A Robot Miner for Low Grade Narrow Tabular Ore Bodies: The Potential and the Challenge.

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For the past hundred years, mining methods in South African deep level gold and platinum mines have remained relatively unchanged. Recently. mechanisation has made some impact in how it is done, for example with pneumatic, hydraulic and electric rock drills mounted on mobile platforms, but not what is done. A Robot Miner has the potential to mine in a different way. This project is an initiative to address the challenge of safely mining narrow tabular ore-bodies by targeting the ore with an autonomous mining system that is able to mine at significantly reduced stope heights and grades. Initial investigations indicate a significant gold resource in the Witwatersrand that the Robot Miner could unlock with its capability of focusing on low grade narrow ore bodies that are currently un-minable.

The cyclical nature of mining is fraught with inefficiencies. One incomplete link in the cycle results in an entire cycle being lost as all blasting occurs simultaneously in a mine cleared of personal. A continuous process would increase the mine efficiency. To move away from the cyclic nature of drill and blast, a novel rock breaking technique will be required. The development of such a technique is being pursued in parallel to the development of the robotic platform. While it informs some of the design decisions being made, it is not described in detail in the paper.

The proposal of a robotic platform as the basis for this project has created a focus that has enabled a new direction in the search for a solution. It has also brought new questions and challenges. Underground localization, navigation, mapping, communication, ore-body tracking and power source supply and management are just some of the significant challenges that are being tackled.

The paper focuses on the robotic platform proposed and the intended path for its development. It requires partnerships within the robotics competencies in South Africa, as no single unit or group posses the required skills and knowledge to develop the entire system.

I. INTRODUCTION

This is a project to design, from scratch, a miniature mechanised mining system that would be low in cost and locally produced. It is intended to be able to mine reefs that are too narrow for economic exploitation by miners or by current mechanised systems. It must be truly remote-controlled (beyond the visual range of the operator) and autonomous, as the target reefs are too narrow to allow human access [1].

To achieve this, a series of key questions have to be answered - how to power the machine? How to break the rock? How to transport the rock? How does the machine determine its position? How does it follow the ore body? If successful, some 20 000 t of gold, in currently un-mineable narrow reefs, could be converted from resources to reserves [2].

A significant attempt to introduce mechanization was undertaken by the Chamber of Mines Research Organisation (COMRO) in the 1970's with limited success. The stoping review [3] is a comprehensive evaluation of this work, with a portion analyzed further in [4]. A major question arises: What is being done differently now with this work that will result in success unachievable in earlier attempts? It is important to determine this answer prior to continuing. In summary, this machine will be built to fit an ore body, with later modifications to potentially expand its application, rather than finding a generic solution upfront to meet all potential mineral deposits. This machine will target narrow tabular ore bodies in the Witwatersrand Basin [5].

There have been significant technical advances in the last 20 years that make available tools and techniques that were science fiction 30 years ago. By applying these techniques and doing something different, rather than changing the way things are done, a revolution in the mining methodology may be possible. One such advance is in the geophysical tools that now allow us to track the ore-body [6].

The Centre for Mining Innovation within the CSIR has the objective of doubling South Africa's Mineral reserve by 2020. The Robot Miner meets this challenge by targeting previously un-minable narrow low grade deposits and enabling their conversion from resource to reserve. Research in the last couple of years has focused on the rock breaking technique that would be needed, and on the evaluation of non explosive alternatives to the current drill and blast methodology. This project is focusing on developing the robotic platform so that when the supporting technologies mature there is the potential of delivering a system solution.

II. THE JUSTIFICATION

A resource is the quantity of a mineral in the ground. For example, the total gold resource in the Witwatersrand, past and present, is variously estimated at 150 000 tonnes. A reserve is the quantity of gold that can be expected to be removed from the ground. A reserve discounts gold resources lost for any reason, for example because the grade is too low, or because gold bearing rock has to be left *in situ* to support the excavation [7].

The reserve, therefore, is a function of the mining method.

