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New technology for improving entry examination, thereby managing the rockfall risk in South African gold and platinum mines

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Abstract

Rockfalls are responsible for more than 30 percent of the fatalities on South African gold and platinum mines, with associated costs and lost productivity. One of the most important activities in the mitigation of rockfalls is the entry inspection that occurs before workers enter a newly blasted workplace. It is also one of the more dangerous activities that takes place in a workplace.

The CSIR has developed a sensor, called the electronic sounding device (ESD) that mimics the performance of a experienced miner, in order to determine whether loose rocks are present in the roof of the excavation, during the entry inspection. Tests of the ESD show a high degree of correlation with skilled human operators, allowing the device to be used where skilled operators are not available, or when skills are no longer viable due to hearing loss.

Another sensor of loose rock is thermal infra-red imaging. This has also been proven to show the location of loose rock, but there is a practical problem in its routine implementation underground, due to its narrow field of view. This problem will be overcome using overlapping images that are stitched together.

The combination of two sensors further increases the chances of correct decision making, and the visual sensing of the infra-red imager makes it harder to inadvertently miss inspecting risky areas. The combination can then be made available to unskilled workers through the addition of an augmented reality system based on a laser projector, that make the risk assessment system as easy to use as a torch.

The ultimate aim is to combine both systems with positioning provided by an in-stope navigation system, in order to combine current data with historical results from a particular working place to further improve the estimate of risk.

1. Introduction

1.1 The risk of rockfalls

A rockfall is defined as an *uncontrolled fall (detachment or ejection) of ground of any size that causes (or potentially causes) injury or damage* (Minerals Council of Australia, 2003). Rockfalls pose unacceptable risks to the South African mining industry. Using a methodology described by Terbrugge *et al*. (2006) and data published by the Department of Minerals and Energy (2009), a fatal injury rate for South African miners exposed to rockfalls of worse than 10^{-3} is obtained. This is at least ten times higher than the acceptable fatal injury rate for voluntary risk as stated by Wong (2005).

1.2 Gold and platinum mining in South Africa

The majority of South African gold and platinum mines have thin tabular seams in a hard rock environment. The mining process is mainly based on conventional drilling and blasting (as depicted in Figure 1), resulting in a significant number of mining personnel being exposed to fall of ground hazards. The working area, or *stope,* is typically about 1 m high, while tunnels leading in to the stope are larger, usually at least 2 m high. The stopes themselves are gently dipping, with slopes ranging from about 8° to 25°. Mining occurs largely as a batch process: each mining cycle consists of drilling; charging holes with explosive; blasting; cleaning; and placing support.

Figure 1. Gold and platinum in South Africa are mined in a thin tabular seam in a hard rock environment.

Rockfalls can be classified in a number of ways: by size or by relation to support units. One of the most important types of rockfall is the small fall that occurs before support is installed, or between support units. These rockfalls are approximately only 25 kg and larger, but still have the potential to result in a serious injury or fatality (Stacey and Gumede, 2006). The falls typically occur within meters from the face (Brink and Roberts, 2007). In most cases the disturbing force or trigger is just gravity, but could also include ejection due to local face bursting; or even shakedown from nearby seismic events. Only small rockfalls are considered here.

1.3 Making safe

While rockfalls account for a significant number of injuries and fatalities, the risk of being injured due to a small rockfall is substantially larger than the risk of multiple injuries due to a large event (Stacey, 1989). Small rockfalls are relatively common, and while proportionally a given event is less likely to cause harm, the frequency leads to a large number of harm-causing events.

One of the most important processes to manage the risk of rockfalls, particularly small rockfalls, is that of *making safe*, undertaken by the miners as they enter the stope for the first time after the blast. Currently, part of the process of making safe consists of using a pry-bar to tap the roof of the excavation. The miner then listens to the sound of the tap, and if the rock sounds loose, the miner will attempt to pry it from the roof or *bar down*, using the same pry-bar used to sound the hanging wall.

