CAN A ROBOT IMPROVE MINE SAFETY?

Green JJ[1], Bosscha P[2], Candy L[3], Hlophe K[4], Coetzee S[5] and Brink S[6]

[1] Council for Scientific and Industrial Research (CSIR)
Centre for Mining Innovation (CMI)
P.O Box 91230
Auckland Park 2000
Johannesburg
South Africa
e-mail1: jgreen@csir.co.za
[2] Council for Scientific and Industrial Research (CSIR)
Materials Science and Manufacturing (MSM)
Mechatronics and Micro Manufacturing (MMM)
Pretoria
South Africa
e-mail2: pbosscha@csir.co.za
[3] Council for Scientific and Industrial Research (CSIR)
Mobile Intelligent Autonomous Systems (MIAS)
Pretoria
South Africa
e-mail3: LCandy@csir.co.za
[4] Council for Scientific and Industrial Research (CSIR)
Centre for Mining Innovation (CMI)
Johannesburg
South Africa
e-mail4: KHlophe@csir.co.za
[5] Council for Scientific and Industrial Research (CSIR)
Materials Science and Manufacturing (MSM)
Mechatronics and Micro Manufacturing (MMM)
Pretoria
South Africa
e-mail5: scoetzee@csir.co.za
[6] Council for scientific and Industrial Research (CSIR)
Centre for Mining Innovation (CMI)
Johannesburg
South Africa
e-mail6: SBrink@csir.co.za

ABSTRACT

Safety in mines is of paramount importance, especially in the labour intensive operations of South Africa, where upward of 300 000 people are employed on a daily basis in an environment that is inherently dangerous. On average approximately 50 people die annually in underground rock fall related incidents with an estimated economic cost of R800 million.

This paper explores the potential for deploying an autonomous robotic platform with specialised sensors to measure the roof integrity between blasting and human re-entry. The Platform will attempt to prevent the rockfall incidents by identifying the high risk areas. The CSIR has developed a hard hat mounted electronic sounding device to assist the miner in analysing the sound. It has also been shown that a temperature differential exists between stable and unstable areas.

A robotic platform will use a thermal imager to determine potentially loose areas, and then a modified sounding device will probe the hanging wall to delineate the high risk zones and indicate them on a map. The automation of this process removes any variance or ambiguity that is present with a human operator thereby providing consistent results.

Localisation is paramount to the success of this robotic application. The dynamic environment in the mine would make any pure SLAM (Simultaneous Localisation And Mapping) application extremely complex. A CSIR developed ultrasonic beacon system will be adapted to meet the need of a disposable low range localisation system. The localisation system will enable the roof integrity measurements to be geo-stamped and therefore superimposed on a map of the area.

A 3D map will be composed by the autonomous robot using a time of flight (TOF) camera fused with position and attitude data. The map will then be used for path planning and exploration planning to ensure that the entire area has been inspected, and a complete map is made available to the miners once they re-enter the mine after a blast, thereby enhancing mine productivity by pre-inspecting the stopes.

Keywords: Mining robot safety enhancement autonomous.

1 INTRODUCTION

Mining in South Africa employs 495 000 workers directly and a similar amount indirectly – providing daily subsistence for approximately 5 million South Africans. Safety in mines in South Africa is overseen by the Mine Health and Safety Council (MHSC)[1] and advised by the Safety In Mines Research Advisory Council (SIMRAC) [2].

In 2007, 76 miners lost their lives in rockfall related incidents, of which a large proportion could have been prevented through better entry examination and barring so that miners were not exposed to loose hanging walls while working.

Conventional drill and blast mining operations are cyclic. After each blast, the first people arriving in the blasted area (called in this paper the “barrers”) are required to test the hanging wall (roof) to determine if it is safe to enter [3]. The barrer enters an unsafe environment and assesses the roof integrity using a barring tool. The barring tool is similar to a crowbar, and roof integrity is determined by tapping or ‘sounding’ the roof with the barring tool. Unstable blocks of rock are then safely brought down (barred) if possible, or identified for additional support to hold them up, to prevent possible dangerous falls of ground. The barrer is under great time pressure as he is on the critical path for production. The longer he takes to make safe, the less time the rest of the mining team has for continuing the other mining operations as they may not enter the area until it has been declared safe to do so. This pressure forces a very critical job to be conducted in a rush. At a recent Southern African Institute of Mining and Metallurgy (SAIMM) conference on mine safety, several speakers stressed that poorly executed entry inspections were a major cause of accidents at the stope face (or working area). In general, most mining incidents resulting from a fall of ground occur within five metres of the stope face in the area that should have been made safe by the barrer. An improved entry inspection would decrease the likelihood of accidents and increase production efficiency, especially if the entry inspection can be undertaken off the production critical path.