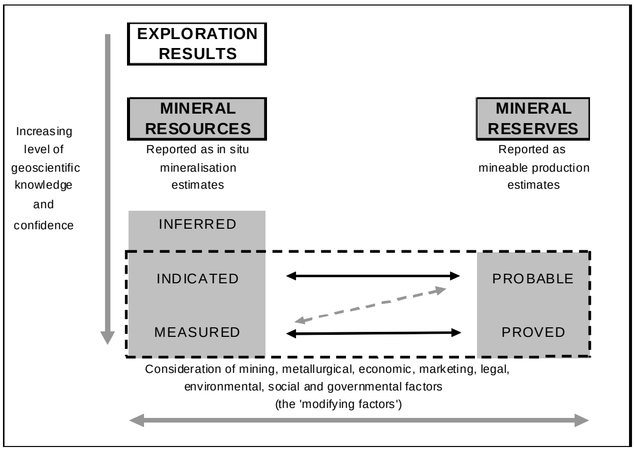

Figure 1. Resource to Reserve Conversion [8].

For example, in a coal mine a room and pillar mining method is often employed, where the rooms are mined out and the pillars are left behind to support the roof. The maximum extraction in room and pillar is about 70%. By contrast, a longwall coal mine will remove all the coal in an area, allowing the roof to collapse behind the mining face. Given the same resource, longwalling will yield a higher reserve.

The relationship between exploration results, mineral resources and mineral reserves is shown in Figure 1 from [8]. It is a complex relationship dependant on factors ranging from exchange rates, mineral prices, labour relations, inflation and safety records, to the existence of a calculated mine plan. A resource is an identified mineral deposit that, with the addition of more knowledge, and the development of a mine plan, could be translated into a reserve. Should the mine plan development show that the grade is too low for economic extraction, then the deposit remains a resource. This is where a Robot Miner can make an impact.

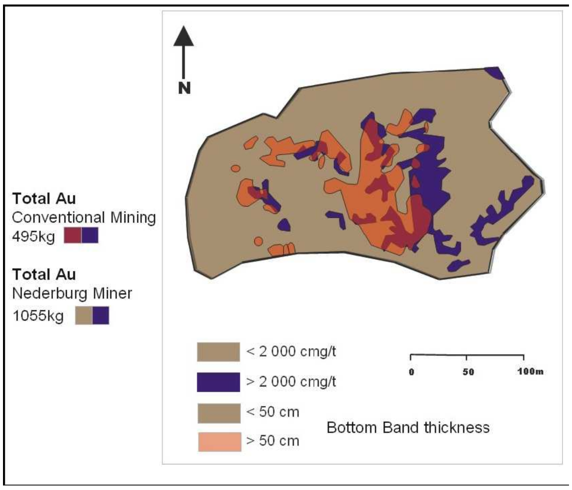

Figure 2. MiddleVlei deposit evaluated for narrow stope mining [2].

The question for the Robot Miner is the size of the reserve it can impact. A study was commissioned from Shango Solutions [2], a geological consulting company, to answer that question. Shango considered a mining machine that could extract reefs of less than 50 cm in areas where conventional mining is sub-economic at mining heights of greater than 80 cm.

The Middelvlei reef is used as an example. In Figure 2, it can be seen that any mining system capable of economically mining reefs at a stoping width of less than 0.5 m significantly increases the reserves from any existing resource. The minable gold in the approximately 250x150m block is more than doubled from 495kg to 1055 kg.

