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Technical Note

An acoustic sensor for prediction of the structural stability of rock

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1. Introduction

Relatively small rocks that detach from stope hanging walls during periods when miners are working in the vicinity pose a lethal risk, and contribute significantly to underground fatalities in the South African mining industry, totalling 89 in 2014. The rock fall risks in deep rock mining are related to the behaviour of the rock surrounding excavations under high confining pressures. This is a particular concern in South African gold mines, where tunnels and stopes are excavated at depths of up to 4000 m. The failure of hanging walls has been an area of extensive research in rock mechanics,[1] as it is the cause of many rock fall-related injuries and deaths.[2]

This workplace risk to miners is addressed by various standard mining practices, one of which is the entry examination procedure. Members of the entry examination team evaluate the hanging with the use of a pinch bar to both ‘sound’ the rock and to bar it down safely, if it is found to be dangerously loose. ‘Sounding’ a rock is the evaluation of the rock's structural stability by judging the noise generated when the rock is struck by the pinch bar.

Experienced miners familiar with the sounding process know that an intact rock mass, i.e. a rock mass that is considered sufficiently stable to be regarded as safe, will respond to the applied tapping with a relatively high-frequency sound. A detached rock mass, i.e. a rock mass that is insufficiently stable and therefore regarded as unsafe, will respond to the applied tapping with a relatively low-frequency sound.[3]

Regardless of the experience of the operators, human error limits the reliability of this approach, and as a result, a significant effort has been made to develop acoustic systems that could assist operators in their task. The propagation of acoustic waves through rock is characterised by an elastic displacement of the material. This is directly influenced by the degree of elastic coupling between the different media through which the acoustic wave propagates.[4] A rock with discontinuities presents a mixed media environment for a propagating acoustic wave, resulting in a higher reflection rate of the acoustic wave. This is characterised by a higher portion of the impact spectrum being reflected back to the source of the impact.

Lower frequencies propagate more readily in an elastic medium such as rock. Moreover, a rock mass without discontinuities will attenuate higher frequencies to a greater extent than a heterogeneous rock mass. This is known as anelastic attenuation in reflection seismology.[5] Over significant distance rock as a propagation medium can be seen as a low-pass filter. The size of the homogeneous environment is therefore inversely proportional to the presence of lower frequencies in the reflecting wave. This can be empirically observed in the case of acoustic entry examination, where the sounding response from a loose rock will typically contain more non-absorbed lower frequency energy.

Numerous studies have been done on the analysis and use of the acoustic frequency response of rocks in testing for structural cohesion in mining environments.[2,6,7] Allison and Lama[3]

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experimented with a technique that can determine the rock characteristics by applying ultralow frequency vibrations of a small magnitude to the rock, and detecting the response with a sensor attached to the rock. A shortcoming of this technique is the preparation of the rock to attach actuators and sensors to it, a process that would have to be repeated for each rock tested. Instrumentation developed by Hanson[6] consists of an accelerometer mounted on the pinch bar connected to two band-pass filters which calculates the energy in a defined high and low band of the spectra. The frequency ranges chosen were [500–1000 Hz] for the low-pass band and [3000–3500 Hz] for the high pass band.

The main shortcoming of the device is the strictly defined frequency ranges evaluated. A patent by Lux et al.[7] describes a loose rock detector with the innovation being the implementation of variable defined frequency ranges to compare with each other. The features used in these studies were derived from methods similar to band pass filters, resulting in total or averaged spectral energy values obtained from specific frequency band ranges.

2. Hardware

During 2008–2010, the Council for Scientific and Industrial Research (CSIR) in South Africa has designed and tested a prototype electronic sounding device (ESD) to provide an additional concurrent assessment of the rock in the sounding process. The ESD can be broadly described as an audio input classification device.

