

Development of Test Rig for Robotization of Mining Technological Processes – Oversized Rock Breaking Process Case

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Abstract. Production chain (*PCh*) in underground copper ore mine consists of several subprocesses. From our perspective implementation of so called ZEPA approach (*Zero Entry Production Area*) might be very interesting [16]. In practice, it leads to automation/robotization of subprocesses in production area. In this paper was investigated a specific part of *PCh* i.e. a place when cyclic transport by LHDs is replaced with continuous transport by conveying system. Such place is called dumping point. The objective of dumping points with screen is primary classification of the material (into coarse and fine material) and breaking oversized rocks with hydraulic hammer. Current challenges for the underground mining include e.g. safety improvement as well as production optimization related to bottlenecks, stoppages and operational efficiency of the machines. As a first step, remote control of the hydraulic hammer has been introduced, which not only transferred the operator to safe workplace, but also allowed for more comfortable work environment and control over multiple technical objects by a single person. Today literature analysis shows that current mining industry around the world is oriented to automation and robotization of mining processes and reveals technological readiness for 4th industrial revolution. The paper is focused on preliminary analysis of possibilities for the use of the robotic system to rock-breaking process. Prototype test rig has been proposed and experimental works have been carried out. Automatic algorithms for detection of oversized rocks, crushing them as well as sweeping and loosening of material have been formulated. Obviously many simplifications have been assumed. Some near future works have been proposed.

1. Introduction

Ore extraction in underground copper ore mines is realized mainly with drilling and blasting operations. Utilized room-and-pillar system is based on cyclic operations of self-propelled machines. After blasting operation, load-haul-dump machines (LHD) carry ore from mining face and dump their load onto belt conveyors. Then ore is transported to retention reservoir and in next step to the surface using skips. Reloading from non-continuous to continuous transportation assets is performed in dumping points with oversized rock breaking station. At those points rock material is dumped onto so called screen, which classifies the material into two categories: coarse and fine. Material that did not fall gravitationally on the conveyor below, is being broken into pieces with hydraulic hammer (Figure 1).



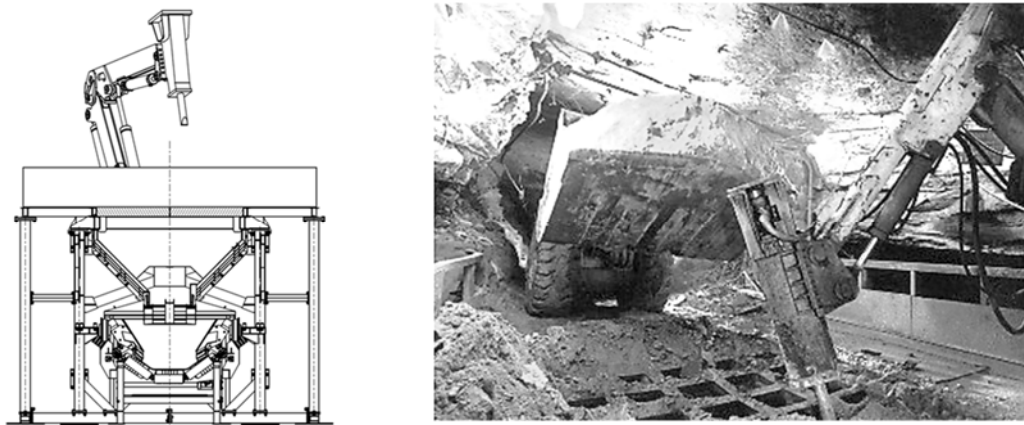


Figure 1. Cross section through reload point (left), dumping point – moment of unloading of LHD machine (right)