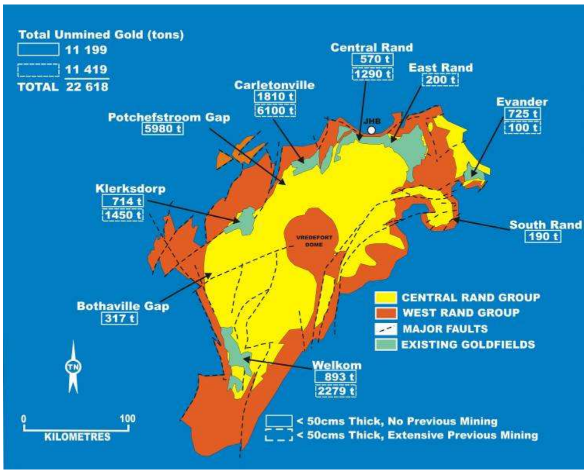

Figure 3. Gold Reserves for the Robot Miner [2].

Applying a similar analysis to all the South African gold resources results in an additional estimated reserve in excess of 22 000 tons, shown in Figure 3. To put this into perspective, the total gold removed from the Witwatersrand to date is estimated at 40 000 tons, and current mining is extracting about 350 tons per year. In other words, the narrow deposit mining method could create a gold reserve comparable to the Witwatersrand itself.

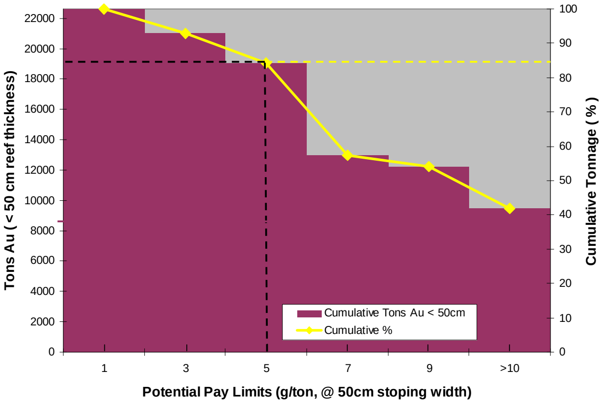

Figure 4. Cut off grade vs potential reserve [2].

However, no method will be able to economically extract all the gold. At a cut off grade of 5 g/ton the projected reserve is 19 000 tons of gold (Figure 4). Should the Robot Miner system be capable of economically mining lower grades, then a commensurately larger increase in reserves would be achievable as demonstrated in Figure 4. Should the stope width be reduced to 30cm then there may be a further increase in the potential reserve.

III. ROCK BREAKING.

Significant work has been completed on evaluating the potential of existing rock breaking technologies for a machine targeting narrow ore bodies [9]. Work to date within the CSIR has been focused on large machines to remove the narrow seams. The project has shifted the mindset and focus to a Robot Miner machine of comparable size to the deposit to be mined.

The use of electric rock breaking has been investigated with specific reference to South African ore bodies and fits this requirement well. It also has a significant spin off potential in the form of an electric discharge rock drill (EDD), which will be the initial developmental focus of the technology.

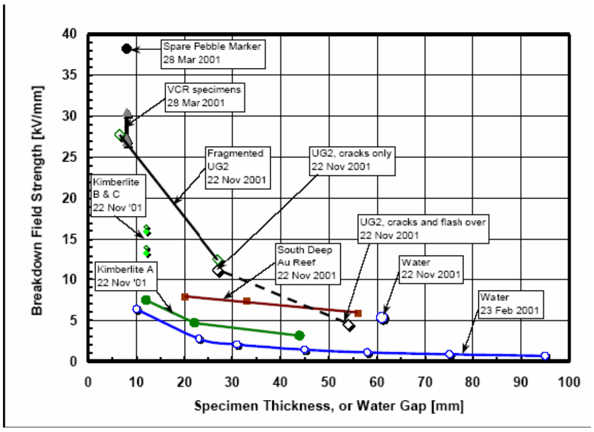

Figure 5. EDD applied to SA Ore Specimens [10].

Electric rock breaking requires very little thrust force and therefore is well suited to an autonomous robotic platform. The challenges will be the power supply and control.

Work done at CSIR [10] has shown that South African rocks can be broken using electrical discharges (Figure 5). Electric rock breaking has been around since the 1960s. The main technology that might enable the breakthrough required for a production machine is the emergence of low cost power electronics.

