

Novel Sensors for Underground Robotics.

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Abstract—The end state of an autonomous system in South Africa’s deep mines is a “fait accompli”. The current unacceptable safety records, and the increasing dangers as the mines get deeper, necessitate the removal of miners from the dangerous stope areas. Robotics seems an obvious solution. An autonomous robotic system to inspect the mine ceiling (hanging wall) is being developed at the Center for Mining Innovation as an initial robotic application for South African deep gold mines. A number of the key technologies needed to enable this are discussed. The localization system, the underground alternative to the GPS, is perhaps the single biggest hurdle needed in enabling underground robotics. A low cost, disposable solution for the small area gold stope (30m x 3m) is presented. Machine sensing of both the environment and of humans is critical in a shared working environment. Here we discuss alternatives to the current sensors used above ground for machine perception. In the deep gold mines the geothermal heat result in hot walls and thermal imaging becomes an option for structural imaging. The combination of temperature with a 3D data enables the determination of a risk measure, indicating potential danger areas. Potential methods of representing the risk data for the miner to interpret are discussed. Finally, the thermal camera in conjunction with a distance sensor is used to identify and track pedestrians in order to predict potential collisions.

I. INTRODUCTION

Underground robotics is enjoying a renaissance of sorts. The focus from the turn of the century on load haul dump trucks (LHD) [1] [2] being tele-operated and progressing to wall following [3, 4] has been superseded by a focus on the opportunities for mine search and rescue [5] and the reconnaissance opportunities, without forgetting the mine mapping opportunities[6], [7] that are still being pursued. In the past, the state of the art deployed technology in underground mining has been in wall following for tramming activities by the Sandvik Automine system [8] and more

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recently the Atlas Copco equivalent [9]. The most popular implementation of technology has been in remote controlled applications underground, allowing for safer operators, which has had the expected positive effect on safety statistics. The delayed adoption by the underground mining community of more advanced robotic technologies may, in part, be due to the fact that there are limited off the shelf components suitable for underground use, which would enable a machine to operate autonomously.

With very limited implementation and a large degree of resistance to adoption. Even exiting implementations are not being expanded. South Africa’s’ Finch mine is not moving their autonomous haulage system from the current level 5 installation to the deeper level 6 expansion. This is in spite of all proven and known benefits of such a system. These include continuous operation with hot seat change over, longer machine life and lower machine running costs. An understanding of this resistance will assist in achieving more success in the future.

This paper addresses some of the challenges of underground sensing and discusses the sensors needed for underground autonomous behavior. The sensors that enable an underground system to sense its environment are significantly different from those that are used above ground. Thus, new novel sensors are required to enable autonomous behavior underground.

This paper explores the work completed at the Center for Mining Innovation in addressing the needs of underground sensors for autonomous behavior.

The work covered in this paper has targeted a very specific working environment in South African mining, namely, the stope of a conventionally mined gold mine. The first robot deployment in the gold stope will be one to improve safety as discussed in [10].

The remainder of this paper is structured as follows:

Section II explores the target application for the autonomous mine safety platform in a gold mine stope. It explores the working environment and the unique challenges that it poses. Section III discusses the current sensor limitations and explores three new sensor applications for underground autonomy, namely localization, perception and human robot interaction (HRI).

Section IV explains the data gathered for enhancing mine safety in automating the making safe process. Finally, sections V and VI close out the paper with a discussion on the autonomous machine and conclusions.

II. THE APPLICATION IN THE GOLD STOPE

The implementation of a robot in gold mines is to enhance the mines safety by reducing rock fall risk as expanded on by Vogt[11] and Green[10]. After a blast the miners may not enter the area until the noxious fumes have been ventilated and the seismicity has reduced to background levels. The robot will traverse the stope during this time, inspecting the hanging wall with a thermal camera to identify potentially unsafe areas and confirming the classification with a robotic arm and tapper discussed in section IV. The output of the inspection will be a risk map akin to a weather map, indicating the expected conditions for the coming shift, indicating which areas would be more susceptible to rock fall risk.