In mines with room-and-pillar system, dumping points are located in a close vicinity of mining faces. Distance of hauling route typically does not exceed 1 500 meters what makes the dumping point very dangerous area. In practice, one can observe global trend to eliminate people working in regions with a high hazard of rock bumps as well as harsh environmental conditions (high temperature, dust and humidity). The first solutions known since 1990s concerned teleoperation. Early trials showed that it is a reasonable direction of development even considering only the safety aspect of moving the operator to safer location, eliminating laborious working conditions and increasing operator's effectiveness. As shown in [1,2,5,6,8,11] the biggest challenges for development of remote control of hydraulic hammers are related to correct online recognition of scene image from video camera and control aspects in underground mine reality. In general, teleoperation is widely used in mining sector of industry, different options of teleoperation for rock breaking process are well recognized field. Current mining demands are focused on robotization of this process, which is in accordance with so called 4th industrial revolution [4]. In the literature, this subject is completely marginalized – algorithm for automation of rock breaking process is unknown. Such attempts for prototype version are currently conducted by Polish group of researchers in the CUBR project of National Centre for Research and Development but still there are a lot of problems which have to be solved [9]. At a first glance, this seems like an easy task but other studies [7,10,15] indicate that problem of rock breaking process requires to develop algorithm including reliability of hydraulic hammers, plastering of screen holes with the material, the self-cleaning system for screen, removing metal parts from the material (e.g. bolts), possible collisions with LHD machines and work safety.

In this paper a test rig has been presented for robotization of selected mining processes. In this work many simplified assumptions have been made in accordance with the criteria of safety issues, minimization of test rig costs and its size. Developed algorithm includes recognition of screen load and control of hammer motion. The research involved the use of small size industrial manipulator without hydraulic hammer equipped with solution to measure the impact force. In simulations of rock breaking process, lightweight and low cohesion material has been used. It should be underlined that core objective is focused on online scene monitoring, object recognition and tracking, adaptive path planning of the hammer tool according to time-variant position of detected objects. The paper is organized as follows: a short review on the subject and current practice in the world mining will be discussed; operational conditions of hydraulic hammer in underground mine and main exploitation issues of typical dumping point will be described; design and assumptions of developed test rig will be presented and considered; algorithm of robotic system for rock breaking process will be proposed and explained; finally, its application and testing will be provided.

2. Description of operational conditions of hydraulic hammer

To better understand exploitation issues of hydraulic hammer, observation of its operation in real conditions was needed. The main purpose of experiments in underground mine was focused on the analysis of reload point utilization time, identification of factors that influence effectiveness and safety, and determination of key assumptions to develop algorithm for rock breaking process. The subject of case study was one of the KGHM underground mine, where haulage from exploitation front to the screen is realized with haulers and loaders. Nominal capacity of the hauler cargo box equals about 20 Mg. If the route of haulage is not longer than 800 meters, very often cooperation of haul trucks with bucket loaders is applied - with the bucket capacity of about 4-6 Mg - or loaders work alone. Total amount of material transferred to the screen during single shift is treated as its nominal load. In practice this amount varies significantly ranging from 130 up to 1300 Mg. In extreme cases it can reach even 2000 Mg. In evaluation of the degree of screen load authors used data from monitoring system [13] and previously designed algorithms for work cycles identification [12,14].

Dumping screen load should be defined as derivative of mine division efficiency and mostly depends on types of transportation assets used for the haulage. Duration of haulage cycle for a single machine ranges from 150 to about 210 seconds. In practice it is desired to optimize the screen management in order to match the waiting time on one screen with the operation time on the other one. Analysis of data from monitoring system allowed estimating average haulage time for the individual machines. In case of haul truck (payload: 20 Mg) it lasts about 2.8 minutes, for A-type loader (payload: 6 Mg) it is about 1.3 minutes, and for B-type loader (payload: 4 Mg) it is about 1 minute. For example, during one work shift single haul truck is able to perform up to 60 courses. For all types of haulage machines, screen operator has about half a minute downtime between the time that current machine leaves, and the next one arrives. As mentioned above, daily division efficiency is significantly variable. Analysis of work time of screen operator indicates a need of development of haulage optimization methods. The best proof is variable load of dumping point: total duration of machine unloading (5-20%), total duration of hammer operation time (30-70%) and total duration of waiting (10-70%).