IF EDD can be successfully developed, it is a short step to design a head for a rock cutter rather than drilling, and hence continuous mining operations.

IV. POWER

A mining machine will consume a considerable quantity of power, especially if electric discharge is the chosen rock breaking method. Un-tethered autonomous operation is favoured for logistical reasons in cable management, but the ability of the machine to store its own energy may be problematic. The use therefore of an umbilical supplying power (and potentially communications) is not ignored. However, it is hoped that the progress made in battery technology over the next few years will supply a power pack suitable for the Robot Miner. This aspect of the system has therefore been parked for the time being, until the electric rock breaking technology is ready to be integrated with the robot platform.

V. DATA COMMUNICATION

CSIR has developed an open standard architecture called AziSA for communication of sensor data, and a reference implementation using that standard [11]. AziSA is an architecture for measurement and control networks that can be used to collect, store and facilitate the analysis of data from challenging underground environments. AziSA is intended primarily for use in underground mining environments where there is limited power and communications infrastructure. AziSA was created because the existing identified protocols could not offer an organized and open architecture for low-power, low-cost, wireless systems [12]. It allows for dense sensor arrays in the workplace, wire less communication to the closest power line, and TCP/IP communication to a central server[13]. Most underground communication equipment and infrastructure is still largely experimental and under development with no one system emerging as superior [14]. The Robot Miner will therefore piggy-back on the AziSA system of communication as far as possible.

A wireless communication system would be advantageous for the autonomous system as it would remove the need for a tether. However the trade-off between bandwidth, transmission distance and power consumption will have to be optimised before a final decision is made.

The decision to tether the robot or not is unlikely to be driven by communication requirements. With the Robot Miner using electric rock breaking, it is likely that the communications power requirement would be insignificant in comparison to the power required to break the rock.

Consideration must therefore be given to the data requirement of the system. The fact that the robot will be in an area that is inaccessible to humans, or that is potentially unsafe for humans adds another dimension to the challenge. Should the unit malfunction or be damaged and be irretrievable, any data would be lost. Therefore the data needs to be retrievable by being transmitted out of the working area. Short distance communication to another unit may be possible depending on the degree of damage to the robot, and the level of the battery pack in an un-tethered configuration.

The current communication standard of choice is WiFi with its open architecture, high bandwidth and freely available hardware [15]. The ZigBee [16] standard has the potential to be a repeater system for longer distance transmission as part of the AziSA network, and is being considered as an alternative standard. However the reduced bandwidth available compared to WiFi implies that not all data could be transmitted to a base station so there would be a requirement for on board data processing and the transmission of only significant data and information.

VI. LOCALISATION

Within the development of AziSA a sonic beacon has been designed to be used for underground localization of the AziSA sensors [17]. This sensor will be upgraded to enable the Robot Miner to localize in 3 dimensions in the stope environment.

The sonic beacon is mounted on the end of a roof bolt and transmits both a 40 kHz ultrasonic signal and a 2.4 GHz radio (EMS) signal simultaneously. The receiver, mounted on the robot platform, calculates the difference in time of flight for the two signals. This is used to compute a distance that the platform is from the transmitting beacon. Triangulation of the signals from multiple beacons with known position allows the Robot Miner to determine is position accurately. Essentially the sonic beacons create an underground GPS system.

It is possible to use low cost robust accelerometers and electronic compass to determine the platform orientation, and therefore, together with the beacon system, solve the 6 degrees of freedom of location and orientation. The complexity of adding a robot arm to the platform, and the added pose complication, is to be tackled in later phases of the project.

Extending the navigation capability from the stope environment into the tunnel network is more challenging due to the linearity of the tunnel system. It will be difficult to surround the platform with beacons and enable it to triangulate within a tunnel network. It is likely therefore that an alternative methodology will be employed. Potentially RFID tags or sonic beacons at tunnel intersections only, and odometry for tunnel progress will provide sufficient information for navigation and localisation within tunnels.