The process is often not conducted properly, due to problems with the process itself: the pry bar is heavy, the physical effort of tapping the roof in a confined space is high as is the barring, and there is pressure to get the making safe process over as quickly as possible so as not to delay production. In addition, the sounding process is an acquired skill, performed more competently with more experience. It is also somewhat subjective, and the quality of sounding is related to the physical state of the miner undertaking the sounding. Hearing-impaired miners obviously cannot sound as effectively as their un-impaired counterparts, and hearing is only checked annually. Fatigue and illness also affect the competence of individuals, even within a single shift.

In an attempt to reduce the risks associated with rockfalls, the Mine Health and Safety Council has sponsored a multi-year project that is being undertaken by the CSIR. The new technology being developed to improve entry inspection and making safe is considered here.

2. The Electronic Sounding Device

As discussed above, the primary method of determining rock mass integrity is sounding with a steel sounding bar. The sound which is heard is caused primarily by the acoustic wave generated through vibration of the rock mass and other sources, for example the sounding bar, in the surrounding environment. The sound has a unique frequency distribution which must be interpreted in order for a determination to be made about the integrity of the rock mass.

Experienced miners know that a rock mass which is sufficiently stable to be regarded as safe, will respond to the applied tapping with a relatively high frequency sound. A rock mass which is insufficiently stable to be regarded as safe, will respond to the applied tapping with a relatively low frequency sound (Allison and Lama, 1979).

To overcome the human factors and subjectivity, a device has been developed that mimics the performance of the human ear and brain: the Electronic Sounding Device, or ESD. It uses a microphone to capture the sound emitted by the rock mass when it is tapped with a sounding bar. The recorded sound is processed by an on-board Linux system through a neural network model. The neural network model distinguishes a safe region from an unsafe region by analyzing the envelope of the spectral distribution generated from the sound emitted.

The ESD is designed to be an integral part of the current sounding and barring method:

- When the sounding bar taps the roof, the ESD captures the acoustic signal generated as a result of the impact.
- It then derives a frequency distribution of the captured signal.
- The frequency distribution is processed by a neural network model trained to apply adaptive intelligence to assess the input data.
- The neural network outputs a signal that is indicative of the integrity of the rock mass.
- If the rock mass is safe, the ESD beeps once, if unsafe it beeps twice.

One of the main design goals of the ESD is for the device to be portable and compact in order to be accepted by the miners. It should be possible to use the device to determine the integrity of the rock mass without any special preparations of the surface of the hanging wall. In its current embodiment, the ESD is adapted to be mounted on a miner’s hard hat (Figure 2). The ESD speaker is directly adjacent to the operator’s ear, so that the audio signal can easily be heard. A green or red LED, visible in the Figure, lights up if the sounding indicates a stable or unstable rock mass. This visual confirmation of the process is visible to the miner’s colleagues, allowing them to monitor progress from a distance.

Figure 2. The current manifestation of the Electronic Sounding Device as mounted on a hardhat.

Before routine operation can commence, the neural network in the ESD needs to be trained. This is done using a special training unit. A skilled operator taps rocks, then tells the training unit whether the rock is stable or unstable. The audio signals captured by the training unit, together with the stable/unstable classification are later run through a computer-based neural network simulator to determine the neural network coefficients for the operating units. The coefficients are programmed into all the units that will be used under the same conditions as the training unit.

Figure 3 shows the frequency response of typical unstable rock on the left, and stable on the right. The bins used by the neural network are superimposed in purple.