Let us focus now on dumping process and cleaning the screen. First stage of dumping process is unloading of haul machine, which takes about 30 s. For example, single haul truck cycle delivers about 20 Mg of copper ore raising heap of material. In practice, shape of heap, size of rock material is different each time. Second stage is related to loosening and breaking material. Now, gravity flow of fragmented rock is formed. Small size rock material falls automatically through the screen holes on conveyor. Further gravity flow requires sweeping and breaking remaining oversized rocks that could not fit through screen holes by hydraulic hammer. Single event of processing the material on the screen takes from a few up to over ten minutes. Typical dumping screen has 400 mm by 400 mm holes and this is theoretically maximum diameter that rock falling onto the conveyor below can have. As for today, in the mines of KGHM Polish Copper operates about 250 such screens.

In haul truck unloading case, average total time of rock breaking process is 165 s. For 4 Mg copper ore delivered by A-type loader it takes about 60 s.; for 6 Mg delivered by B-type loader – 80 s. Exemplary rock unloading and oversized rock breaking process has been presented in Figure 2.

If screen holes are not blocked up, the gravity flow from haul track takes about 1 minute – unloading of cargo box lasts 25 s., initial spontaneous gravity flow of rocks lasts 10-30 s., and sweeping-loosening-breaking of material remaining on the screen lasts for up to 30 seconds. When screen is not clean or blasted ore is significantly bigger duration of gravity flow extend to few minutes. Frequently, there is no spontaneous gravitational fall of rocks and operator directly proceeds to cleaning of screen that last even for 8 minutes.