VII. NAVIGATION

To mechanize, machines need to know where they are, where they are going, and how to get there. The current design philosophy that is being followed is based on a combination of inertial navigation, dead reckoning, and sonic beacons. While this equipment is commonplace above ground, dealing with the challenges of robustness, space efficiency and accuracy required underground take the problem to a new level.

The challenge of creating and using an underground map in 3 dimensions is not to be taken lightly. The mine tunnel network is extensive and the 3 dimensional nature of the system results in a large amount of data.

VIII. TOOL GUIDANCE

The Rock breaking technique is likely to be a contact method that will be mounted on the end of a robot arm. The control and tracking of the robot arm on the mobile platform complicates the control of the system, especially as each 'contact' will result in a change in the environment that potentially needs to be tracked, recorded and made available to other robots in the vicinity. It is likely that an on-tool guidance system will be required to achieve the accuracy needed for EDD to be successfully deployed.

The CSIR has developed a sounding device [17] as part of the AziSA system. It determines the hanging wall integrity based on reflected sound waves from a controlled contact with the wall. This instrument will be modified and mounted onto a platform mounted robot arm prior to the implementation of the EDD tool. This will enable the testing of the robot tool system, guidance, tracking and control, without the added complexity of managing the broken material and a changing environment.

IX. DATA REPRESENTATION

The 3 dimensional nature of the mining environment, as well as the continually changing nature creates a challenge in the data representation. The current techniques for displaying the data limit the amount of information that is concurrently displayable. Particularly while the Robot is remote controlled, it is important to develop methods of representing the 3D situation surrounding the robot for the operators reference, preferably in an environment integrated with the mines existing CAD or mapping software.

X. REEF TRACKING

The novelty of the Robot Miner will be its ability to follow the reef. However, this requirement is not trivial. Sometimes, gold reefs are difficult for a geologist to identify, relative to their hanging and footwall rocks. The challenge for a machine geology system in a limited space is even greater [5].

Perhaps the most ill defined challenge in the system is in reef delineation and tracking. On a macro level it is needed for mine planning, enabling the prediction of faulting and significant changes in dip, but it is also required on a micro level where each Robot Miner needs to ensure that it is mining the ore as opposed to host rock.

Currently this is done by experienced people, in cooperation with the mine geologist, marking out the blast hole positions for drilling and thus ensuring that the reef is tracked and the host rock dilution kept to a minimum. Should a fault intercept the ore deposit then the mining plan can be modified to cope with the geology.

There will be no geologist able to approach the stope and make those decisions so the intelligence will need to be embedded into the Robot Miner. Alternatively, appropriate data must be collected to enable a human to determine the mining conditions and requirements offline, and then direct the mining system accordingly.

Laser spectroscopy has been identified as a potential target technology, as has using a gamma-ray detector mounted on a robot arm. This area of the project is still in its infancy.

XI. SYSTEM MANAGEMENT

The concept of using a team of small robots may require the implementation of swarm robotics. Although initially it is likely that: the robots will not communicate directly with each other; may not be considered small to many people; and may not be cheap - all theoretical prerequisite for swarm robotics. Conceptually swarm robotics may still be applied as there is a team of robots with a common and combined goal where team work may generate a better result then the sum of the parts.

Their behaviour will be monitored and controlled by a central supervisory computer powerful enough to do the computations necessary for the system control. The supervisory computer will also schedule and direct the robots in their tasks in a coordinated manner as well as map and track the continually changing mining face.

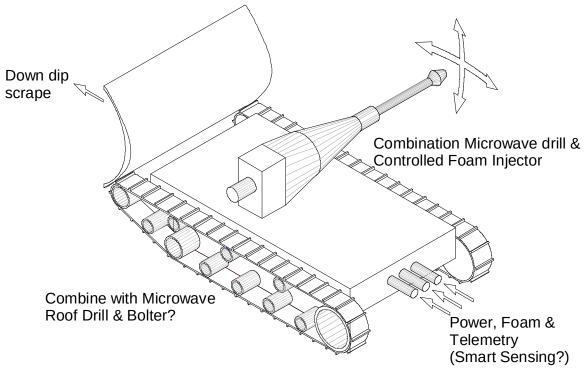

Figure 6. A concept for a Robot Miner.

