \( f_1 \) was produced by Hemami [14] using knowledge about the geometry developed during the loading operation. It was also concluded that an analysis of the force \( f_4 \) should be done experimentally.

Finally, Hemami [15] provided a somewhat lengthy discussion of the fundamental analyses required for the design of an automated excavation machine. One interesting inclusion in this work was the consideration of a mass-spring-damper model for the excavation machine, as well as the excavation media (such as is common in compliant motion analysis). However, it was suggested that this type of model cannot be used in practice, since there is insufficient understanding of the model coefficients. In addition, the problem of choosing an entity to be exploited as error, to be measured and used for feedback in a control scheme, was considered. On this, it was stated:

Having taken a look at how an excavating machine is manually operated reveals that the motion of such a machine is continuously corrected and readjusted by the operator. This adjustment is based on the performance of the machine in accomplishing its task... and not the motion itself. The same procedure must be automatically followed in an automated machine [15, page 178].

It was concluded that bucket trajectory control cannot be entirely based on position or velocity errors, nor on a vision system that monitors the progress of the excavation process. A dual-level control was suggested, where a nominal trajectory is followed and modified through higher-level force measurements.

Excavation planning

Other authors have approached the problem of autonomous rock excavation from a perspective similar to Hemami’s. Generalized machine dynamics were set up by Sarata et al. [34], although not actually computed. Marshall [25] showed that computation of these dynamics is in fact not an entirely trivial matter. Under a pioneering Russian project, Mikhailov formulated a set of ideas relating to force, motion, and trajectory control for various loader mechanism styles [26, 27]. Mikhailov’s analysis was based on a technique using work functions to find an efficient bucket trajectory that would minimize the work for scooping rock masses, with complete filling of the bucket. Additional constraints were determined by the bucket capacity, the natural slope angle, and the pile height. The resistive force modelling portion of this research is discussed later in this paper.
However, as a result of rock pile resistance analysis, Mikhirev advocated that measurement of the resistive forces to excavation could be used as a signal for automatic activation of the mechanism for bucket rotation in the vertical plane (which, in the case of the LHD machine of figure 1, would correspond to motions of the dump cylinder). Since reactive forces were thought to decrease as the bucket moved along a continuous curvilinear path towards the pile surface, it was proposed that a force threshold be used to alter the bucket trajectory, resulting in a stepped path (i.e. zig-zag shape) along some nominal trajectory.

Machine vision

In other literature, machine vision has been put forward as a means for autonomous loading of mining machines. In the research of Ji and Sanford [18], a laboratory-scale excavation system was developed that utilized a video camera for environment sensing. Digitized images were then interpreted to develop control and navigation signals. More recent work, using machine vision, has been performed by Petty et al. [28]. Once again, a scale model was developed. However, in this case, the model was constructed to mimic the motions of an LHD vehicle as closely as possible. A loading strategy was formulated such that the bucket followed one of a range of trajectories developed for various rock pile conditions. In the case of oversize or other problems, it was suggested that a simple algorithm be used to briefly alter the bucket path. The proposed algorithm included a means of detecting instability in the rock pile as well as choosing the location where scooping should take place at the next iteration.

Similar, though perhaps more rigorous, research techniques were employed by a group at Tohoku University in Japan [44]. A CCD camera vision system was used to obtain images of the rock pile, from which the excavation task was planned based on an estimated contour of the rock pile. Experiments were performed using a scale model excavator, similar in configuration to an LHD machine. The authors suggested that such a camera based system would be advantageous in its capability for recognizing changes in rock pile shape at each iteration towards an excavation goal. Although the results were promising, it was conceded that illumination became an important factor for success, a problem that would likely be compounded in an underground mining situation.

Towards automation

Researchers at the University of Arizona have proposed an autonomous rock excavation system for front-end loader type machines that uses bucket force/torque feedback, fuzzy logic, and neural networks for control [23, 24, 35]. Lever et al. [23] justified their approach by stating that a mathematical model for the bucket-rock interaction would be too complex and computationally expensive. Instead, a set of basic bucket action sequences, typically used by human operators, was compiled for use by the controller. A method using finite-state machines (FSMs) was described. The FSMs were used to define all feasible action sequences required to accomplish the task, and were derived from "expert excavator operators and detailed analyses of the excavation process" [24, page 137]. Neural networks were used in the FSMs to determine what state to enter following an action or behaviour. A reactive control approach, using fuzzy behaviours, was utilized to compare and act on force/torque data in order to assess the excavation situation and determine the appropriate control output. Some experimental results using a PUMA 560 robotic arm were also presented. This work is fully disclosed in a recent book [36].