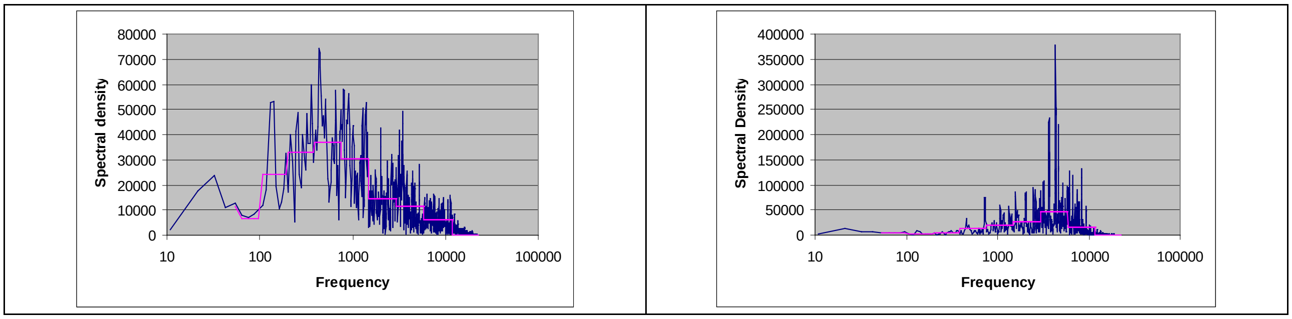

Figure 3. The spectrum recorded on the left is typical of the lower frequency, ‘hollow’ sounding response from loose rock, whereas the right-hand spectrum represents solid, intact rock.

2.1 Trial results

The ESD was tested at a number of different sites on the Driefontein gold mine. The sites had different gold reefs, ground water conditions and rock mass classifications. A single set of coefficients was created with training data from the many different environments.

As there is no truly objective measure of rock stability, each ESD sounding was compared to the opinion of a skilled operator. Correlation between the human and machine judgments is taken as a measure of success (Table 1).

Table 1. Performance summary, in terms of positive correlation between the operator and the ESD

Stope	Judgement correlation success
Middelvlei Reef	78.40%
Carbon Leader	78.48%
Carbon Leader	89.19%
VCR-Alberton Reef	78.38%
VCR-Westonaria Reef	76.47%

The correlation mismatches between the ESD and an experienced operator can be sub-divided into the cases where the ESD was overly cautious, i.e. the ESD predicted an unsafe rock mass where the operator judged it safe, and where the ESD made a potentially dangerous error, i.e. the ESD predicted a safe rock mass where the operator judged the rock mass to be unsafe.

It is evident in Table 2, below, that the increase in unsafe errors correlates to the ground conditions of the stope where the ESD was tested. Higher unsafe errors are observed from the testing results of stopes where the ground conditions are described as ‘intact’ and ‘stable’. Possible solutions to minimize the amount of unsafe errors would include sampling more recordings during the training process from stopes with intact ground conditions, and then evaluating whether increased exposure to such recordings increases the efficacy of the neural network model under these conditions. It is suspected that the make-up of the rocks in an area with intact ground conditions might deliver a different frequency response from those in a crushed and fractured type of ground condition environment.

Table 2. Performance summary, in terms of correlation mismatch between the operator and the ESD, broken down in the relative geotechnical areas

Reef	Cautious errors	Unsafe errors	Ground conditions
Middelvlei Reef	7.80%	13.80%	Intact
Carbon Leader	16.46%	5.06%	Crushed, fractured
Carbon Leader	6.76%	4.05%	Crushed
VCR-Alberton Reef	16.21%	5.41%	Crushed, fractured
VCR-Westonaria Reef	11.77%	11.76%	Intact

It is also important to remember that the process has some subjectivity, both in training and in trials, and it is unlikely that perfect correlation between a single expert and the ESD will ever be achieved. However, the addition of the ESD to the miner’s safety equipment adds a check to the human sense of hearing and the human intelligence that will function consistently without fatigue or other human factors. The ESD will go into production shortly.

3. Thermal imaging

While the ESD mimics an existing process, there have been studies into other methods of determining rock stability, using different sensors. It has already been shown (Oldroyd, 2006) that loose hanging wall rocks can be identified using thermal imagery because they are cooled more by ventilation than rocks that are more firmly connected to the surrounding hot rock mass (Figure 4). In Figure 5, the results can be seen when a camera is used to view a loose rock underground.

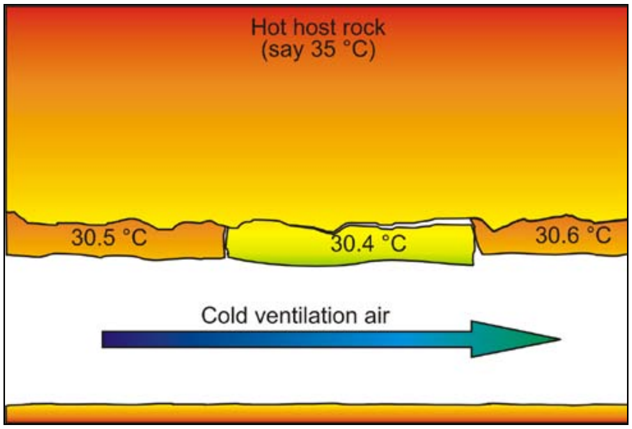

Figure 4. An illustration of the concept of heat flow from warmer solid rock, with the more detached rock being more insulated and cooler.