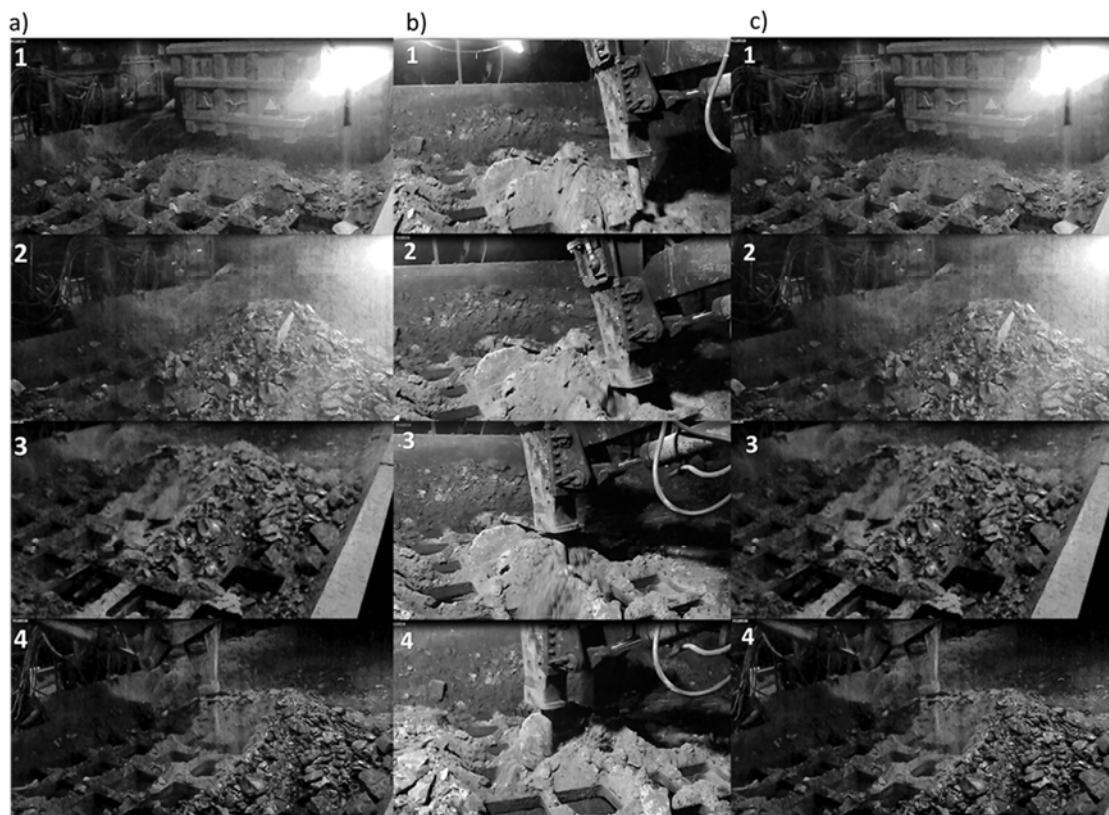


Figure 2. a) stage 1: unloading material on the screen, spontaneous gravity flow of rocks smaller than screen holes (<400mm) - interrupt in hydraulic hammer operation, b) stage 2: sweeping and loosening of material remaining on the screen - pieces smaller than screen holes fall down on the chute, oversized material is prepared to be broken, c) oversized rock breaking process

Operation conditions are really harsh – hammer operates in high temperature, dusty and humid environments. Furthermore, cab is situated about 1.5 meters away from the screen and light intensity is very low what are another factors causing fatigue and discomfort during use and decrease of effectiveness. Work of screen operator usually lasts 6 hours and consists of several main stages. Example of work time chronometric is presented in Figure 3.

3. Primary research in term of possibilities of rock-breaking process robotization

3.1. Development and tests of a test rig

For the purpose of identification of basic problems related to the robotization of rock-breaking process, dedicated test rig has been developed. It has been assumed that the test rig is a small scale model. Due to the small scale of the test rig, it was assumed that the rock-breaking itself would only be simulated. The test rig design conforms to the rapid prototyping idea, which is widely used in manufacturing. Its goal is to obtain a fast and low-cost verification of new ideas. Only after expected properties of a tested method are confirmed, a solution is transformed to the full scale system.

The main components of the test rig are the six-axis manipulator with maximum working load not exceeding 5 kg and its operating platform with functional module for simulation of rock-breaking technique. The rock-breaking process is performed using a chisel which smashes rock material on the screen. Base structure design assumed balance and stability, what is essential for further manipulator precision. The operating platform also includes stand on which the light and video module are mounted (Figure 4). The manipulator is connected to a computer via Ethernet interface with using TCP/IP address and Wi-Fi router.

Briefing and departure into the mine															
Transfer from the shaft to remote control station															
Waiting for arriving machines															
Regular work on the grille															
Tasks related to finishing work and passing the grille to next operator															
Transfer from remote control station to the shaft															
Waiting for the shaft elevator and leaving the mine															
Time [min]	15	10	45	240	30	10	20								

Figure 3. Chronometric of work time of screen operator

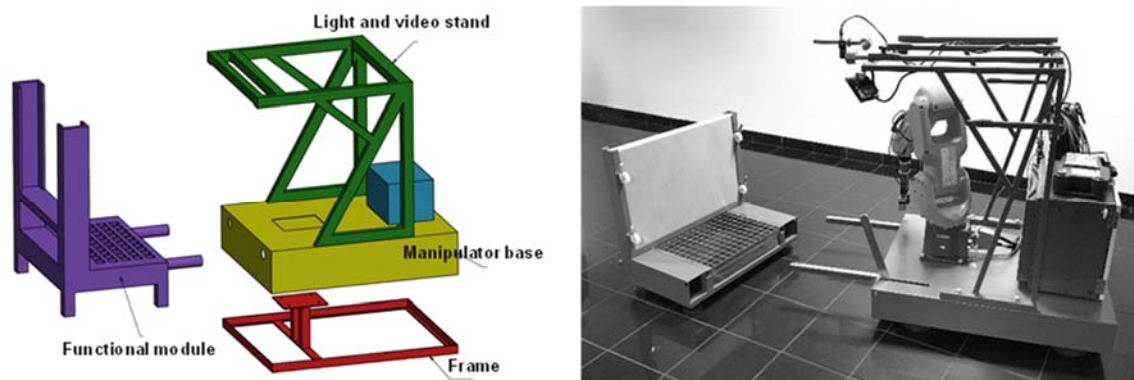


Figure 4. Developed test rig for investigations of rock-breaking process robotization

3.2. General screen sweeping process

A general algorithm of the screen emptying process is presented in Figure 5. It begins with an acquisition of the image of the screen with rock material and image interpretation. If rock material is detected, motion of the tool is planned and executed. The above steps are repeated until the screen is empty. There exist various possible realizations of each step of the general algorithm. The test rig was designed with a purpose of allowing easy substitution of each block with a different method. This approach follows the results of the BRICS project [1] where the component oriented design [3,4] was indicated as the methodology allowing reduction of the development time.