Recent work by the authors [25] has suggested the use of ideas from the field of compliant motion control, and more specifically the application of an admittance control scheme for autonomous loading. The proposed system utilizes hydraulic cylinder pressures as a measure of the bucket-rock interaction intensity. Consequently, a force compensator acts to change the cylinder velocity based on prescribed admittance dynamics. Furthermore, it was recognized through experimental observations that it may be appropriate to also induce variations in the buck-rock interaction intensity, so as to fluidize the rock pile during scooping. To this end, a potential technique for realization of the admittance controller commands cylinder velocity, based on pulse-amplitude modulation (PAM), was put forth. It was suggested that the frequency of pulsation could be suitably related to the size distribution of particles in the rock pile, where lower frequencies correspond to the presence of large rock fragments, and higher frequencies to smaller particles.

Studies in bucket-rock interaction

What makes the excavation of coarse, fragmented rock significantly different than that of ideal, homogeneous materials (e.g. soil or gravel) is that there is not one defined shear plane. In order to force an excavation tool through fragmented rock it is necessary to not only overcome the particle to particle frictional resistance, but also to make the particles move up and over one another [8]. In justifying their behaviour-based control approach to the problem at hand, Lever et al. [23] argued the difficulties of mathematically modelling the excavation tool-media interaction.

It is impossible to generate a rigorous mathematical model to describe the unstructured environments common in mining operations. The conventional proportional-integral-
derivative (PID) or even modern stochastic controllers that read exact sensor values, apply a mathematical model, and generate precise output from the mathematical algorithm are impractical for use here [23, page 18].

However, it was viewed by Marshall [25] that, although the problem of rock pile interaction modelling may be very difficult to quantify, it should not be considered as a decidedly impossible task, as suggested in the above quotation. Moreover, such difficulties should not preclude the use of an approach to the excavation problem based on ideas from systems and control theory. As will be shown, some headway has been made in this avenue by other researchers in the field.

**Empirical studies**

Some interesting empirical work was done by Forsman and Pan [8] regarding the shear properties of fragmented rock. Loose material, such as broken rock, will not move (i.e. fail) until the applied force reaches a yield level, called the shear strength for granular media. The shear strength of fragmented rock is hence an important property in the context of material loading. Forsman and Pan suggested an improvement over Coulomb’s equation, commonly used for modelling fine grained materials, in the form of a mathematical expression, derived empirically, for the shear strength of large grained loose material. It is interesting to note that the material porosity was implied to be related to the size distribution of a fragmented rock pile, as well as the degree of interlocking between particles. In addition, Forsman and Pan related the material porosity to fluctuations of the measured normal force in their experimental results.

Analysis of the resistance of fragmented rock to scooping by a bucket was reported in some Russian literature [7, 26]. With regards to the work by Fabrichnyi and Kolokolov [7], a means for calculation of the scooping resistance to blasted rock was given, based on knowledge of the rock pile’s changing shear angle.

It is known that in general the scooping force is governed by the volume of the rock to be shifted, which in turn depends on the angle between the horizontal and the shear surface of the rock. The experimentally recorded variations in the scooping resistance can only be due to changes in the inclination of the shear surface, leading to increases or decreases in the volumes of rock being shifted [7, page 438].

Unfortunately, key references were made by Fabrichnyi and Kolokolov to obscure experimental work (performed much earlier, circa 1957, and available only in the Russian language) by an investigator named Rodionov [32].

In related work, Mikhirev [26] reported some potentially applicable results. Although techniques for control and bucket trajectory generation were the focus of this research, insight into the forces associated with resistance to movement of the bucket through rock was provided. Mikhirev also cited the experimental research of Rodionov, which apparently established that a compact nucleus is created in the pile in front of the working edge of the bucket. The characteristics of this compact nucleus were found to relate most notably to average particle size, bucket shape, and bucket pose.

