EVALUATION OF ROBOT TECHNOLOGIES FOR DEEP LEVEL MINING APPLICATIONS

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ABSTRACT

Mining starts with the extraction of effortless resources, but quickly progresses to more complex situations. As the mining depth increase the technical challenges and difficulty to retrieve resources rises. The future deep-level mining environment is considered too immense a risk for human labour. Therefore, robot technology is considered as an alternative. This imposes the need to develop and improve current mining technology and equipment. This study evaluates robot technologies for deep level mining applications. Firstly, the constraints of robots associated in deep-level mining environments are identified. Thereafter, various existing robot technologies are analyzed to categorize functional attributes of each robot. These were assessed with regard to the constraints, establishing a basis for selection of a feasible robot technology platform. Recommendations are made on how to improve the existing robot technology to compensate for specific conditions. It is concluded that it is vital to improve existing robot technologies in order to mine at deeper levels. In collaboration with technology- and mining companies a mechanized mining concept was developed from these evaluations.

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1. INTRODUCTION

Thomas Edison created the electric light bulb and then wrapped an entire industry around it. The light bulb is most often thought of as his signature invention, but Edison understood that the bulb was little more than a parlor trick without a system of electric power generation and transmission to make it truly useful. So he created that, too. Edison’s approach was an early example of what is now called “design thinking” – a methodology that imbues the full spectrum of innovation activities. Innovation is powered by a thorough understanding, through direct observation, of what people desire and need in their lives and what they like or dislike [1]. Technology teams and groups [2] are currently designing an innovative robot platform that can mine reefs that are too narrow for economic exploitation by miners or by current mechanized systems. These groups together with mining companies helped evaluate and give suggestions for a robot platform. This innovative solution can convert in South Africa 22 000 tons of extra gold in currently un-mineable narrow reefs, from resources to reserves [2]. Currently 40 000 tons of gold is removed from Witwatersrand and mining is extracting 350 tons per year. Thus, the narrow deposit mining method could create a gold reserve comparable to the Witwatersrand itself. The Chamber of Mines Research Organization (COMRO) attempted to introduce mechanization, but the technology at the time limited the success of the outcome. The stopping review [3] is a comprehensive evaluation of this work, with parts analyzed [4] even more in depth. Technology has shown tremendous advances in the last 20 years compared to science available almost half a century ago [5]. Therefore, there are developed technologies that can open new possibilities if applied in mining. The latest geophysical tools nowadays allow us to track the ore-body [6]. The purpose is of this project was to develop a mining concept for deep, narrow reef level mining operations. Various robot technologies were evaluated and considered. A design thinking approach was used to create a concept.

2. RESEARCH APPROACH

As a design engineer it is important to understand the people and environment for which the innovative robot technology is designed. Therefore, in order to evaluate and design for deep level mining companies the engineer must build empathy for *who they are* and *what is important to them*. As illustrated in Figure 1 the first phase of this study was to understand the mining environment better. This was done by contacting specialists in the field and conducting a thorough literature study. Thereby, it was possible to understand possible robot applications for the mining environment. In the second phase various robot technologies were explored for these applications.

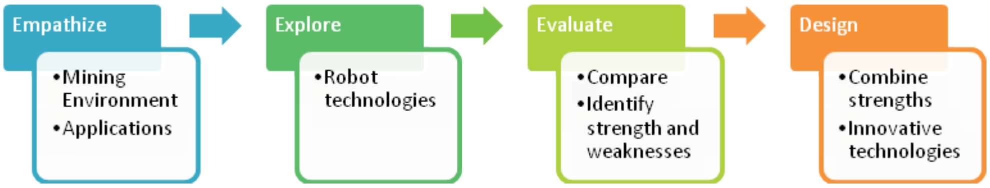

Figure 1: The research approach to design robots for deep level mining applications

Thereafter, various robot technologies could be evaluated from questionnaires by comparing different functions and the effect of the demands from the mining environment. The strength and weaknesses were also identified. Finally, a robot concept could be developed for a specific mining application by combining these strengths with innovative technologies. Knowing that key growth imperatives succeed best when specialized teams share skills, experience and insight across the silos [7], collaboration with specialists, technology- and mining companies was a necessity.

3. TOWARD UNDERSTANDING THE MINING ENVIRONMENT

Various constraints were evaluated on the basis of the environment associated with deep level mining (>3 km deep). The typical life cycle for robot technologies in deep level mining applications as illustrated in Figure 2. Each constraint is assessed under the different phases of this life cycle.

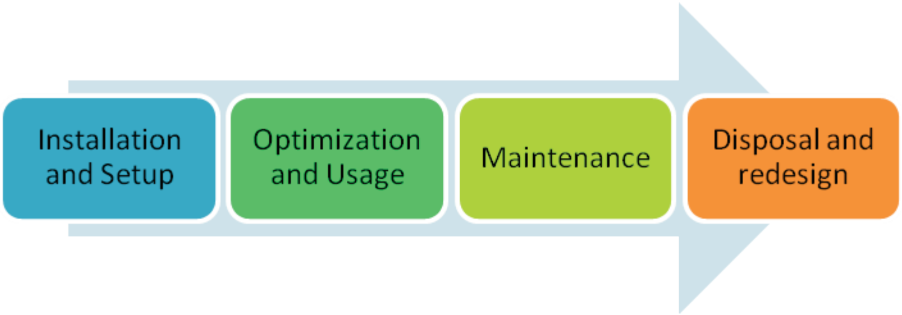

Figure 2: Life cycle of robot technologies for deep level mining applications

Many of the installation and setup constraints are identified during this study. It was also important to consider the deep level mining factors that limit the usage and maintenance of the technology. The disposal and redesign phase received proper attention before the evaluation part of this research was conducted.