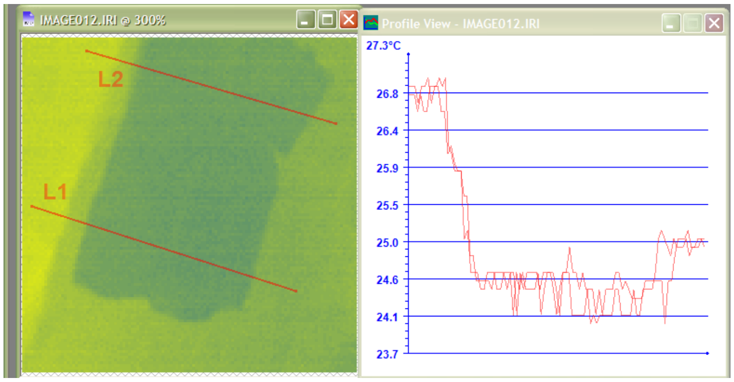

Figure 5. A loose section of rock at a Klerksdorp mine with dimensions of 0.8 m by 0.3 m and an estimated mass of 65 kg. With relatively newly exposed ground, the temperature differential between the rock and the surrounding rock is more that 2.5 °C as shown in the temperature profiles along L1 and L2.

This process has become much more feasible with the drop in price of thermal infrared cameras over the last few years. The price is expected to come down further, as thermal infrared has been identified as a technique for assisting drivers to see pedestrians at night (IOL Motoring, 2005).

3.1 Limits of wide-angle vision

While thermal imaging is a viable technique for determining which rocks are loose, readily available infra-red cameras have an angle of view of about 55°. In large excavations such as tunnels, they work well, but in the stope itself where the floor and roof are just 1 m apart, only a very limited portion of the roof can be viewed at one time. At that distance, the angle of view delineates a target of only 0.5 m across.

Thermal imaging for loose rock detection functions by comparing the temperature of particular rocks, such as that seen in Figure 5, with the average temperature of the background. With a limited angle of view, it becomes possible that the target rock will fill the whole image and cannot be compared to the background. In Figure 6, the large anomaly cannot be differentiated from the surroundings from a single image only. It becomes necessary, therefore, to stitch thermal images together to create a larger view, which clearly displays single cooler rocks. The stitching is an automatic process that does not rely on human intervention. An early attempt to do this is presented in Figure 7.

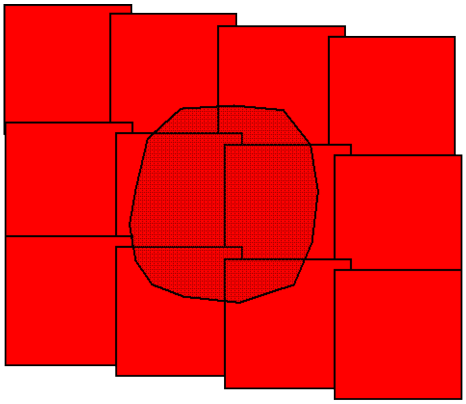

Figure 6. An illustration of a hanging wall viewed thermally with a view 0.3 × 0.3 m and a thermal anomaly with an approximate radius of 0.6 m

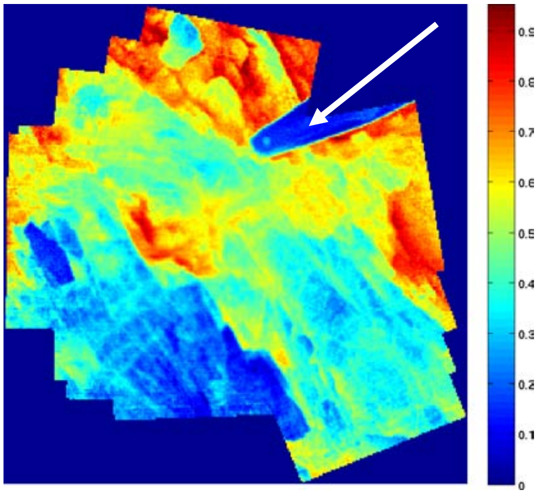

Figure 7. Thermal images stitched together (images obtained at Driefontein mine). The temperature scale is relative to the average temperature in the image. The highlighted feature is a steel support unit attached to the roof.