Pioneering full-scale, experiments in rock excavation were conducted recently by the authors [25], using a Tamrock EJC 9t LHD machine, with the intent of developing further a practical understanding of the fragmented rock excavation process, and in particular, the interaction that occurs between the bucket and rock during the excavation process and its impact on operational parameters such as actuating cylinder forces and displacement. Through a series of aggressive excavation trials, conducted in an underground muck extracted from Inco Limited’s 175 Orebody (Copper Cliff, Ontario, Canada), it was observed that displacements of, and forces within the hydraulic dump cylinder contained a great deal of information regarding each excavation operation. An example of the mentioned trial data is provided in figure 2 for the dump cylinder of a LHD machine having geometry as shown in figure 1. The period prior to approximately 5 seconds represents the penetration phase, while the period up to approximately 14 seconds is scooping phase, followed by breakout from the rock pile.

Subsequent to experimental studies, the data collected was used in an attempt to identify the excavation process by means of a nonlinear system identification technique known as parallel cascade identification (PCI). The modelling results indicated that simulation, to a certain degree, of the scooping phase of the fragmented rock excavation process may be possible through application of PCI to measured dump cylinder velocity and force data.

**Analytical studies**

Hemami et al. [17] acknowledged that the forces involved in excavating fragmented rock are functions of a large number of parameters, which makes the study of such forces particularly difficult. In this work, the various physical factors that contribute to the complexity of the problem were categorized. Major categories included the operation to be performed, the form of the excavation tool to be used, the material properties, and other machine or application factors. In further studies of the forces acting on a bucket during a scooping operation, five force components were identified. The cited article gave references to works where analysis of these forces had been attempted (as was previously discussed). Some simulation results were also presented. However, it was admitted that random fluctuations of
these forces would likely exist in reality.

Perhaps the most relevant and complete research in bucket-rock interaction modelling is some very recent work completed at Tohoku University, in Japan [43, 45]. In this work, Takahashi et al. essentially proposed a means for calculation of each of the resistive forces \( f_1, \ldots, f_6 \) described previously. For analysis purposes, the loading operation was partitioned into two stages: (i) a penetration phase, where the bucket is inserted into the rock pile, and; (ii) a scooping phase, where the bucket tip is lifted and curled to complete the loading task. Given an assumed bucket trajectory, the resistive forces were computed analytically using geometric and frictional parameters of the bucket and rock pile. Equivalent scale model experimental results confirmed the calculated forces to be approximately valid. Unfortunately, the derived equations failed to capture the inherently stochastic nature of the loading process.

Analytical research has been completed in the area of numerical modelling of granular assemblies. Consider the work by Cundall and Strack [5], where a distinct element method (DEM) was used to numerically model the mechanical behaviour of assemblies of discs (and spheres in three dimensions). "The method is based on the use of an explicit numerical scheme in which the interaction of the particles is monitored contact by contact and the motion of the particles modelled particle by particle" [5, page 47]. In recent work by Takahashi [42], the ideas of Cundall and Strack were applied to simulation of particle behaviour in a virtual rock pile. Excavation of a rock pile having uniformly sized particles was simulated using a DEM approach and the bucket-rock interaction forces were computed for a predetermined trajectory. Once again, equivalent scale model experiments confirmed the simulated interaction forces to be approximately valid. However, it was also admitted that full-scale experiments would be required to truly validate the given computational results.

**Studies in soil excavation**

What distinguishes the problem of autonomous excavation of fragmented rock from the research presented in this section is simply the nature of the excavation media. In general, the work discussed in this section concerns itself with the problem of soil excavation. Soil, as opposed to fragmented rock, is generally homogeneous in particle size and typically consists of relatively small particles, such that a bucket may be passed through it without the need for significant trajectory alteration. Soil excavation could be appropriately characterized as a cutting exercise, rather than the task of maneuvering a bucket such that it is properly filled with large and small fragments alike, since forces at the tool would evolve smoothly instead of abruptly. Nonetheless, research in this field shares some common attributes with the problem of rock excavation. Moreover, the lack of commercial technology seems to contrast the fact that there appears to have been a considerable amount of research completed in the field of autonomous soil excavation. In this section, only a selection of the available literature is discussed.

