MINING PROCESSES OF DRILLING MACHINES. INFORMATION ABOUT THE TECHNOLOGICAL ALARM SYSTEM OF DRILLING MACHINES

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ABSTRACT
The monitoring of drilling processes is a well-known topic in the mining industry. It is widely used for rock mass characterization, bit wear monitoring and drilling process assessment. However on-board monitoring systems used for this purpose are installed only on a limited number of machines, and breakdowns are possible. There is a need for a data acquisition system that can be used on different drilling rigs and for an automatic data analysis procedure. In this paper, we focused on the automatic detection of drilling cycles, presenting a simple yet reliable system to be universally installed on drilling rigs. The proposed solution covers hardware and software. It is based on the measurement of electric current and acoustic signals. The signal processing methods include threshold-based segmentation, a short-time envelope spectrum and a spectrum for the representation of results. The results of the research have been verified on a real drilling rig within the testing site of its manufacturer by comparing the results with the data of the on-board monitoring system installed on the machine. Novel aspects of our approach include the detection of the pre-boring stage, which has an intermediate amplitude that masks the real drilling cycles, and the use of the percussion instantaneous frequency, which is estimated by acoustic recordings.

Keywords: Audio–Video Recording, drilling rig; process monitoring; operational cycles; sound measurement; electric current acquisition; threshold-based segmentation; envelope spectrum.

INTRODUCTION
All of the leading producers of drilling rigs in the recent three decades have devoted their attention to the development of process monitoring systems to enhance the control and quality of blast-hole drilling. This initial step of ore extraction in mines using blasting technology has to be performed with an excellent, repeatable accuracy and high efficiency in order to ensure the economic feasibility of mining operations in the reality of the currently worsening mining–geological conditions, meaning

decreasing thickness of the deposits, their depletion and deepening location. Since on-board monitoring systems have became a standard for this type of machine, to utilize their potential, it is crucial to develop accurate data processing algorithms that will enable the assessment of the efficiency of the blast-hole drilling process. To date, there have been several research directions regarding monitoring and data analysis systems related to the drilling process. Equipment could be used for rock mass characterization, drill bit wear monitoring, the assessment of the performance of the drilling process and operator's skills, development of the design of a machine, minimization of the energy consumption for the drilling, etc. One of the most important parameters in blast-hole drilling is the service time of drill bits. Their design and gradual deterioration are the principal components influencing overall productivity and machine down-times. Although some methods for the on-line condition monitoring and wear prediction of drilling bits are currently under development, efficient diagnostics of these elements is still not a trivial task. The information about the number of drilling cycles as well as the quality of the drilling may be also used for maintenance policy. Another issue arising in the real conditions of underground mines is the setting of appropriate
drilling parameters for the usually not definitely known and varying rock media hardness, namely the drill bit rotation speed, feed pressure and percussion frequency. Although certain practical recommendations are given for each type of drilling tool by their producers, operators of machines need on-line data processing methods to adequately react to quickly changing geological conditions. Regardless of the source of the measurement data, one can easily achieve very good results in the monitoring of the drilling process using basic analysis methods. In this work, it is shown that, with the help of very basic data acquisition systems, we obtain valuable measurements that allow us to avoid sophisticated and expensive measurement methods. The paper is organized as follows: first, we recall some work related to the monitoring of the drilling process; then, we define a research problem and propose a solution to it that includes experimental work, hardware and software solution. The validation of the proposed methods is conducted by comparison with an on-board embedded monitoring system installed on the machine as an option.

Technical monitoring of the drilling process

The Measurement While Drilling (MWD) methods were used to evaluate roof strata based on feed pressure and acoustic data. The detection of the abrupt changes in data patterns related to drilling, which was exhaustively presented in, has been applied to detect interfaces between different lithological types or to locate voids in the roof layers. A brief introduction to one of the techniques that allows for the detection of discontinuities, voids, cracks and the identification of different roof strata—a cumulative sum algorithm (CUSUM)-based program—has been shown in. An accelerometer and acoustic sensor, independent of other sensors, have been successfully used to detect small apertures and voids in. A simple and widely used support vector machine (SVM) pattern recognition algorithm has been successfully used to classify different soft and hard rocks in real-time, as presented in.

