Mine safety sensors: Test results in a simulated test stope

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***Abstract*—The South African mining industry is plagued by accidents, the most common of which are rock falls. In order to carry out its mandate of improving the quality of life of South African citizens, the Council for Scientific and Industrial Research (CSIR) is undertaking research into how these accidents can be mitigated. One such method is the use of sensor equipped robotic platforms. The CSIR's mine safety platform is a robotic system for inspecting the working area of hard-rock mines to determine areas of rock fall risk. The mine safety platform uses two sensors to locate unstable areas of the hanging-wall, the 3D-thermal sensor and the wall stability assessor. The robot and its safety sensors have been tested in the CSIR's re-configurable stope test facility that enables the testing of mine equipment and machinery in a variety of simulated mine environments without the arduous and costly trips underground to various locations to encounter the various scenarios that the equipment needs to deal with.**

***Index Terms*—safety, thermal imaging, acoustic sensing, mining, robot, simulated stope**

I. Introduction

The CSIR has developed a robot platform to assist with the dangerous job of mine entry inspections. The conventional method of mining in hard-rock mines (gold and platinum) involves a continuous cycle of drill, blast and clean processes. The process starts with the drilling of holes in the mining face, these holes are then filled with explosives and the whole mine is cleared of personnel. Once the mine is cleared the explosives are detonated, which induces seismic activity and releases toxic fumes. After approximately four hours [1], when seismicity has settled and the work area has been ventilated, the fragmented rock is cleared and the stope is ready for the re-entry inspection, or making safe process. The making safe process involves tapping the hanging-wall (roof) with a metal bar, known as a pinch bar, and based on the resulting sound; the inspector can determine if the rock is stable or at risk of separating. If the area is determined to be at risk, then there are a number or potential actions. The entry team can attempt to make the loose rock fall, a process called 'barring down with the pinch bar', which is arduous and dangerous work. They can support the area with temporary or permanent supports, or mark the area as dangerous and no further work may occur there.

Previous studies have identified a correlation between loose rock and its relative surface temperature. Kononov [2] showed that a non-contact temperature measurement sensor can be used for loose rock detection, particularly in newly mined areas. Further work by Kononov [3] confirmed that infrared thermography can be used to detect loose rocks for a few days after a blast provided the ventilation is stable. Oldroyd [4] continued the work of Konnonov under the assumption that the visibility of loose areas may be improved by using a thermal-imaging camera, in contrast to the infrared thermometer used by Konnonov. Oldroyd showed that loose rocks and cracks can be seen in thermal images of the hanging wall. Vogt et. al. [5] discuss the limitation of the field of view of a thermal camera for identifying the entire extent of a loose rock in a narrow mine stope. Due to the field of view limitations of even wide-angle thermal cameras it is necessary to stitch together multiple image to get a full view of many of the larger loose rocks.

The identification of loose rocks using temperature differences relies on the fact that an underlying crack behind a block of rock interrupts the heat flow from the host rock causing preferential cooling in a localised area. This effect can be detected by long-wave infrared (thermal imaging) cameras and used to identify areas that are potentially unsafe. Local areas that protrude into the mine's ventilation air-flow will also be preferentially cooled therefore, in our system, a thermal imaging camera is combined with a 3D imager to enable the decision regarding the stability of a block to be made using a combination of the structure and thermal gradient.

The 3D-thermal (3DT) scanner will quickly scan fairly large areas of the stope (the working area in an underground mine) and identify areas of potential danger. The robot will then use a device called the wall stability assessor (WSA), attached to a robotic arm, to confirm if a section of rock is unstable. The WSA is an acoustic sensor that mimics the performance of an experienced miner in determining the stability of rocks in a mine hanging-wall. The WSA consists of; a solenoid for applying an impact to the hanging-wall, four proximity sensors to ensure the impact is from a consistent distance and an electronic sounding device (ESD) to analyse the sound produced by the impact. The ESD records the sound produced by the impact and analyses it using a trained neural network model. This process is similar to the manual method of entry inspection currently used, where a miner strikes the roof with a pinch bar and listens to the sound to determine whether he thinks a rock is safe or not.

The robot and the sensors need to be tested, however, the logistics and harsh underground conditions mean that it is not feasible to test the robot and sensor systems underground. To address the challenges of testing underground and to allow better control of the environment, a simulated test stope has been built.