4. Spatial augmented reality

The CSIR is investigating the use of *spatial augmented reality* to present data in an intuitive manner to users underground. Wikipedia (2010) defines augmented reality (AR) as a term for a live direct or indirect view of a physical real-world environment whose elements are augmented by virtual computer-generated imagery. A good early review is provided by Azuma (1997). AR is often achieved by placing a screen between the observer and the environment on which augmented data is added. This screen could be a head-up display on a fighter aircraft, or a head mounted device (HMD) that might project augmented data onto glasses worn by the observer. The screen may also be the screen of a mobile phone that adds legends to items seen by the phone camera (Figure 8). The spatial AR used by the CSIR is created by projecting augmented information onto real scenes.

Figure 8. Augmented reality: details of a tourist site overlayed on a picture of the site itself, and found by knowing the location of the mobile phone and direction of view (Clellan-Jones 2009).

In the underground environment, augmented data can easily be presented as Spatial Augmented Reality, where projectors are used to display graphical information onto physical objects. In the CSIR's first proof of concept for rockfall management, the thermal imager discussed in the previous section is coupled to a micro projector, which projects the thermal image as an optical image with a colour scale back onto the surface that generated it (Figure 9).

As an example, in Figure 10 a heater in operation is placed against a cold wall. The thermal information for the heater and the wall around it is projected back onto the area. In the Figure, the temperature of the heater is projected onto the heater in a red colour. It can also be seen that the wall, which is cooler, has the cooler colour, blue, projected on to it.

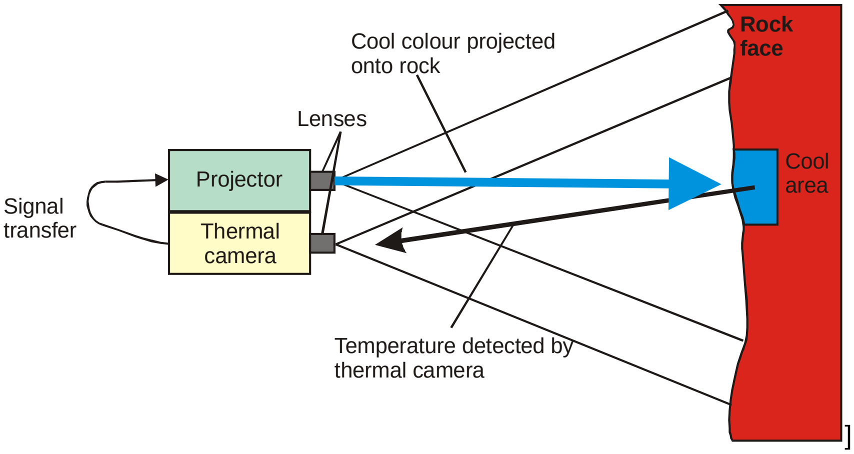

Figure 9. Augmenting reality by projecting thermal images back onto the source.

Figure 10. Demonstration of augmented reality: the warm heater is coloured orange by the projector, while the cool wall is coloured blue and green.

A combination of thermal sensor and projector in a single tool would produce a ‘safety torch’, which would illuminate rocks in colours that would depend on their likelihood of coming loose. As discussed below in the section on future work, there are some restrictions on a simple safety torch: it works best when the distance from torch to rock is 2 m or more, but the technique lends itself to further elaboration.

5. Conclusion

Small rockfalls have a disproportionate effect on injury and fatality rates in deep gold and platinum mines in South Africa. The procedures of entry inspection and making safe are designed to lower the risk of rockfall by identifying and bringing down rocks that are not firmly attached to the roof. These procedures are, however, physically demanding and not always conducted as thoroughly as is necessary. Any technolgical assistance is therefore welcomed.