Input parameters such as the penetration rate, rotation pressure, feed pressure, vibration and acoustic signals have been used in combination with time series classification. Parameters such as the weight on bits or thrust and accelerometer data related with drilling—measured on the drill head as well as on other parts of the machine—have been used to estimate the mechanical properties of rock mass. Another contribution to the evaluation of rock mechanical parameters with MWD measurements was presented in, in which an analytical model of a process that could be useful to evaluate the uni-axial compressive strength was described. The authors broke the process down into the repetitive cycles of feeding and cutting, and based on the fact that only cutting and indentation are effective, while friction on the flank surface and idle running do not contribute to the effective drilling work, an effective specific energy parameter that is independent of the penetration rate was derived. MWD data, compared with geophysical loggings, were proven to be appropriate for determining rock properties in a method to derive operational parameters of the drilling jumbo (rate of penetration, rotary speed and torque and pulldown force) from voltages and currents was described. Data of this type have been applied to estimate rock-breakage characteristics, aimed at mine-to-mill optimization solutions in open-pit mining, as conceptually presented in. Another example of the characterization of drilled material in open-cast mines, performed based on the drilling performance indicator linked with geomechanical parameters and in which the new measure of the Modulated Specific Energy (SEM) was introduced, can be found in. Other interesting instance of the MWD technology application is the prediction of Excavation Damage Zones sizes, which are induced by blasting in underground excavations. As can be seen, the focus of researchers was aimed at obtaining information about the rock mass, indirectly and automatically, leading to an increase in the understanding of the interactions between the machine and rock material. In addition to the characterization of rock properties, process parameters can be used for the on-line diagnostics of drilling tool wear and other parts of machine equipment. By conducting

laboratory tests or their optimal selection and performance , it is difficult to approach the real contact conditions due to the possible dynamical effects related to elastic deformations of the drill-string and other structural elements. For example, the effects of coupling modes on torsional, bending and axial vibrations can be observed in drilling units. Therefore, the simultaneous observation of the acoustic data, voltages, currents and other signals available from the on-board data acquisition systems—e.g., bailing water pressure or temperature —should help to better understand some hidden dynamical processes in the machine, leading to higher performance via its automation and control. Acoustic telemetry and mud pulse telemetry are the communication methods used in deep-well drilling to provide valuable on-line information from the underground. However, acoustic signals have a significant attenuation and need repeaters for their transfer to on-surface monitoring systems. The horizontal blast holes have a comparatively small depth (2–6 m); thus, acoustic signals can be directly registered by a properly installed microphone. This particular feature constitutes a physical basis for drilling process and tool condition monitoring by the acoustic waves generated in the rock deformation zone. To correctly understand the events in the drilling process and equipment, the adequate segmentation of continuously recorded signals is absolutely necessary, as in any other types of underground mining machines. The task of the identification of operational cycles in the monitoring systems of underground vehicles is solved in. Cycle extraction from process data has been discussed in .proposed several algorithms for the multidimensional analysis of the data from an on-board monitoring system used in the underground heavy duty load-haul-dump trucks (LHDs) . The problem of drilling robotization has been. proposed a method for the automated operating mode classification of online monitoring systems. Wodecki discussed long-term data analysis for condition monitoring purposes discussed the problem of reliability in drilling. The problem of data acquisition, validation and analysis for LHD machines has been discussed in . Acoustic emission and different acoustic signals have also been used for drilling monitoring in various contexts. However, as mentioned in the discussed case, blast-hole drilling in the considered mine is a specific problem due to its enormous scale. Precise information about the number of holes, their lengths and the manner in which the drilling was performed is required; in that sense, the monitoring of the drilling process and drilling related-knowledge acquisition is very challenging.

PROBLEM DEFINITION

To properly assess the efficiency of the works performed by mobile machinery, the division of the generic process of blast-mesh preparation into sub-processes is required. Cyclically repetitive processes, which are completed by the drilling jumbo included in the preparation of the mining face before the injection of explosives in blast-holes, include the positioning of the drill, hole pre-boring, the actual drilling of the blast hole and blast hole flushing. The identification of the above-mentioned sub-processes and the definition of their duration is undoubtedly valuable from the perspective of efficiency and quality assessment. The problem can be approached by taking advantage of the electrical current signal, which varies when the load on the working unit changes consecutively with the succeeding sub-processes comprising the drilling cycle. Moreover, inspired by the operator's experience, an additional source of information regarding drilling performance can be taken into account, which is the acoustic signal. Being aware of the characteristic patterns in sound emission related to consecutive actions of a drilling rig, namely idle running (when the drill is positioned), pre-boring and the actual drilling, some informative features can be found in a pre-processed signal. The identification of such features can be used for the automatic distinguishing of the sub-processes and their duration and to count the number of drilled holes. This paper outlines part of the fully automated evaluation of the operator's and machine's efficiency. The methods presented by the authors have potential for the monitoring of drilling in mining faces, with special attention being paid to the identification of the drilling of individual holes, based on three separate sources of information:

#The automatic identification of cycles and analysis of their features (electric parameters, time, amount, presence of pre-boring etc.) based on signals registered by the on-board data acquisition system;

The automatic identification of cycles and analysis of their features based on the raw electric current consumption signal measured directly on the power line;

#The automatic identification of cycles and analysis of their features based on external noise recording.