The ESD records the acoustic waveform generated from the rock and pinch bar during the sounding process. It is designed to classify the structural state of the rock as either 'safe' or 'unsafe', based on the use of a classification model listening to the tapping of the sounding bar. After classification, feedback is audibly given to the miner to assist in his judgement of the rock's structural safety. One of the main design goals of the ESD was for the device to be portable and compact in order to be accepted by the miners. It is envisioned that it should be possible to use the device to determine the integrity of the rock mass without any additional effort on the part of the miner.

The ESD is adapted to be mounted on a miner's hard hat, as shown in Fig. 1. The sounding process is currently dependent on the miner's attention and experience, and it is hoped that the inclusion of the ESD would mitigate human mistakes during the process.

The ESD is provided with a training dongle that has three buttons on it, coloured green, blue and red. Each of these buttons corresponds to a label of the rock being sounded. In training mode, the ESD listens for an impact sound in its environment, and records the acoustic waveform of the event. It then prompts the operator with an indicator on the dongle to provide a state label corresponding to the perceived structural safety of the rock being sounded. The green button records a 'safe' state, the red button an 'unsafe' state, while the blue button discards the recorded event. The remote indicator on the dongle prompts the operator to provide a state label corresponding to the perceived structural safety of the rock being sounded and the device does not record any additional waveforms until such a state has been provided.

Fig. 1. Photograph showing the attachment of the ESD to a miner's hard hat for operational use (left), and the training dongle (right) that enables the user to label training data recorded. Note that the entire system consists of the headpiece and dongle shown in the figure. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

This modification to the ESD allows for quick recording and labelling of sounding events without requiring specialised skills by the operator. The feedback provided on the dongle itself, by means of its indicator, allows the operator to use the device without having to interact with the main ESD mounted on the hard hat. Since the training ESD stops recording waveforms until a label has been provided, the operator can put aside the dongle during times when training is not being done.

The hardware platform of the ESD was designed with these goals in mind. The block diagram layout of the hardware implementation of the ESD is given in Fig. 2. This diagram shows the main components of the ESD, and the main connections between the components.

As can be seen in Fig. 2, the central component of the ESD is the Gumstix motherboard. Gumstix motherboards are single board computers or computer-on-module (COM) systems. The design is centred on a microprocessor with RAM, input–output controllers and all the other features needed to be a functional computer on a single board. However, unlike some variants of single board computers, a COM lacks the standard connectors for input–output peripherals to be attached directly to the board.

Owing to the modular design of these peripherals in the implementation of the ESD, the COM motherboard is connected to a baseboard of the CSIR's own design. The specific Gumstix COM model used in the ESD is the Basix model, which has an XScale PXA255 processor, 64 MB RAM and 16 MB on-board flash memory. In addition, an extra 1 GB of memory is connected to the board for loading of the ESD's main programs, as well as the storage of audio samples collected for research purposes.

The microphone that is used for audio input into the ESD is an omnidirectional, waterproofed two-wire microphone. The audio signal between the microphone and the Gumstix board is amplified by an external 36 dB preamplifier with digital gain control, controlled via the Gumstix I2C bus. The signal is sampled at a resolution of 20 bits. The frequency range for the microphone is 80 Hz to 10 kHz, and the sensitivity to sound is rated at -87 dB at a 73 dB sound pressure level.

The sound recording on the ESD is sampled on two data channels at a rate of 44.1 kHz. This is a legacy artefact associated with the sound processing chip typically deployed in stereo recording applications. In the case of the ESD, one channel is discarded, owing to the mono-recording limitation of one microphone.

3. Data acquisition

Data were collected under laboratory conditions, as well as in the field. In the former, the acoustic signals were generated by solid and structurally defective rock specimens simulating conditions in the mine. In contrast, the operational data were classified by experts on the mine, as the actual conditions of the rock that generated the data, could not be verified.

3.1. Laboratory data

The ESD was designed to be used in underground conditions and trained by experts on in situ examples of loose and solid rocks. Since rock mass in the mines could generally not be barred down to be tested, the labels are based on expert assessments. Despite