The South African gold mines are facing ever increasing challenges[12]. As the mines go deeper the dangers and cost increase with each meter. The gold deposits are in narrow bands, called a reef, with an average thickness of 30cm. The mines however need to extract 1m of ore to enable miners to enter the mining area. The extra mined barren rock dilutes the gold grade, also diluting profit for every meter mined.

The gold reef dips at 18 to 22 degrees and is accessed by way of a series of tunnels. Km's of vertical shaft deliver the miner to the correct depth, then km's of horizontal tunnels bring the miner to the reef intersection. Typically, as the rock is extracted, waste rock is pumped back into the mined out areas to support the closing roof (hanging wall), as well as direct ventilation to the mining area. This results in a mining area that is 30m long, 1m high and expands from 2m wide before the blast to approximately 3m wide after the blast. This is the most dangerous part of the mine from a rock fall perspective, and approximately 35 miners perish in this environment every year in rock fall incidents. This is the environment that the robot will work in.

III. SENSORS

Robots in general need to know where they are and what the world looks like. Typically, outdoor robotics rely on a GPS signal to determine location, and then a variety of other sensors to sense the immediate environment. This information is then used to make the planning and control decisions. The most popular of these sensors are GPS for localization and visible spectrum cameras and laser scanners for perception. Simultaneous Localization and Mapping (SLAM) [13] as well as structure from motion [14] is focused on removing the reliance upon a global localization system (GPS in most cases) to give the platform its position. Underground mining robotics has a number of applications where autonomy will result in both a more productive and a safer working environment [15]. However, there are not yet the sensors available for underground implementation.

For obvious reasons, a GPS will not work underground [7], and standard cameras will suffer in the lightless environment, while also suffering from flaring when a light is directed at

the camera. Laser scanners are the obvious best choice and have been deployed underground for more than a decade. There is the need for some novel sensors to make underground autonomy feasible [16].

A. Localization

Hlophe [17-19] has built on Ferreira's work [20] to create a low cost, wireless, disposable GPS type beacon that will create accurate enough localization information in the gold stope, similar to the WASP system from CSIRO[21], and the cricket from MIT[22]. The premise is that a difference in time of flight principle between radio frequency (RF) and ultrasonic pulses gives a distance from receiver to transmitter. Hlophe used Triangulation data fused with inertial measurement unit (IMU) data through an unscented Kalman Filter to generate sufficiently accurate localization data for in stope navigation and measurement data localization. The array of transmitters (beacons) positioned in the stope can be optimized, as shown by Burke [23], for any number of specific criteria. Maximum coverage, or optimum accuracy for an intended route, are both possible optimization criteria, and may result in an apparently random beacon distribution as (artistically) illustrated in Figure 1.

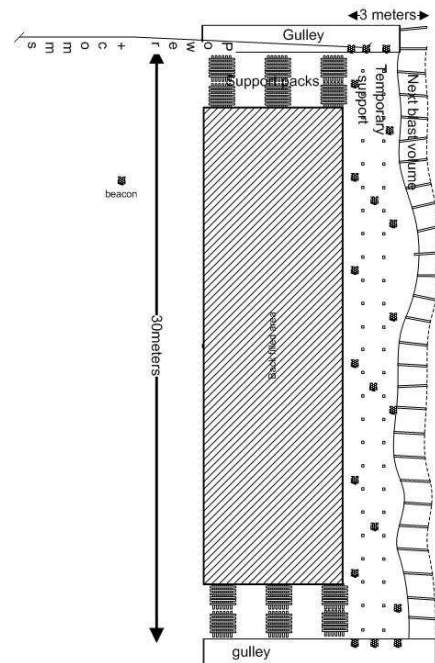


Figure 1. Typical conventional gold mine stope. Beacons distributed in the gulley and optimized in the inaccessible stope.