This post-blasting inspection can be achieved through the development of an autonomous robot platform that can enter the unsafe area, withstand the hazardous conditions, and record data on the roof stability using CSIR-developed sensors. . This will occur during a period when it is unsafe for humans to occupy the mine after the blast, due both to the noxious fumes from the blast, and to the increased seismic activity. These data will then be displayed as a risk measure with suggested mitigating actions. As the robot is capable of entering the stope almost immediately after the blast, significantly earlier than the barrer would be able to, the risk map will be available when the mining team re-enters the stope after blasting. Potentially shaving hours off the mining cycle time. The harsh underground environment requires an extremely robust system, potentially with disposable beacons. As the mining face progresses, backfill fills mined out voids and destroys any beacons in that area.

The impact on production must be stressed. For example, in two shifts, during the course of one day, the workers must clean the blasted ore, place support, drill and charge blast holes and retreat at blasting time. Workers cannot remain in the mine during blasting due to the high seismic risk and the presence of poisonous explosive fumes. Blasting occurs at roughly the same time throughout the mine, typically between 4pm and 6pm. If a crew cannot complete preparing for the scheduled blast at their working stope face, then they will miss the blast and only blast the following day, losing a whole day's production. An indication of the lost blast rate is calculated as follows: blast holes are 1.1 m long, and there are usually 22 working days in a month, so face advance rates should be about 24 m per month. In fact, typical face advance rates reported by the mines are closer to 16 m per month, strongly suggesting up to six missed blasts a month, resulting in a blast rate of 66%.

Robotics in South Africa is a fledgling research area with little hope in competing with the larger international institutions and it is important that a niche application is found where South Africa can make a significant contribution. The narrow tabular hard rock mines of South African and the unique mining methods employed could provide that unique opportunity. Developing an autonomous safety platform for in stope entry inspections and other mine search and rescue operations would enable a significant robotic contribution as well as a significant contribution to the mining industry.

2 JUSTIFICATION

Determining why work is necessary and valuable is as important as actually doing the work. The following sections discuss the motivation and justification for this work.

2.1 Fatality statistics described

MHSC keeps record of mine accidents and has provided the following graphs to illustrate the annual trend, as well as a breakdown of the cause of mining fatalities. For this robotics application the focus is on the classification "Fall of Ground (FOG)". This is the term given to incidents that occur when the hanging wall (roof) collapses, and in so doing causes injury or fatality.