The simulated test stope will be described in the following section. This will be followed, in Section III by a description of the 3DT scanner and then in Section IV the details of the WSA will be provided. The robotic mine safety platform (MSP) will be detailed in Section V followed by a discussion of the results of the tests performed in the test stope.

II. The Simulated Test Stope

The simulated test stope (STS) extracts the essential characteristics of the mine environment necessary for testing of the MSP and its entry inspection sensors. The STS also offers a safe environment that is readily available for use by researchers that may want to test other systems. The STS was required to have an adjustable dip angle of between 0° and approximately 30° to allow the STS to simulate various gold and platinum reefs. The most economically important gold reefs dip at between 20° and 25° and platinum deposits are generally flatter [6, 7]. It was desired that the foot-wall (floor) material be interchangeable to allow the testing of the robot platform on different surfaces. The height of the hanging-wall needed to be adjustable between 0.75 m and 1.5 m to simulate the typical stoping heights in South African gold mines. The STS also required an area with a simulated unstable rock that would provide an acoustic and thermal difference for testing the WSA and 3DT sensors.

The STS comprises seven main components, as shown in Fig. 1, these are; the foot wall, the lifting cylinders, safety supports, hinge mechanism, the locking mechanism and the wooden hanging-wall supports. The final structure included a simulated stope face in addition to the parts shown in the concept. The simulated stope face can be seen on the right of the stope in Fig. 2.

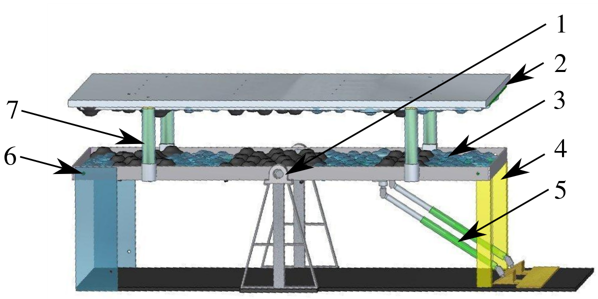

Fig. 1. A model showing the components of the simulated test stope: 1) hinge mechanism, 2) hanging-wall, 3) foot-wall, 4) safety supports, 5) tilting cylinders, 6) locking system and 7) hanging-wall supports

The hydraulic tilting cylinders enable the stope to be tilted from zero to 28°. The locking system then allows the stope to be locked in place at predetermined angles of 0°, 8°, 12°, 20° and 28°. Fig. 2 shows the stope locked into its steepest angle of 28° with the robot being driven in it.

Fig. 2. The MSP robot navigating the stope at a 28° angle

The foot-wall has a 6 $m \times 3$ m frame with a grating bolted on the frame. Simulated rocks are secured through the gaps in the grating and small loose rocks fill in the gaps between the larger secured rocks. Larger or smaller rocks can be secured through the grating to evaluate the robot's traction in different scenarios. The sides of the foot-wall are surrounded by a number of simulated mine support packs. The simulated packs provide a reference boundary to prevent the robot from attempting to navigate out of the stope.

The wooden hanging-wall supports are similar to the support poles that would be found in an operating hard-rock mine stope. The height of the hanging-wall can be changed manually by changing the length of the hanging-wall supports and the simulated face. The stope height of the STS is currently set at 1 m.

The hanging-wall consists of seven light-weight segments and one granite test block. The test block is a 1 $m \times 1$ $m \times$ 20 mm granite block with a 300 $mm \times$ 300 mm cut out. The bulk of the block simulates intact rock mass and a block mounted in the cut out simulates the loose rock mass. The off-cut from the 300 $mm \times 300$ mm cut out is mounted on a 400 $mm \times 400$ mm granite block and fit through the cut-out section, as shown in cross-section in Fig. 3. The simulated loose rock is not in good thermal contact with the bulk of the granite block so it can simulate a temperature difference similar to what is expected underground due to a fracture. Additionally the mass difference, between the cut-out and main block, means that the loose rock has a different acoustic response to the WSA impact.