B. Machine Perception

An important component of the first robot deployment is illustrated by Price [24]. Representing the risk measure to the miner in a meaningful way is critical to having a useful outcome. Several methodologies have been investigated. A

mesh created from the 3D point cloud (Figure 2), which results in a very large continuous surface model of the area, requires offline and prolonged data processing. It can result in glaring errors when there is a slightly imprecise scan match. Surfal representation, which maintains discontinuous surface elements whose size and orientation are representative of the local area, and whose colour is representative of temperature or risk, is a much lighter method of calculation that can be executed in almost real time as the data is gathered. Representing the data on a 3D screen with glasses can prove very efficient in assisting the miner to 'see' the stope that he was about to enter.

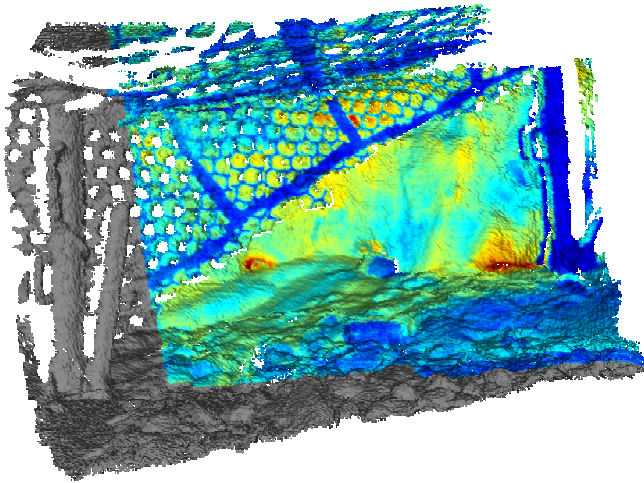


Figure 2. Thermally textured 3D model of a stope. (after Price)

C. Human Machine Interaction

In order for machines and humans to work together in the future the sensing of humans is critical. Not just proximity sensing as is now the case with trackless underground vehicles, but sensing that will enable the prediction of future implications such that the machines can make judgments about the best next step. Dickens [25] has shown that it is possible for rail bound systems to predict an imminent collision with a pedestrian when sharing a tramway (Figure 3).

Image segmentation [26] is used on a thermal camera to identify potential humans in the tunnel ahead of the rail car. A distance sensor calibrated to the thermal camera then determines the distance to the target. A relative velocity is calculated from subsequent images to determine the likelihood of a collision. This calculation does not require a 3D model of the tunnel to be processed.

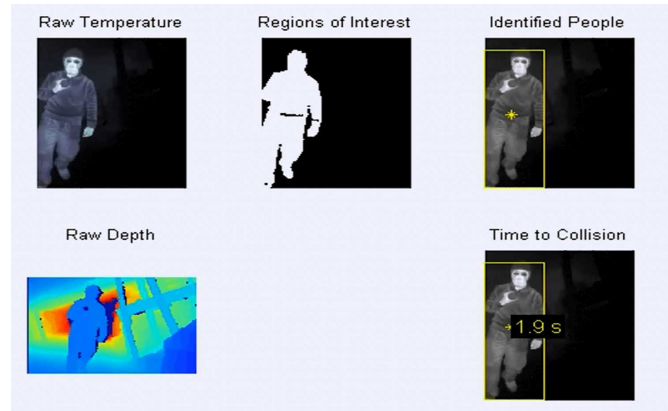


Figure 3. Thermal segmentation and ranging for collision prediction. After Dickens[27]

However, further work will project the point of collision ahead of the pedestrian to determine if there is sufficient space in the tunnel for the pedestrian and the rail car to pass one another (Figure 4). This will enable a warning to be sufficient for the pedestrian to alter their course to avoid a collision. Should there be insufficient space, then immediate and drastic action will be needed by the rail car.