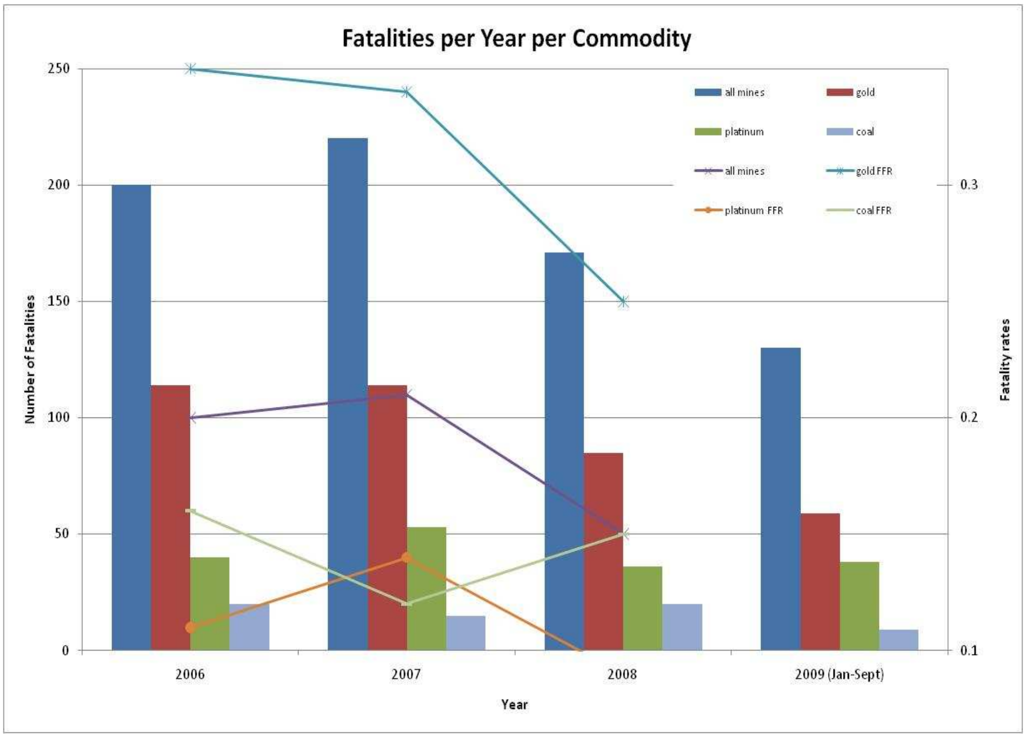

Figure 1. Annual fatalities in South African mines by type.

Figure 1 shows the annual mining fatalities as a declining trend, although the actual numbers are still significant [4].

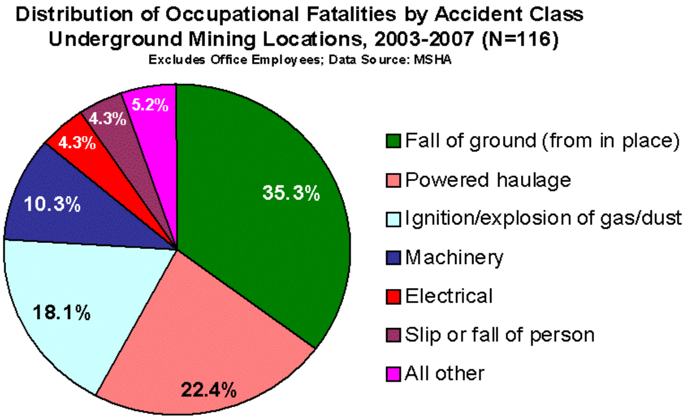

Figure 2. Accident class averaged 2003-2007.