III. The 3D-Thermal Scanner

The 3DT scanner uses temperature differences on the rock surface to identify loose rocks in deep hard-rock mines. The virgin rock temperature in a deep, South African mine is too high to allow miners to work safely, so the stope has to be cooled [8]. The cooling air travels past the hot rock and creates a constant heat flux from the rock to the air. If the heat transfer is interrupted by a crack, as shown in Fig. 4, the heat

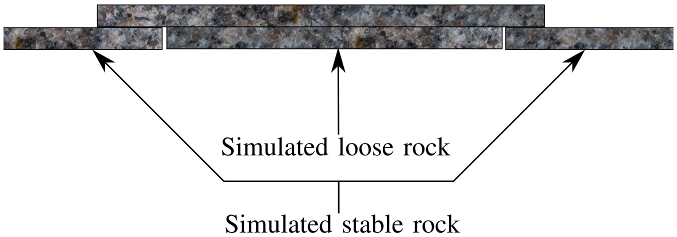

Fig. 3. A cross-section through the STS's simulated unstable rock

into that rock mass will be reduced by the crack while the convective cooling from the air remains constant. This creates a preferentially cooled area that can be searched for using thermal imagery [3].

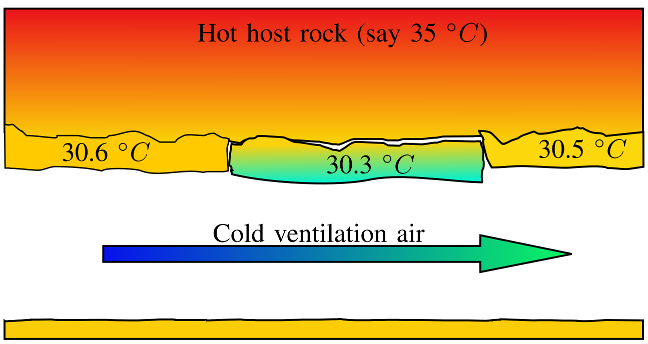

Fig. 4. Heat flow interrupted by crack causes a loose block of rock to be colder than the surrounding rock. After [5]

The nature of forced convective heat flow dictates that a rock mass sticking into the air flow will also experience preferential cooling. It is therefore important to not only measure the rock temperature but also its profile. For this the 3DT includes a structured-light 3D sensor in addition to the thermal camera.

The 3DT consists of a thermal camera, a structured-light 3D sensor and a pan-tilt unit, as shown in Fig. 5. The 3DT performs a scan at the same time as the robot stops and does a laser scan to plan the next part of its path. The pan-tilt unit rotates the sensor head through $\pm 158^\circ$ and then tilts the sensor up and performs another pan. This process is repeated multiple times until the 3DT has scanned a hemispherical volume above it. The scanner can image a hemisphere above it of up to 10 m in diameter (dependent on the hanging-wall profile and obstructions such as packs, supports etc.). The computer on-board the robot processes the thermal and 3D data to produce a thermally textured 3D model of the stope.

The 3DT uses the thermally textured 3D model, like the one shown in Fig. 7, to identify areas of unstable rock. The algorithm is based on the broad objective of locating changes in temperature that correspond to non-protruding (i.e. flat) surfaces. We know that protruding areas are likely to be colder due to their increase surface area in contact with the ventilation but we are trying to locate areas that are colder due to a fracture. To do this we compute: (1) a measure of flatness within a fixed radius, and (2) the coefficient of variation of temperature (CVT) within the same neighbourhood. The flatness and the CVT are weighted and combined to produce a measure of risk. Areas of low point density are discarded since they correspond to a locally incomplete map.

Fig. 5. The un-mounted 3D-thermal scanner

IV. The Wall Stability Assessor

The WSA works by mimicking the manual process of 'sounding' the hanging-wall with a pinch bar. The WSA comprises a solenoid to create a sound by applying an impact force to the hanging-wall, four proximity sensors, a gimbal system, a microphone and a processor to analyse the sound. The gimbal and proximity sensors ensure that the hanging-wall is always tapped vertically from the same distance, to produce a consistent impact. The processor captures the sound generated when the hanging-wall is tapped with the solenoid and analyses it through the use of an expert trained neural network to determine stability.

The WSA will be mounted on the end of a robot arm on top of the MSP. Once the 3DT has produced a risk map of the hanging-wall near the robot the arm will extend and use the WSA to verify the areas of the scan that are indicated as high risk. The results reported by the WSA will be saved with 3DT based risk map for display to the miners.

V. The Mine Safety Platform

There is a period of approximately four hours after a blast during which miners cannot return to the face. The MSP makes productive use of this time between blast and entry to perform its entry inspection. The robot will enter the stope, autonomously navigate it and build a rock-fall risk map as it proceeds. The MSP is being developed by three units at the CSIR; the Centre for Mining Innovation (CMI), the Mechatronics and Micro-Manufacturing (MMM) group and the Mobile Intelligent Autonomous Systems (MIAS) group.