It is also likely that there will be several types of robots within each robot mining team. Reef tracking or mapping may require a dedicated unit. It may not be possible to integrate ore removal into the rock breaking robot (Figure 6), in which case an ore removal unit will be needed. A recovery unit may be needed to recover robots that have malfunctioned, broken or become immobilized. It is likely that an inspection unit would be required with high bandwidth communications and visual feedback to a human user who can provide additional input to the system.

Battery/power management will be required to ensure a smooth battery changing process – and not all the robots standing in a queue to be recharged and none of them actually mining.

XII. THE PLAN

The immediate focus will be on the stope environment and the 'mining team' operating therein.

An additional tunnel mining system is needed to gain access to the deposit so that the support infrastructure to the robots can be inserted and the ore removed, but how this will be done is not currently being considered. Being able to create support tunnels without using drill and blast is significant: perhaps technology similar to EDD could be used, or a technique like controlled foam injection (CFI) may be more appropriate?

Rock Engineering has an important role in designing the mine and the mining procedure. The evaluation of alternatives like room and pillar or long wall mining with planned hanging wall collapse will be crucial for an efficient and safe system to be developed. Current modelling will focus on generating concepts for a narrow stope miner and determining theoretical limitations of hanging wall extent. The interaction of the narrow stope with the support tunnels is currently unknown and will be modelled and verified.

The robot platform will be less than 30 cm high to fit into the planned narrow stope. It will be both autonomous and remote controlled so that a human user can take control when necessary as well as be able to manipulate it into the stope area that is covered by the sonic beacon system.

As an interim step, a robotic platform is being developed for a safety application. After the blast in a conventional mining operation, the roof, or hanging wall is ‘made safe’ by a process of prying of ‘barring down’ all the loose rock. To lower the risk involved, and to improve the quality of the barring down process, a robot is being developed that will carry a sounding devise and an infra-red thermal sensor [19]. It will also carry a tool that can mark the roof as unstable, such as a paint spray can.

Another potential interim deliverable could include a tunnel evaluation platform that detects unsafe areas in tunnels. This system would compare measured data with a known map – identify rock falls or unsafe areas.

The human machine interaction will be kept out of the equation for the time being by ensuring that the machines do not operate where there are humans and visa-versa. Eventually however the human machine interaction problem will need to be addressed to keep humans safe from the machines.

XIII. CONCLUSIONS

This Project has the potential to revolutionise both South African narrow reef mining and the robotics arena. However it will need to leverage expertise in areas within the robotics community so that each contributing group can play to their strengths. Some areas that will need a champion include:

- Platform development in terms of dynamics and control of the machine and navigating terrain, speed, direction.
- Obstacle avoidance – rocks, walls and cliffs potentially with one or more of: sonic sensor array, laser range scanner.
- SLAM (simultaneous learning and mapping) – tracking the mining face.
- Navigation within a known map.
- Localization in real time and recalculating projected trajectories.
- Robot arm control for the electric rock breaking tool.

There is no doubt the potential rewards of a successful Robot Miner system are substantial, offering increased reserves of a magnitude close to the Witwatersrand itself and a mining system that can be fully mechanised and automated whilst providing increased levels of operator health and safety. However, the effective development of a Robot Miner system through to a production reality will require the collective, integrated and managed input and support of all stakeholders.

ACKNOWLEDGMENT

Thanks must go to Liam Candy and CSIR Mobile Intelligent Autonomous Systems group for their patience with my silly questions. To Riaan and Peter at CSIR MMM at MSM for their enthusiasm in joining in the challenge and offering their support, and to Francois at UJ for aligning their activities with these projects requirements.

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