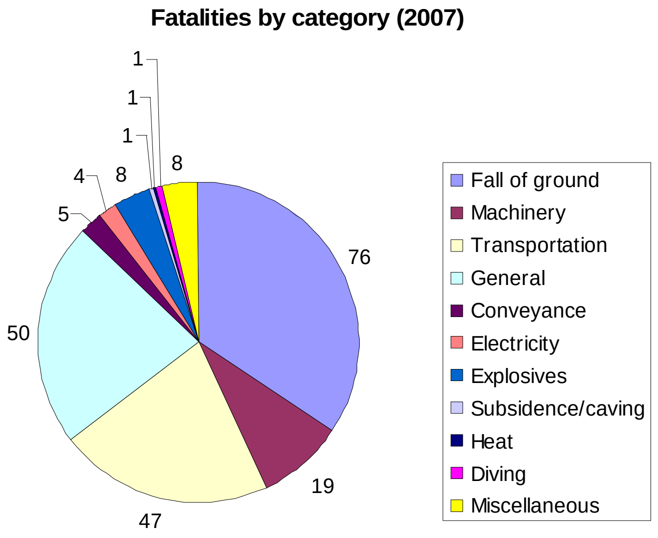

Figure 3. Accident by classification in 2007

Figure 3 shows 2007 figures and translates to a FOG contribution of 43%

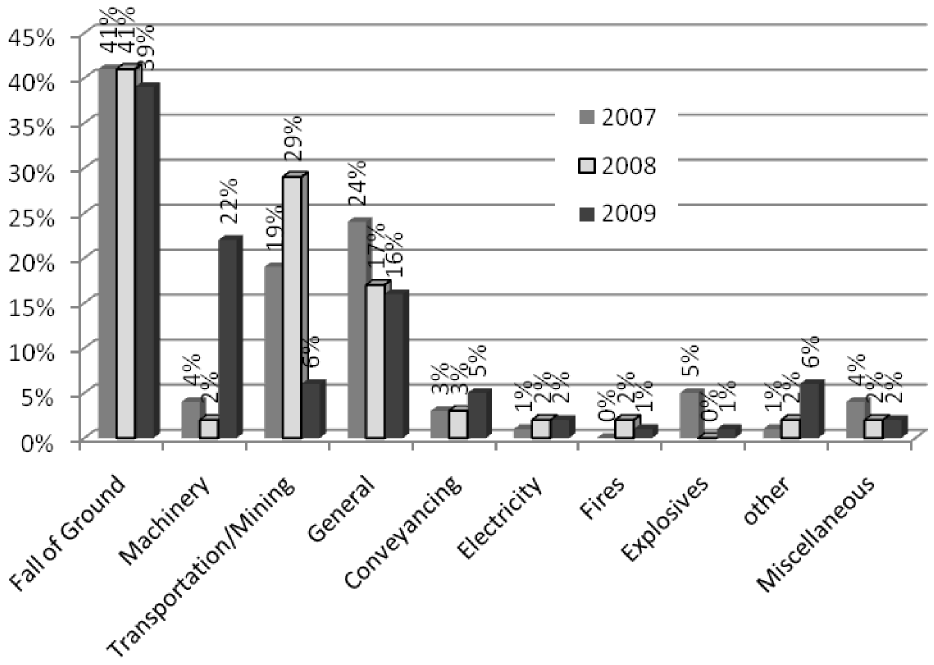

Figure 4. Accident classification 2007 to 2009

An analysis of Figure 2, Figure 3 and Figure 4 seems to indicate that the FOG contribution to fatalities is increasing. However, a common hypothesis is that the FOG incidents are simply a statistical event of being in the wrong place at the wrong time. It would therefore stand to reason that this should be a constant number, assuming constant mining rates and numbers. The increased contribution of FOG to the statistics is therefore due not to increasing numbers of FOG incidents, but rather a decrease in other forms of fatalities and incidents, where the increased focus on safety is showing dividends.

By avoiding placing any human under a high risk area it stands to reason that the overall rate of FOG incidents would decrease, even though the event count would inevitably remain the same, without miners exposed to the fall, there would be no harm. It is for this reason that the proposed autonomous safety inspection could make a significant impact to the fatality figures due to FOG.

2.2 The impact of a fatality

According to MHSC regulations [1], upon a fatality the mine must be closed down until the recovery of the deceased and the completion of an MHSC inspection. This period can often run to days of lost production, and the impact of this is a significant loss in revenue from suspended mining activities.

The time taken for a search and rescue operation to be completed could be dramatically reduced with the use of autonomous safety robots.

A significant issue that hampers the rescuers or searchers is the unknown environment that they must enter whilst executing their duties. The air quality is unknown, the hanging wall stability is unknown and in many cases with FOG incidents, the extent of the incident is also unknown. All these questions and uncertainties would be removed with the deployment of an autonomous system that could enter the high risk area and create a map of the physical environment, detailing the extent of fallen roof or collapsed walls, as well as detail of both air quality measured and the potential risk/safety of further hanging wall collapse. All this information is displayed on a map available to the rescuer prior to entering the incident area. It is also feasible to capture or stream video of the inaccessible area back to the rescuers, and an infrared imager could be used in the identification of injured miners requiring assistance. This has the result of reducing the closed time that the mine experiences while the rescue operation and the subsequent safety investigation are under way.

This would have assisted the rescuers at the recent West Virginia Coal mine disaster in the USA where 29 miners lost their lives. Although all 29 perished in the initial blast, there was a lot of time spent searching for them in the hope that a rescue was possible. A platform like this could have entered the fume filled area and sent images back to the rescuers. Rescuers were repeatedly [5][6] forced to pull back from the search area because of a continuing threat of a further methane gas explosion underground injuring the rescuers.

In 2009, Anglogold Ashanti (AGA) SA ops lost 166 shifts,with 98 of those due to Department of Mineral Resources (DMR) safety stoppages, and 68 shifts due to voluntary safety stoppages. During that period, there were 16 fatalities. At an average cost of R3 million/ shift in lost revenue this translates to half a Billion Rand in lost revenue for a single gold mining company.

2.3 Entry inspection (making safe)

The current method of entry inspection, or making safe, is on the critical path of the mining process. Human entry cannot take place until the inspection has been completed and the entry inspection cannot occur until conditions are safe for human access, in terms of both noxious fume ventilation and attainment of seismic stability. A robot however, need not wait for conditions to be right As it can operate in high risk conditions. The entry inspection can therefore be completed by the autonomous system before humans enter. The actions to rectify the identified potentially unsafe or high risk areas can then be implemented immediately upon human arrival. This process is estimated to save as much as an additional hour in the mining cycle. This would potentially increase the blasting percentage from the poor 67% of possible blast shifts where a blast actually takes place, by a significant amount, thereby increasing productivity.

In context, even a 1% increase in the gold output from a single mine has the potential to add millions of rand to the gross income of the mine.