3.3. Screen sweeping example

The process of emptying a screen of the test rig begins with an acquisition of an image of the loaded screen. It was assumed that the state of the screen is obtained from a vision system. The grayscale image from a camera is then processed to recognize a configuration of the rock material at the screen. Based on results of image processing, a largest group of rock material at the screen is selected to be processed. Then a path of a tool to break bigger rocks and sweeping of rock material is planned and executed. After the tool motion is finished, a new image is acquired from the vision system and the whole sequence is repeated until the screen is cleared. The process can be described with the following algorithm that was used at the test rig:

- **Step 1:** Positioning of the chisel in the neutral location (outside the camera field-of-view),
- **Step 2:** Launching a real-time video processing (determining a location of the biggest rock pile),

- **Step 3:** Positioning of the chisel over the centre of the pile, at a desired height,
- **Step 4:** Lowering the tool to predefined location (smashing the material)
- **Step 5:** Horizontal movement shovelling broken material,
- Repeat steps 3-5 for all detected rocks,
- **Step 6:** Return to neutral location; repeat the process from step 1 until the screen is completely empty.

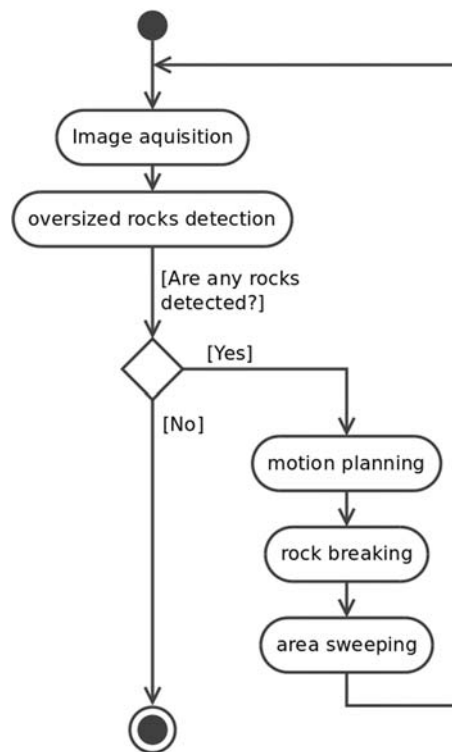


Figure 5. A general algorithm of the screen emptying process

During the simulation objects of various shapes has been used. The objects are detected by an image processing algorithm with an assumption that for every image a single blob is processed – after the robot's arm motion is finished, it returns to the primary location and new image of the scene is acquired. Setup of image processing algorithm requires some process parameters to be determined. General setup of the vision system consists of setting the contrast of the image and defining brightness thresholds to separate rock material from a background of the scene. Further, parameters of the detected objects are to be determined. Due to the fact that the material at the screen has no specific shape, a blob recognition algorithm is used. The location of rock material to be processed is determined by the minimum and maximum area and circumference of blobs found in the image. The minimum values result from the size of screen holes and the maximum values base on range of the visual field of camera. The last of the vision process parameters to be determined is the order of blob processing if more than one is found in the image. In the tests it was assumed that the blobs are ordered by their size, so the one with the biggest area is processed first.

The tests have confirmed that after block detection robot moves to above the position of the blob center and next it lowers to a given altitude in relation to the screen level and breaks any block present under the tool. A course of the rock-breaking process for the first few demonstration cycles has been showed in Figure 6.

3.4. Tests summary

The exemplary test has allowed us to indicate several issues related to the screen emptying process. It is clear that some of those issues will be present only in real mine conditions (like dusty air) and full-scale operation (breaking hard rocks which require a use of hydraulic hammer). However, some other issues may be examined at the developed test rig.