**Excavation control**

The problem of autonomous excavation in soil was approached from a motion and path control perspective by Bernold [3]. Bernold advocated the use of impedance control, utilizing force and position feedback. In the case of robotic excavation, the robot was considered as an impedance, translating motion into force, and the soil as an admittance, reacting with a change in position or motion. A mass-spring-damper model for the tool-soil interaction was presented. An attempt was made to determine an optimal path for excavation. With regards to this effort, Bernold concluded:

> In summary, the selection of an optimal path, resulting in lowest energy consumption per excavated volume, is a nontrivial problem which hinges mostly on the proper characterization of the soil-tool interaction and the soil itself. Although static soil experiments can provide the cohesion factor, the complexity of the remaining coefficients for cutting-moment calculation make a static approach to the problem impossible [3, page 9].  

To this end, a method of trajectory selection using pattern recognition was suggested. Experimental work was performed using a scale modelled backhoe style excavator (a modified RM-501 micro-robot). Force and position data were collected to create characteristic patterns for various soil conditions. Results were used only
to show that it may be conceivable that soil characteristics could be established while excavating, leading to the possibility for trajectory planning and control for autonomous excavation. A similar approach, using impedance control for backhoe excavation control, was also proposed by Ha et al. [9]. In this recent work, a sliding-mode controller for impedance control was developed. Having produced kinematic and dynamic models for the excavator, the control scheme was subsequently implemented, with apparently promising results, on a retrofitted Komatsu PC105-7 mini-excavator.

Vähäi and Skłubiewski [46] presented a method of cognitive force control for an excavator. A dynamic model was developed for the excavator and used in conjunction with a model for the soil (referred to as the regolith), which was based on the breakdown of resistive forces into a resistance from cutting, frictional resistance, and the resistance of the material in the bucket.

Further details of the backhoe style excavator dynamic model were derived later in a publication by Koivio et al. [19]. Simulation results compared the preplanned bucket trajectory with its actual trajectory, which was adjusted when hydraulic ram forces exceeded preset limits. In a technique proposed by Bullock and Oppenheim [4], strain gauges were used during a laboratory study to measure the resistive forces encountered by the excavator bucket. A supervisory control scheme, where force feedback data are processed at a higher level to produce low level trajectory changes, was considered as an online tactical planner for excavation.

**Automation systems**

There exists an apparently ongoing project at the University of Sydney, Australia that aspires to develop a system for autonomous excavation [22]. Although it was stated that the ultimate objective of the project is to demonstrate fully autonomous excavation for a variety of tasks, including excavation not only in soil but also in fragmented rock, the described experimental hardware consisted of a backhoe style mini-excavator. Moreover, it was implied that future experiments and analyses were to be carried out in soil type media.

Researchers at Carnegie Mellon University [40] proposed a technique for robotic excavators to predict resistive forces during excavation using computer learning methods. Included in the presented work is a development of the mechanics of excavation, resulting in the formation of what is known as the fundamental equation of earthmoving (FEE) for a flat blade moving through soil. The assumptions required to validate the FEE were used by the authors to demonstrate its impracticality in the context of excavation.

More recent work at Carnegie Mellon University [2, 33, 41] has resulted in a patented system for robotic excavation and autonomous truck loading. In summary, the system described utilized two scanning laser range-finders to recognize and localize the truck, measure the soil face, and detect obstacles. Onboard software was used to make decisions regarding digging and dumping operations. Actual digging was described as executed by a force based closed loop control scheme, after previous research in excavation planning by one of the authors. Dumping and truck detection routines were also included as part of the project.

**Patented technologies**

In this section, a selection of patented technology is presented in order to provide an understanding of the work that has been considered commercially feasible. The majority of existing patents relate to the automation of soil excavation tasks, generally using backhoe style excavators [2, 29, 33, 37, 38, 39]. However, there does exist recent work relevant to autonomous excavation of fragmented rock, using LHD-style machinery, as in an underground mining application. It is these patents that are discussed in the subsections that follow.