[3][5] writes about the barman and his responsibility and the job being the most stressful and difficult in the mine and indicates that 8 minutes of work is possible before a recovery break is necessary. While the making safe per se will not be removed, the continuous checking for the entire roof stability will be replaced by the safety platform creating a map of the roof stability

measurements. Attempts to make this job easier have been made [7] but to date it has remained unchanged for decades.

3 MINE SAFETY PLATFORM

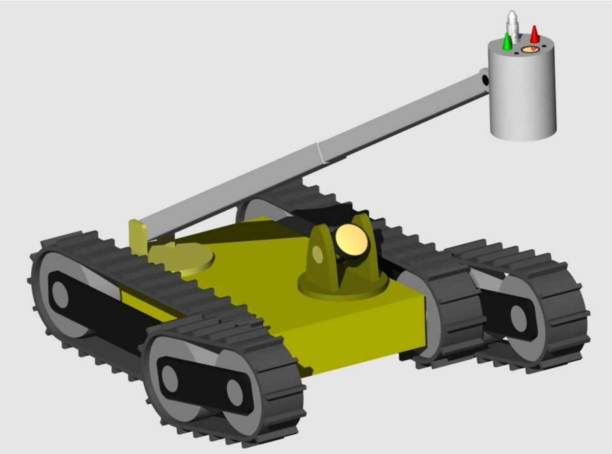

Figure 5. Artists impression of possible Mine Safety Platform.

There is a period of time when miners cannot enter the blasted areas for two reasons: a) The presence of noxious fumes and b) dust from the blast, and the increased seismic activity present after a blast. The following section discusses in more details the reasons for delayed miner access to a blasted mine area.

3.1 Noxious fumes and dust

The process of blasting in gold and platinum mines results in noxious fumes that are harmful to humans. These fumes are cleared from the mine using forced air ventilation. Dust produced in the blast is also harmful to humans, potentially causing respiratory diseases like silicosis. Therefore airborne dust must first settle, and then water (usually cooled) is used to control the dust. Typically this process takes between 30 minutes in some mechanised mines to as long as 4 hours in others, depending on the ventilation conditions and size of the blasted area and ore characteristics.

3.2 Seismicity

After a blast, typically at 5pm at shift change, after the day shift has exited the mine and before night shift enters, there is a significant increase in seismic activity (Figure 6). This implies that there is an increased likelihood of FOG events occurring. However, as the mine is void of personnel, there is no risk of injury.

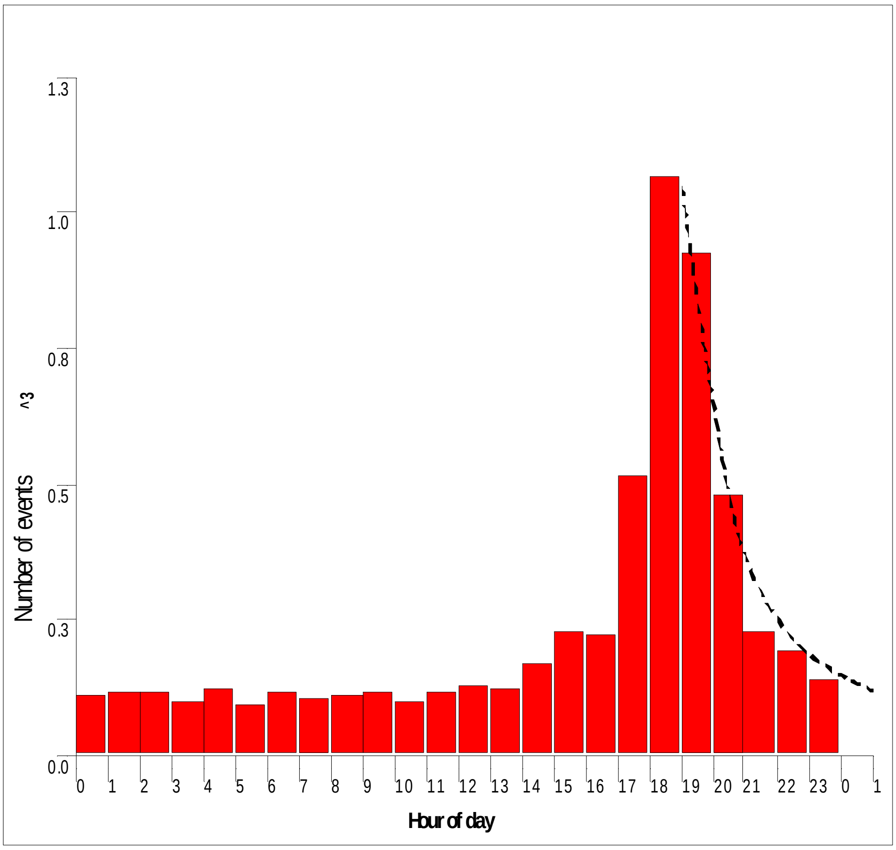

Figure 6. Seismicity count vs time indicating increased seismicity during and after the blast, from ***Error! Reference source not found.****.*