In the image acquisition and processing phase solutions alternative to the selected vision processing may be used. Options include a full range of image analysis algorithms and methods of automated tuning of vision system parameters. It is also possible to evaluate and compare usage of greyscale and colour images. A separate direction of development is extending the vision system with additional sensors which would provide depth measurement capabilities (analogous to the laser scanning proposed in [9]). That would allow testing another group of algorithms which analyze not a planar image, but a spatial reconstruction of the scene. Separate tests should be made to develop algorithms dedicated to recognition of steel elements present in the rock material.

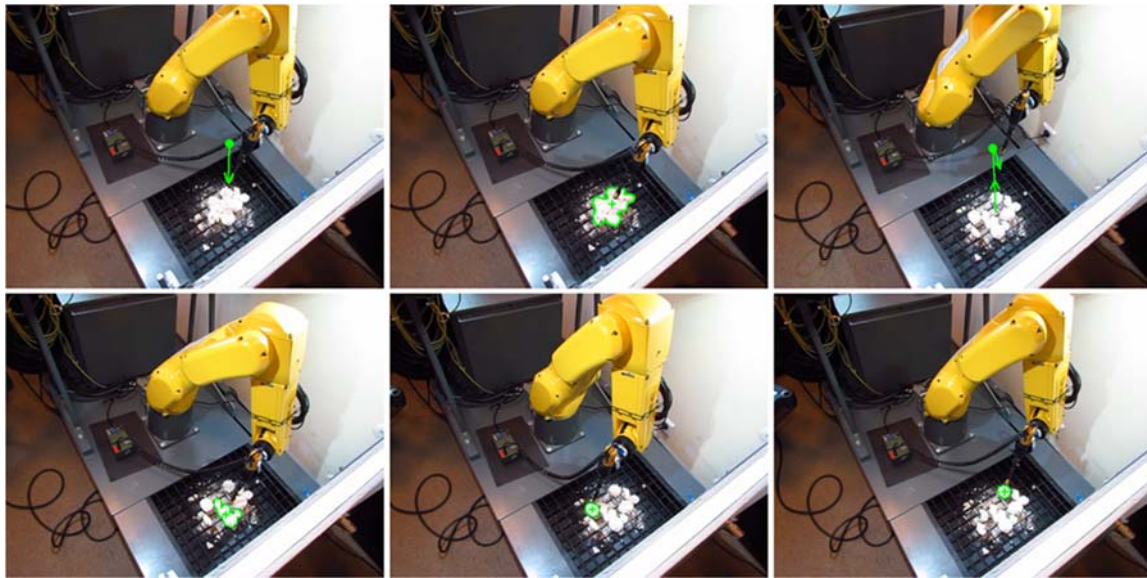


Figure 6. Block recognition process: the green arrows show motion between initial point and block; currently processed blocks are marked with green lines

The test rig also allows for validation of various methods in the breaking and sweeping phase. Planning algorithms based on various assumptions may be evaluated to determine which approach would clear the screen the most effectively, using the shortest tool path and motion time. Similarly, the methods of selection of the blobs to process and parameters of each phase may be optimized to shorten the total time of the whole process. Apart from the improvements of the algorithm components, parallel path of development should lead to scaling up the test rig to the operational rock breaking station.

4. Summary

Literature analysis shows that mining industry around the world is oriented to automation and robotization of mining processes and reveals technological readiness for 4th industrial revolution. In this paper, preliminary analysis of possibilities for the use of robotic system for rock breaking process has been presented. Research has been carried out on the described test rig. Using many simplified assumptions in comparison with real object, general algorithm for breaking oversized rocks has been developed using analysis of images from the camera as a base for material tracking. Tests performed in unaided operation mode with softer material imitating real rocks showed highly satisfying results of breaking oversized rocks. The achieved results indicate that automation of rock-breaking process is

possible to achieve. Although, presented test rig provides simplification of rock-breaking technique. The most important action is block recognition by vision system basing on the assumption that there is appropriate contrast between block and background of scene.

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