Machine and Experiment Description

In underground mines that exploit deposits with the use of blasting technology, the drilling rig is the first machine in the technological cycle, the performance of which affects the general efficiency obtained in the exploitation area. Self-propelled drilling machinery for mining purposes can be decomposed into key elements, which are the operator's cockpit, electric cabinet, water hose and electric cable reeling units, diesel engine (or electric motor in case of battery-powered rigs), hydraulic system, leveling jacks, boom, arm and drill. In addition to drill carriages, there is sometimes a platform for a miner incorporated in the machine's structure. Currently, drilling jumbos are adjustable to local mining conditions, and therefore there are a multitude of available sizes—from the large sizes designed for large excavations and construction of tunnels to small, compact versions that are appropriate in cramped conditions (in ultra-low seams, for example). The rigs are equipped typically with up to four booms. It should also be noted that the other type of machinery—the bolting-rig—that is responsible for the reinforcement of the excavation after the blasting and loading of ore is very similar from a design point of view and also performs drilling to prepare anchor holes. Thus, not only can the performance of the drilling rig operating at the first step of the technological cycle be approached with the method described in this study, but the efficiency of rotary drilling and the preceding injection of the resin bolts can be evaluated as well.

Figure 1. The drilling machine used in experiments.

Geological Conditions

The experiment comprised the drilling of multiple blast holes with standard-diameter granitoid blocks at their full length (70–80 cm). The rock composition predominantly included feldspar, quartz and plagioclase, containing minor micas and amphiboles. Grains of the rock were relatively coarse and uniformly distributed. The lithology of the sample designed for the experiment was a rough approximation of the actual rock types encountered in the ore zone in the mines, where the following lithological sub-types of rocks were present (see Figure 2): dolomites and sandstones; grey, streaky dolomite; dark-grey, clayey dolomite; dolomitic shale; pitchy, clay-organic shale; grey, dolomitic sandstone; grey, clayey sandstone; and red, clayey sandstone. Furthermore, drilling performed in a uniform rock mass that is devoid of discontinuities, voids and interbeddings does not reflect the conditions present in the mining faces. Such occurrences of non-uniformity are suspected to cause changes in the instantaneous performance of rock drill, and thus other parameters are related to it, including those analyzed in this study. It should be noted that a granite rock was chosen because its average compressive strength was approximately the same as the average compressive strength in an ore deposit profile, at approximately 130 MPa. The aforementioned rock was easily accessible on the surface and had similar mechanical properties to the ore raw material. This made the experiment a good simulation of the conditions in an underground copper mine.

Induction Clamps for Current Measurement

As with many sensors used for current measurement in the automation industry, the majority of solutions are based on in-circuit measurement. It is necessary to apply this apparatus to the design level of machine development. On the other hand, current clamps are more convenient, as the current measurement system can be applied without any intervention in the machine's electric circuits. The center of the measured conductor should be installed in the current clamp jaw. Additionally, it is necessary to consider that the clamp is perpendicular to the conductor, which helps users to gather appropriate results. For experimental purposes, Fluke's current clamp i400s (see Figure 4) was used. An output AC voltage signal of 0–400 mV was received. For data handling, the cDAQ-9171 USB chassis with an analog-to-digital converter (ADC) module was used. The frequency of measurements was 2000 Hz; as a result, we observed a quick-change pulse at the moment of the engine starting. The second approach relied on the microcontroller-based measurement system, which omitted the presence of additional software from the signal card producer. All data were saved in .txt format on an SD card.