Figure 6 shows increased seismic activity from 5pm till 10 pm. The blast in this instance was scheduled for 6pm and it is fair to reason that the increased activity between 5 and 6 is due to some of the blasts going off slightly prior to 6pm and registering in the previous hour's data.

The FOG is generally a fatal incident if there is a human at that location. Intuitively, although undocumented, increased seismicity can be linked to an increased likelihood of a FOG. Therefore it is necessary to wait until the seismicity reduces back to background levels, typically 3 to 4 hours in deep level gold mines, before humans re-enter the mine.
The statistical likelihood of a person being at a FOG location is small even at the elevated rate immediately subsequent to a blast. But it is still too large a risk to expose miners to. A robot would also be in the risky position of being crushed by a FOG event, but the finical justification would substantiate the periodic replacement of damaged safety platforms in exchange for the accelerated availability of a risk map of the stop upon the miner entering the stope.

4 ROOF ANALYSIS

The time between the blast and access is used productively for more than simply venting the environment and waiting for the seismic stability to return to the environment. It is used to determine the local hanging wall risk and indicate areas where remedial action is required.

The roof analysis will be undertaken using two sensors in combination. A Thermal imager [9],[10] will be used to identify the general areas of potential instability by determining which areas are cooler than the surrounding host rock. Then an automated sounding device will be used to delineate the borders of the unstable/ high risk areas.

4.1 Thermal imager.

The thermal imager identifies the temperature of the rock in the field of view. As the host rock in a mine, particularly a deep gold mine, is hot, a cooler rock area will indicate a potentially unsafe or unstable area. This occurs as shown in Figure 7, where cooling by the ventilation air has resulted in a cooler rock area where the rock has begun to separate from the host material. A crack or dislocation some way into the hanging wall will disrupt the heat flow to the rock area, thus resulting in the ventilation air cooling that rock area more than the surrounding areas.

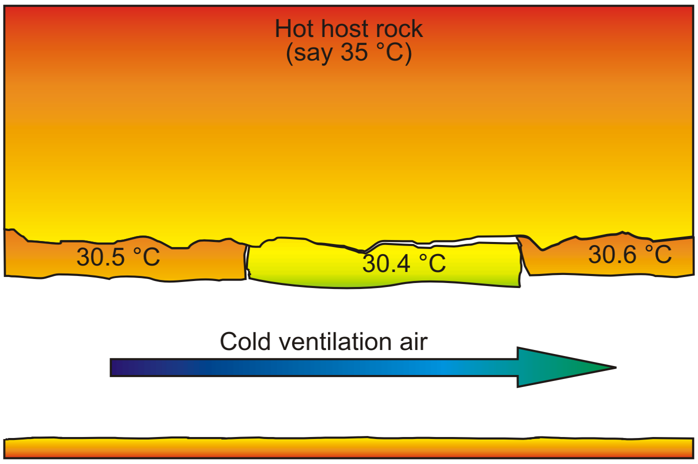

Figure 7. Loose hanging wall is preferentially cooled.

Figure 8 shows a thermal image of an unstable section of rock and shows the temperature difference between the warmer host rock at 31 degrees and the cooled unstable section at 30.5 degrees. Figure 9 is the corresponding area of rock taken with a standard camera and Figure 10 is the thermal images superimposed on the standard image.