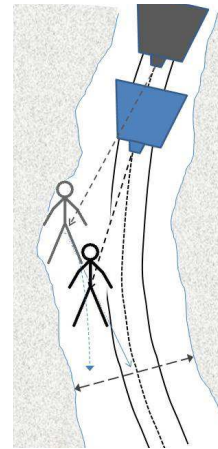


Figure 4. Pedestrian collision calculation.

IV. ENHANCING MINE SAFETY.

The entry inspection process of the gold mines requires a trained miner to enter the gold stope before the rest of the mining team to identify loose hanging wall areas and make them safe. The unsafe areas are identified by tapping them with a tool called a pinch bar, and determining from the resulting sound if they are stable or represent a potential hazard. If they are not stable then the inspector uses the pinch bar to pry them down (bar down). Should this be unsuccessful then the area in question can be supported either temporarily with a wooden support, or permanently with a roof bolt drilled into the hanging wall such that the loose area is supported.

The automation of this process requires a number of steps. The automatic analysis of the sound made by the pinch bar impacting on the hanging wall will remove the need to have a trained experienced miner performing the entry examination has been completed. The Electronic Sounding Devise (ESD) achieved this end (ref the ESD work).

The following step was the removal of the need for a person to provide the impact force to the hanging wall. A solenoid or spring would provide a constant impact force that can be analyzed by the ESD. [28]. Mounting this sensor head onto a telescopic arm will allow the miner to inspect the hanging wall form the safety of a supported safe area, allow then to use less energy per inspection position and potentially improve the measurement coverage of the hanging wall. The integration of this sensor head with the localization system mentioned in section III.A will enable the tracking and mapping of the hanging wall measurements.



Figure 5. WSA prototype, from Teleka[29]

This is the payload for the autonomous mining system

V. THE AUTONOMOUS MACHINE.

Integration of this work with collaborators within the CSIR will enable proof of concept of an autonomous mine safety platform, potentially the first underground autonomous system. MMM's mechanical platform together with the control software (Fig 6) will provide the foundation of the machine. Software developed by MIAS, together with perception sensors, currently an hokoyo laser scanner, FLIR thermal camera and a modified xbox kinect scanner will provide the brains of the system. The CMI sensors for localization and hanging wall measurement will complete the robot.

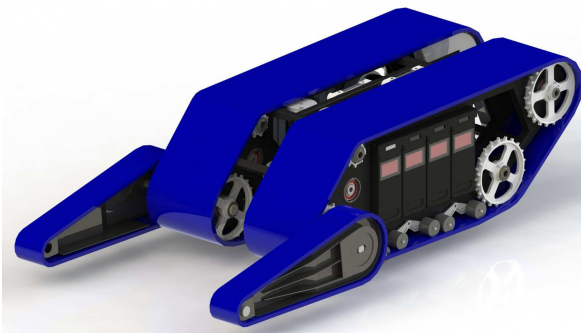


Fig 6. Robot platform without payload

This will be the first autonomous robot deployed in an underground mine, as opposed to the current implementations of simply following a predefined path around a haulage loop. It will be a robot that analyses its environment, determines where it needs to go to best achieve its goal of generating a risk map to improve the safety of the South African gold miner.

VI. CONCLUSION

The vision of this work is to remove the miner from the dangerous stope face, and enable them work safely in the gully (see Figure 1). A continuous robot mining system to replace the current cyclic drill and blast technique will require a novel rock breaking technique as well as some progress in swarm robotics to guide the robotic mining team of the future.

Critics of this research often bring up the need to create jobs in South Africa and incorrectly claim that this will cost miners their employment. The move from a cyclic drill and blast technique to a 24/7 continuous mining method will increase the manpower requirement if the full benefit of the system is to be utilized. The implementation is likely to be manpower constrained.

This will enable gold mines to remain profitable past the current life of mine projections. And with the operation of this continuous mining system, the technical support and maintenance requirements will create the need for up-skilled labour for the new robot miners. The children of today's gold miners may well still be gold miners, but they will not be holding drills, using explosives or scraping rock. They will be servicing, maintaining and assisting teams of mining robots deep under the African soil.

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