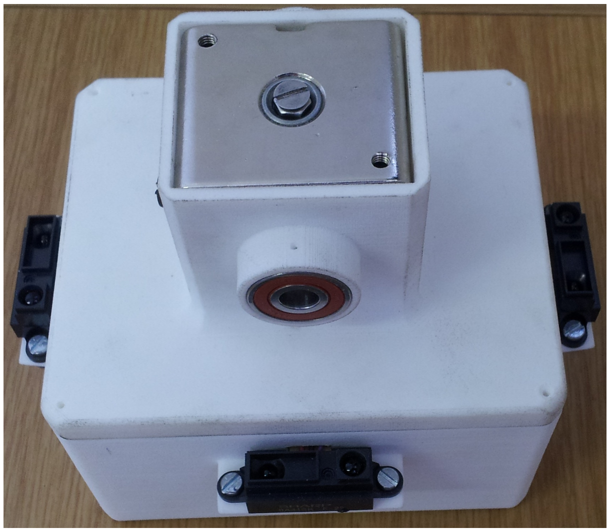

Fig. 6. The wall stability assessor

The CMI is developing the ‘eyes’ of the robot; the hanging-wall inspection sensors and an underground localisation system. MMM is responsible for the ‘body’ of the robot, the actual mechanical platform. Lastly MIAS is developing the ‘brains’ of the robot, the algorithms for autonomous exploration and mapping of the stope.

The MSP is a robust track driven vehicle designed to be modular and easily repaired. The robot is driven by two wide tracks with a small gap between them to prevent beaching. In addition to the main drive tracks the robot also has two flipper arms that can assist in navigating over obstacles by lifting the front of the robot. Further details about the design of the robot platform can be found in the paper by Coetzee et al. [9].

The robot will make use of the WSA and 3DT sensors to scan the hanging-wall and identify risk areas using the method described above. In addition to the rock-fall risk sensors the robot will be equipped with further sensors to enable it to navigate and map the stope autonomously. The robot will be equipped with an ultrasonic localisation system. The localisation system will use a number of ultrasonic receivers placed around the stope and a transmitter on the robot. The localisation system uses ultrasonic time-of-flight to determine the distance to all of the beacons and thereby determine the position of the robot.

Currently only the traction capabilities of the robot platform have been evaluated, further testing will be performed in the STS once all of the sensors have been integrated onto the platform.

VI. Results

A. 3DT

The 3DT scanner was tested in the STS. The simulated loose rock can be easily identified as the cooler blue spots on the flat hanging-wall test area. The loose area is quite evident in Fig. 7 however the unstable rock identification algorithm was not tested because the algorithm requires user defined weightings. While the weightings could be adjusted so the risk algorithm identifies the simulated loose rock the single unstable area does not help evaluate the algorithm.

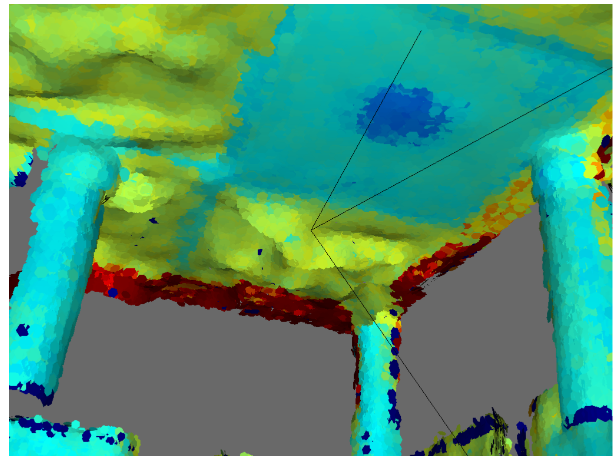

Fig. 7. Thermally textured 3D model of the STS showing the colder (blue) region corresponding to the simulated loose area

The test did show that the 3D-thermal scan was stitched together to produce a model that is accurate enough to still be able to identify the very small temperature difference that is characteristic of our simulated loose rock. This is an important result because the small temperature differences can easily be obscured by bad alignment of 3D-thermal images.

B. WSA

The WSA was originally tested with the microphone mounted on the end-effector shown in Fig. 6. These tests however were unsatisfactory producing frequency spectra for the safe and unsafe sections of rock that were indistinguishable. The poor performance is believed to be due to vibration from the impact being transferred through the enclosure to the microphone. The microphone for the WSA was moved so that it is separated from the impactor and will now be mounted on the robot at the base of the arm.