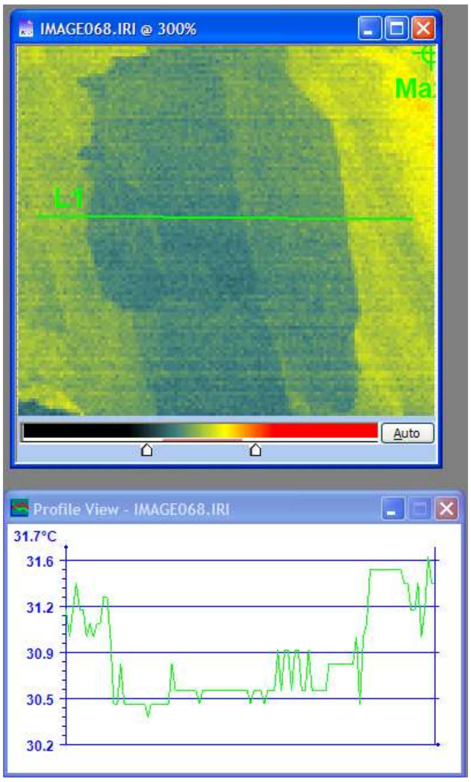

Figure 8. Temperature profile of loose rock

Figure 9. 'Normal' picture of loose rock.

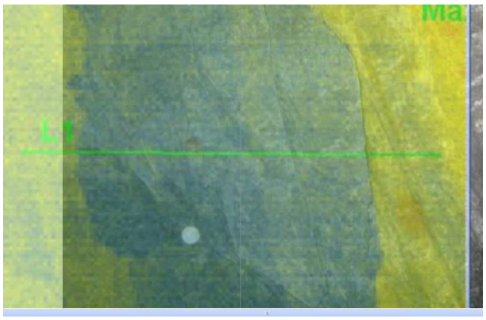

Figure 10. Registered thermal and visible range images

Other work has shown the potential of this technique [11].

4.2 Electronic Sounding Device

The electronic sounding device (ESD) [12][13] has been shown to work in a hard hat mounted deployment. A miner taps the hanging wall with a barring tool and the ESD evaluates the resulting sound frequency response to determine the potential that the rock-mass is stable or unstable. This removes the variability of the human interpretation and the device gives one of three audible outputs, stable, unstable or undeterminable, in which case another reading is necessary. A modified ESD will evaluate the sound generated when a mechanically operated impact is used instead of a human controlled one. The output of the ESD will then not be an audible response but one that is recorded electronically and superimposed onto a map as discussed in Section 6.

5 MECHANICAL PLATFORM

Localisation for the autonomous platform will be done using an ultrasonic time of flight based beacon system [15] that will provide the exact position of the safety data collected, enabling a safety map to be constructed of the collected data.

Some work has been done in abandoned mine entry and mapping – groundhog and cave crawler [16] are but two such platforms that have been developed. University of Kwazulu Natal has developed a search and rescue robot with air analysis sensors on it, in conjunction with the fire department [17]. Military robots are currently commercially available to an elite group of people, but they come at a price in excess of R1 million. For a South African deployment in a mining environment, where the life span of a robot will potentially be measured in months not years, it is not feasible to start with a base platform of that cost. A simpler, more cost effective prototype will be developed, that takes cognisance of, but does not necessarily meet, the requirements of being intrinsically safe, and is built specifically for the environment found in the hard rock mines of South Africa. The environment has a 1 metre maximum height, very unstable and irregular sloping floor - between flat and 30 degrees, high temperatures and humidity, and no ambient light. The platform must monitor the high temperatures, humidity, dust levels and noxious gasses - ammonia dioxide, carbon dioxide, and methane.

The platform also has to be able to move in this hostile environment. All over the world researchers have been working on robots that can follow man anywhere and more. Locomotion is a widely researched area [18],[19],[20] and numerous systems exist that can overcome difficult terrain. Underground, the terrain calls for a solution that can traverse muddy sludge covered loose rocks and not get stuck. Thus, various systems need investigation to select the optimal mobile platform.

Two main areas in mobility exist, i.e. rolling contact surface [21] (tracks and wheels), and bio-mimicry [22] (legged motion). Both of these methods have their shortcomings, like mud and rocks that get in between tracks, and will be investigated in detail to select the top performing methods. A third category will be designed to incorporate a hybrid of the two methods. Wheeled platforms have speed, agility and are easy to control. Legged platforms still need a lot of research and are too complex to control remotely. When the two methods are combined [23] the result is a very agile platform. The chosen locomotion methods will be built and tested on a simulated mine slope above ground before it is taken underground.

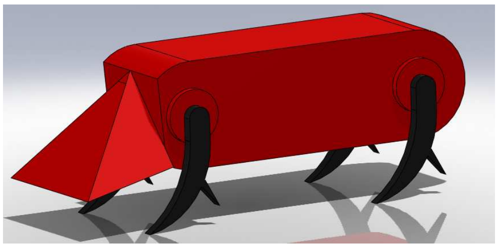

Figure 11: First rendering of platform with hybrid locomotion and shovel front.