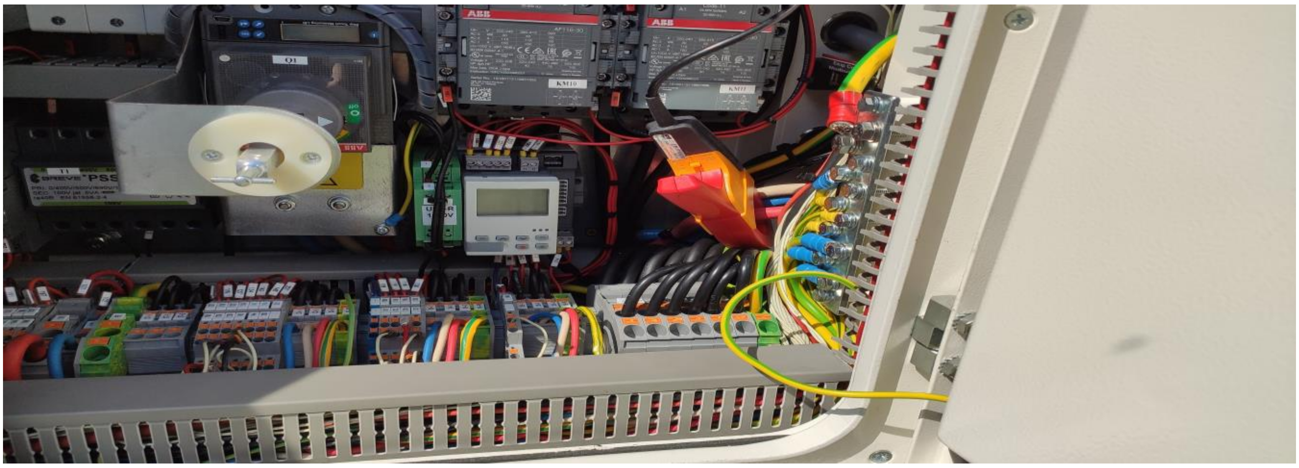


Figure 3. Current measurement clamps mounted on the wire of interest.

In addition to the electrical parameters, the authors registered an audio–video recording of the drilling activity. The recording was taken using a smartphone camera with a video sampling frequency of 60 frames per second and an audio sampling frequency of 48 kHz. The acquired video data provided a reference for other data sources and allowed us to validate timings and actions. Additionally, the audio feed extracted from the video files provided an additional data source for process-related analysis (Figure 5).

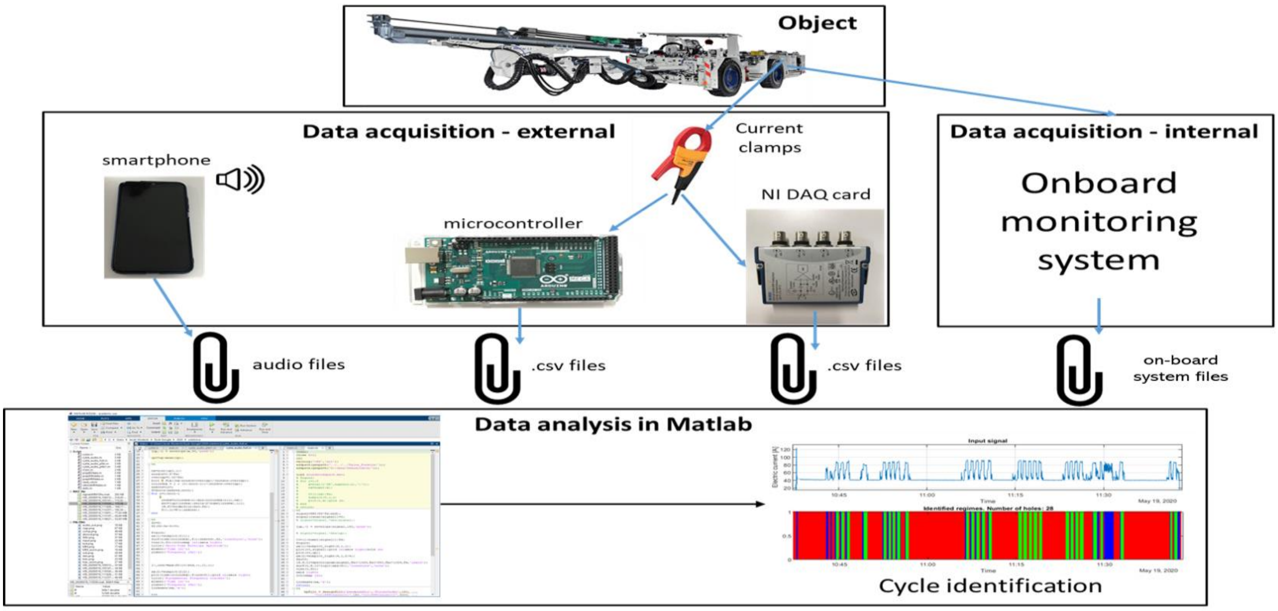
Figure 4. The concept behind acoustic data acquisition

Methods

The purpose of the methodology was to develop reliable raw data processing algorithms that are capable of extracting information about the drilling process. More precisely, it was expected that it would be possible to enable the identification of the number of cycles (the number of drilled holes) as well as information about the cycles' properties (duration of the cycle, pre-drilling phase, etc.) to be provided.