**Fragmented rock excavation technology**

A review of the current patents relevant to the problem of autonomous bucket loading revealed two significant contributions. The most recent, by Dasys et al. [6], as part of a group representing the international mining and metals company Noranda, Inc., revealed a patented system for automated bucket loading of a front shovel loader (i.e. an LHD) that uses “sensor feedback provided by pressure and extension sensors on hydraulic cylinder(s) to control the trajectory of the bucket to be loaded by a computer algorithm” [6]. The described invention does not rely on a model of the rock pile, nor is there any computational attempt to determine an optimal bucket trajectory prior to the scooping operation. Instead, the system reacts, using a decision tree to select actuator commands, only to excessive forces sensed in the actuating cylinders. If excessive forces are encountered, the bucket is tilted so as to attempt to dislodge the rock or other hindrance causing the disproportionate force.

The computer...has a [hybrid] controller which controls the hydraulic valve that supplies hydraulic fluid into both ends of the [bucket dump] cylinder...and if too much force is exerted on the bucket by the rock pile, the command for hydraulic fluid intake will be reversed and the fluid will be injected into the opposite side of the piston...so as to reverse the action of the shaft...until the force drops to a predetermined level. Then, the oil intake will be reversed again and the tilting action of the bucket will be resumed until the bucket...is filled and is in the rolled back position...[6].
Furthermore, Dasys et al. claimed a 9% improvement in loading capacity, comparing their invention with human operation in field trials. A paper related to the work by Dasys et al. was put forward at the 5th International Symposium on Mine Mechanization and Automation by representatives from STAS Ltd. [21], partners in the Noranda, Inc. project. Unfortunately, no technical details were given in the paper. However, the user-level features of the product, entitled SIAMload, were presented. It is worth noting that SIAMload required that an operator choose one of three loading modes, depending on the human perceived loading conditions.

Other excavation technology
A second relevant patent in autonomous excavation was filed by Rocke, a representative of Caterpillar, Inc. [30]. In Rocke’s invention, a control system for automatic loading of a wheel loader (similar in mechanical design to an LHD machine), which is particularly suited to soil excavation, is disclosed. Although references were made to a number of previous patents by the inventor (all of which applied to backhoe style soil excavation), in the current patent, an algorithm that appears very similar to the one that was patented three years later by Dasys et al. (as was discussed in the previous subsection) is given.

As described, the logic means varies the dump cylinder command signal between a predetermined minimum and maximum value to maintain the lift and dump cylinder forces at an effective force range. Accordingly the positions and forces of the lift and dump cylinders are monitored to control the command signals at the desired magnitudes. For example, if the lift or dump cylinder forces fall below the lower predetermined values, the extension of the dump cylinder is halted to prevent the bucket from “breaking-out” of the pile too quickly. Alternatively, if the lift or dump cylinder force exceeds the upper predetermined value, the extension of the dump cylinder is accelerated to prevent the bucket from penetrating too deep in the pile [30].

Furthermore, it should be noted that control of the vehicle active effort was not included in the control strategy as stated, and that the machine was preferably directed to the pile of material at full engine throttle. On the matter of adaptability of the system to varying material conditions, the reader was referred to [31], another patent by the inventor, in which a system for selecting one of a plurality of control curves based on a material condition setting, is disclosed.

In essence, the common theme in these two patents [6, 30] is a cylinder motion control scheme based on some interpretation of the changing pressures in the hydraulic cylinders as an indication of the state of the bucket-rock interaction.

Conclusion
It is evident that undertaking the design of a system intended to perform autonomous excavation of fragmented rock is a task that involves many unique and varied challenges. Most notably, the conditions necessary for a successful scooping operation are seemingly influenced by the complex nature of bucket-rock interactions that occur during excavation.

This survey has presented a relatively extensive review of the most pertinent literature on the subject, while a focus was given to those works relating most specifically to the excavation of fragmented rock, as in a mining application, and to the automation of load-haul-dump (LHD) mining machines. Finally, despite the fact that an apparently broad range of research has already been conducted in the field of autonomous excavation, none has resulted in the prevalence of such technologies in the mining industry.

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References


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