The robotic platform is deployed right after a blast to map the area. The slope is then covered in rubble and the once 1m high roof is now only 0.6m high. The platform therefore needs other methods of getting to its location. This is where the novelty of the South African platform comes in. Most platforms are only designed to get over obstacles. This platform needs the capability to move rocks out of its path if no other path exists. Shovels and plough-like equipment will be added to aid in movement. Advanced fuzzy control algorithms are needed to aid in path planning and rock traversing.

6 OUTPUT

Figure 12 shows the combination of the geo-referenced thermal pictures and the Electronic Sounding Device information, which are used to create a roof stability map for the following shift. Similar in concept to a weather map, it provides information about the potentially risky areas for the upcoming shift. The high risk areas can then be attended to and remedial action taken to ensure that the area is made safe, either by barring down the loose rock, i.e. making it fall in a controlled safe manner, or supporting the rock with temporary or permanent support structures.

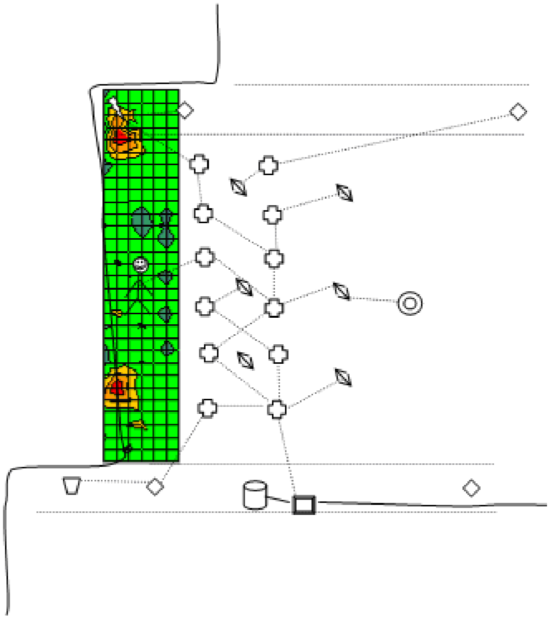

Figure 12. basic proposed risk map of a stope.

There exists the potential for other sensors to be mounted on the platform as well. Air quality monitoring – methane, carbon monoxide, carbon dioxide, ammonia would be beneficial. This could be used in monitoring the in-stope conditions to determine when safe miner re-entry is potentially possible. Combining this with real time seismic monitoring could feasibly reduce, or at least optimise, the re-entry time for each panel of each stope of each mine as opposed to instituting a wait period for the worst affected areas in the mine. For unstable or poorly ventilated areas the re-entry will be delayed until safe, and for those that are seismically stable and quickly ventilated the re-entry will be accelerated. This would create the potential for additional time for the other mining activities of clearing, marking, drilling and charging, thereby potentially increasing the blast ratio of the mine. The blast ratio is a ratio of the potential number of blasts that can occur versus the number of blasts that actually occur. Any delay in the cyclic process of mining results in a delayed or missed blast. Typically this ratio can vary from 50% to 70% and rarely gets above 90%.

It is apparent that the application of this platform and the air quality monitoring is immediately applicable in a mine search and rescue scenario. The robot will be deployed ahead of the rescue team and will be able to create a map of the air quality as well as the roof stability which will allow for rapid access along safe passageways in the uncertain area and will identify the dangerous or risky areas that are to be avoided, as was mentioned previously in relation to the mining disaster in Virginia USA in April 2010.

7 CONCLUSION

Lives can be saved by pre-inspection of the stopes and identifying the potentially unsafe areas timeously, consistently and reliably. Data indicates potentially 50 lives can be saved per annum with an economic cost of approximately 500 million in lost revenue.

The impact of saving lives is not only the obvious life saved, but also the avoidance of the impact of that fatal incident. Shifts will no longer be lost in safety investigations at a cost of approximately R3 million per shift.
The additional productivity as a result of taking the entry inspection partially off the critical path is significant. A 1% improvement in the blast ratio translates to a 1% improvement in the amount of ore processed and commensurate increase in the bottom line of the mine.

The transfer of this technology into search and rescue scenarios is possible where incidents do occur – potentially resulting in rescuers getting to injured or trapped miners quickly enough to impact the outcome of the tragedy and potentially save further lives.

8 ACKNOWLEDGEMENTS

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