Validation

The monitoring system installed on the machine provides high-quality data that allows the precise analysis of the drilling process in terms of the number of holes drilled, the duration of a single cycle, etc. In this work, it was used as a reference system to validate our monitoring devices. The reason for preparing a new monitoring system is simple—the monitoring system proposed by the manufacturer is optional when purchasing the machine, and to the authors' best knowledge, there is no universal system for such a purpose that could be used in the case of the failure of the previous device. Moreover, in older machines, there are no monitoring systems for the drilling process. The proposed system is based on electric current consumption analysis. It provides basic hardware as well as software to calculate the required parameters. The first version of the system is based on a standard Data Acquisition Card from National Instrument, while the second version is based on an Arduino micro-controller with other electronic components to support local data recording on the SD card of the processed signal (amplified and digitized). A schematic representation of different data-acquisition methods that can be used to assess the drilling rig's operation can be found in Each monitoring system provides raw data in .csv format, which is then processed using the Matlab environment (signal processing toolbox). We used Matlab ver. R2020b and personal computers with an average office-class computational speed: an Intel I7 processor operating at 4 GHz and 8 GB of memory.



Schematic representation of different data-acquisition methods and the results obtained on the basis of various types of input data.

Audio–Video Recording

Both cases showed excellent technical parameters and allowed us to measure the current signal with a higher sampling frequency. Increasing the sampling frequency provides increased opportunities for transient events analysis in the signal. Current consumption requires special devices and integration with the electric circuits in the machine. It could be an interesting option to use acoustic signals for the monitoring of the drilling process. It should be mentioned that the diesel engine is switched off during drilling; the process is driven by an electric motor, meaning that background noise should be reduced. In this section, as a reference, the signal from the on-board monitoring system was used. As presented , the signal acquired by the proposed system (blue curve) was very similar to the reference signal. As the sampling frequency was higher, more noise (that could be easily removed) could be observed, as well as some extra information related to transient events—low-frequency sampling was not able to capture this. The difference between the on-board and the proposed systems is related to the technologies used and sampling frequency. Information extracted from acoustic signals has been discussed in detail in the previous section. It can be seen that, thanks to instantaneous frequency monitoring, it was possible to identify the pre-drilling and actual drilling phase. We can therefore conclude that both electric and acoustic measurements are very useful for drilling monitoring.

CONCLUSIONS

In this paper, a data analysis methodology was proposed for three different data streams. The data originating from the on-board monitoring system. The data, namely the current consumption, are a function of the load applied to the drilling tool. As the idle mode current is low, pre-drilling is associated with a medium load (60–70 A) and actual drilling means a heavily loaded system, so significant (>80 A) current consumption is visible. The signal is relatively clear, and so one can distinguish key elements of the cycle using simple statistical pattern recognition tools (threshold estimation based on probability density function). The statistical variability of real signal levels over the phases of drilling cycles is not very wide (up to ±5%); thus, the proposed method is robust and does not need subsequent tuning to account for changes of bits' parameters or rock properties within a certain region of mining. Case 2: The data originating from the proposed electrical current monitoring system. These data should be pre-processed to a similar format as data from the on-board system; then, the processing is performed according to the procedure in case 1. Besides, the higher sampling frequency of a new monitoring system allows the development of algorithms for specific feature detection in the drilling process, which are currently under development.

Case 3: The acoustic signals from the microphones. These data require more advanced techniques as they are processed using the Hilbert-based envelope analyzed in the time–frequency domain in order to extract the instantaneous frequency. It appears that idle mode, pre-drilling and actual drilling have completely different acoustic signatures in terms of sound levels but also in terms of their frequency structure. Thus, instantaneous frequency (IF) may be used as a feature for drilling monitoring. Using the IF as a function of time, one may simplify the situation to case 1 and apply the segmentation procedure. Finally, all three approaches were compared and a very good convergence of results was shown. A holistic solution was proposed that covers the data acquisition system (electric current measurement and acoustic signal acquisition) and data processing algorithms for the extraction of information about cycles related to drilling. The data acquisition system is relatively cheap and may be easily composed of accessible components (induction clamp, microphone and an Arduino microcontroller), but it requires low-level programming experience and knowledge related with embedded electronics design. The second version is even simpler and is based on a simple sound recorder—a standard smartphone was used to capture the video and sound. Future work will focus on large-scale testing in an underground mine to estimate the influence of external noise and repetitive reverberations in the confined space of narrow tunnels.

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