The results with the repositioned microphone were significantly better. The STS dataset consists of 578 samples of the acoustic response of the rock to the WSA’s impact. The dataset is divided approximately equally between samples of the simulated safe rock and those of the simulated unsafe area. The classifier was tested using ten-fold cross validation and its sensitivity, specificity and accuracy were evaluated. The sensitivity (S_n) is the proportion of the ‘safe’ samples in the training set that the classifier correctly identifies as safe, i.e.

$$S_n = \frac{N_{TP}}{N_P} \tag{1}$$

where N_{TP} is the number of samples correctly classified as safe and N_P is the total number of samples from the safe area in the dataset.

The specificity (S_p) indicates the ability of the classifier to correctly identify unsafe areas as such

$$S_p = \frac{N_{TN}}{N_N} \quad (2)$$

where N_{TN} is the number of correctly classified unsafe samples and N_N is the number of samples from the unsafe area.

The accuracy (A) is simply the fraction of images correctly classified

$$A = \frac{N_{TN} + N_{TP}}{N_N + N_P} \ . \quad (3)$$

A summary of the classifier test results is shown in Table I.

TABLE I
SUMMARY OF THE WSA CLASSIFIER'S ACCURACY

Sensitivity	**Specificity**	**Accuracy**
89.3%	86.5%	87.9%

The specificity of the classier is important because ensuring that unsafe areas are correctly identified is essential. Considering that the result of the WSA will be combined with the 3DT scan a specificity of 87% is good. The ESD has been previously tested in-mine using a standard pinch bar to create the impact [5]. The WSA tests in the simulated stope showed simlar or better classification accuracy than the ESD results. This shows that the test stope's simulated loose rock provides a useful test area for demonstrating the operation of the WSA.

C. MSP

The traction capabilities of the MSP were evaluated in the STS. The MSP performed well being able to traverse the stope even at its steepest angle of 28°, as shown in Fig. 2. In addition to simply evaluating the MSP's ability to traverse the steep slope, a number of traction compounds were tested.

The MSP robot has multiple rubber and plastic protrusion to improve the traction of the tracks. Soft rubber compounds provide good traction but wear quickly and are susceptible to damage, the harder compounds provide worse traction but are more robust. The three compounds tested were; a soft rubber, a hard rubber and a hard plastic. The results of the test on the compounds are shown in Table II, these results have led to the modification of the tracks to use a combination of the hard rubber and plastic.

TABLE II
RESULTS OF TRACK TRACTION TESTS

Compound	**Traction**	**Result**
Soft rubber	Good	Compound is too soft
Hard rubber	Fair	Fairly good traction and moderate wear resistance
Hard plastic	Low on smooth surfaces	Little traction on smooth surfaces but provides traction on uneven rocks

VII. CONCLUSION

The CSIR's robotic mine safety platform is a system for inspecting the working area of hard-rock mines to identify areas of rock fall risk. The mine safety platform uses a number of sensors, including two sensors to locate unstable areas of the hanging-wall, the 3D-thermal scanner and the wall stability assessor. The CMI has built a reconfigureable test stope to simplify the process of testing the robot and its sensors without the difficulty, expense and risk of taking the robot and sensors underground.

The robot and its hanging-wall inspection sensors were tested in the simulated test stope. The 3DT produced a thermally textured 3D model of the STS hanging-wall with a clear indication of the simulated loose rock. The loose rock identification algorithm for the 3DT was not tested. The WSA was tested and performed well on the simulated test area with a classification accuracy of 88%. The testing of the MSP platform was successful indicating that the robot can navigate a stope at an incline of 28° and indicating the optimal traction compound for the tracks.

VIII. FUTURE WORK

The STS will be used for future tests of the integrated robot. The platform and the sensors have been shown to work individually and can now feed into the integrated robot system. The platform is capable of navigating in the stope under the worst incline condition so now the autonomous path planning and navigation algorithms can be added (they have been implemented on a different robot platform). The hanging-wall inspection sensors are ready to be integrated with the robot localisation and mapping capabilities to enable the production of a global hanging-wall risk map.

Additional work is planned for the stope hanging-wall, the light-weight sections are going to be replaced with more robust ones and the whole hanging-wall structure will be placed on jacks so it can be raised or lowered to simulate different stoping heights.

Future work will likely include the replacement of one of the simulated face panels with a section of rock to test alternative rock breaking technologies.

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