- The ESD mimics the process of sounding during entry inspection, maintaining quality of inspection under all conditions. The device's second opinion on the state of the rock-mass can reduce uncertainty for operators who sound manually.
- Thermal imaging allows miners to “see” loose rock at a glance and can greatly streamline the process of determining what to sound.
- A process of spatial AR can project the risk back onto the rock in an intuitive way.

These tools can immediately reduce working place risk and when combined, offer the opportunity to reduce the number of undetected hazards and allow the incorporation of other regional information and historical data into the determination of risk. These future developments are discussed in the next section.

6. Future work

6.1 Data integration

Both of the tools presented here, the ESD and thermal imaging, determine risk as a function of immediate location, without any perspective in time. The ESD helps to identify rock that sounds unstable, where there is an increase in risk from that single rock. A single thermal image is similarly closely linked to location: if a rock in the view-finder of the image is cooler than its surroundings, that single rock is at higher risk of coming loose.

While such tools have their place, fusing the results from more than one sensor and from more than one data acquisition time can greatly enhance the risk assessment of a working area:

- **Creating a wider field of view**: if thermal sensor results are stitched together, a large cooler area will be detectable as such by comparison to the entire stitched thermal image.
- **Merging sensors**: if ESD results can be superimposed on thermal images, the combination will quickly highlight correspondence, which will provide greater certainty about unstable areas.
- **Merging historical data**: if ESD results can be presented from a current survey, together with results from historical surveys yesterday or the day before, trends should appear on the roof, showing trends of unstable roof conditions, and again adding confidence to the risk assessment from a single sensor at a single time.
- **Incorporate regional risk**: this paper discussed the assessment of the risk of individual rocks falling from the roof because they are not well attached. However, in general the risk of rocks falling is also controlled by regional effects, such as trends in faulting and jointing. These regional trends cannot indicate which rock could fall, but contribute to an overall understanding of the risk of a rockfall event.

6.2 Localization

Fusing sensor data only becomes possible if the location of each data capture is known. This requires a localization system. While there are many techniques being developed for localization (Comport et al, 2006), the CSIR is initially using simple and robust ultrasonic beacons (Ferreira, 2007).

The beacons are deployed on the roof of the excavation. In tests in a controlled environment, it is capable of determining location in the working area with a horizontal accuracy of 2.5 cm. The stope environment is typically planar, so the resolution in the third dimension is very limited. For many data collection purposes, this 2D positional data is adequate. However, for image sensors and reality augmentation, it is necessary to know the position of the transducer in 3D (the distance to the roof or floor is important), as well as the direction, elevation and rotation of the sensor. Alternatively, image sensors can be roughly located using the 2D beacon system, then can define their location more accurately using a search algorithm where the sensed image is compared to a stitched image already built up in memory. Both approaches are being developed and it is likely that each approach will better suit some types of sensors.

6.3 Data presentation

In its simplest form, the risk of rockfall in a stope can be presented as a map that is colour-scaled or contoured as a function of overall risk. However, for the specific purpose of improving the quality of entry examinations and making safe, it is necessary to identify individual unstable rocks in the roof. Two methods are proposed:

- The spatial AR approach of projecting information onto the rock is simple to use and apply if a beacon system is available.
- The CSIR is also developing a robot that can independently undertake the entry examination before the shift reaches the working place. It is likely that the robot will mark areas of the hanging wall directly, using spray paint.

6.4 System approach

Ultimately, an entry examination tool that would assist with making safe should be part of a more inclusive rockfall risk management system. All the approaches suggested here to advance the current developments fit into the AziSA system currently under intensive development at the CSIR. In particular, an AR solution for data presentation in the stope would mark a major breakthrough in implementing simple communication between a risk management system and an individual miner.

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8. Endnote

Contribution to the paper was not equally distributed: Declan Vogt and Van Zyl Brink were involved in the design and conceptualization of elements of the system; Stefan Brink undertook the validation of the ESD; Mathew Price implemented the thermal image stitching; and Benon Kagezi implemented the augmented reality system. The authors thank the Mine Health and Safety Council for funding part of this work, Driefontein mine for funding and making data available for publication and their co-workers on the AziSA team for providing the framework that made this research possible.