3.1 Installation and Setup

Robots need to have a geotechnical stability to be operationally functional in deep mining environments. This applies that robots must be able to move with ease in such environment described as being high siliceous rock environment [2]. As a result of the high uncertainty of deep mining environment it is vital that robots be well equipped with slip resistant finishes to avoid fall and possible damage. With increase of depth, there is an increase in temperature and humidity. Typically the temperature for 5km deep mining is 70°C and pressure level is 920 times normal atmospheric pressure [3]. Therefore, the robot technology must be corrosion resistant, electrically insulated and in additional to ventilation through the shaft, have a self-cooling mechanism where necessary. The size (dimensions) of the robot must ensure that the robots will be able to fit into most mining shafts. Currently the shaft allows widths of no more than three meters (>3m) [8]. The robots must also be able to be positioned (installed) so that they perform operations continuously, with minimal interference.

3.2 Optimization and Usage

In the deep level mining environment rock falls and backfill effects occur during the mining operation. The robot must be robust and should not have any fragile components. The robot technologies must be able to communicate and be equipped with sensors to be used for various applications. The sensors can help management to monitor rock fall hazard risk and fragmentation. Ultimately, the control unit and specialist team can use this feedback (data) in a 3D-virtual room on ground level to make strategic and operational decisions. Robot technology must also have geological stability especially with slip resistance finishes to operate in the high siliceous environment. The technology will also consume a considerable quantity of power, especially if electric discharge is the chosen rock breaking method [2]. Un-tethered autonomous operation is favored for logistical reasons in cable management, but the ability of the machine to store its own energy may be problematic. Developments in wireless electricity by wiTricity [8] at MIT may also hold the answer. However, it is also hoped that the progress made in battery technology will supply a power pack suitable for the robot technology. Currently, many robot technologies are powered by petrol [9] engines, which unlock more maintenance challenges as discussed below.

3.3 Maintenance

It will be difficult to inspect and recover (maintain) robots mining at such deep levels. Therefore, they must have a long operation life capability and be flexible to protect its own existence. Robots can be developed from self healing materials like shape memory alloys and shape memory polymers. These materials allow recovery when deformation is caused by temperature and stress applied. Epoxy-based anti-corrosion coatings can be used for healing the damage by autonomic means, or mechanically by sealing with corrosion products. Protecting metal substrates with coatings through electrochemical and/or inhibition mechanisms can also be considered [10]. The robot joints may require proper lubrication of gear oil or grease. Screw terminals can loosen from vibration and therefore tightening maintenance of wires should be performed. The concept of self-configurable robots can be applied [11].

3.4 Disposal and Redesign

The robot technology platform must allow for new innovative improvements and upgrading as needs change without losing other essential operational qualities. The materials of the robot technology should also be recyclable.

4. POSSIBLE ROBOT APPLICATIONS

4.1 Rock breaking

Significant work has been done on evaluating the potential of existing rock breaking technologies for a machine targeting narrow ore bodies [12]. 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 technology 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 [13]. 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.

4.2 Monitoring of rock fall hazard risk

An open standard architecture called AziSA for communication of sensor data, and a reference implementation using that standard [14] has been developed. It 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. The architecture was created because the existing identified protocols could not offer an organized and open architecture for low power, low-cost, wireless systems [15]. Innovative robot technologies can therefore make use of this architecture. The current communication standard of choice is WiFi with its open architecture, high bandwidth and freely available hardware [16]. Within the development of AziSA a sonic beacon has been designed to be used for underground localization of the sensors [17]. This sensor will be upgraded to enable robot technologies 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 can allow robot technologies to determine is position accurately [2]. Various sensors can be integrated with robot technologies to help monitor the rock fall hazard risk. The range of sensor functions can include micro-seismic, acoustic, closure and differential movement, infrared, support loading, and seismic velocity. Similar technologies than the GOM ATOS Camera, found in the rapid product development laboratory at Stellenbosch university, can be also be fixed on the platform to capture and convert mine layout in the CAD drawings. Different types of sensors are available for light, motion, temperature and pressure. Infrared sensors have much better coverage of an area. Infrared technologies can be used to monitor gas leak detection, water leak detection, and pipe and cable detection [18]. Sensing of radio activity emitted can allow for the early detection of the amount of gold mined [19].

5. EXPLORING ROBOT TECHNOLOGIES

Numerous robotic technologies for deep mining applications were researched. The initial group of fifty robots was prioritized with the help of mining specialists and mining companies to ten robot technologies. The attributes and limitations of each robot were studied and then compared with the mining constraints. A brief description of the capabilities and the limitations of each robot follow with regard to the constraints.

5.1 iRobot 510 Packbot

The iRobot 510 PackBot shown in
Figure 3 is used for searches, reconnaissance as well as bomb disposal. It has a variety of payloads, sensors and manipulators, and quickly adapts as requirements changes.

Figure 3: iRobot 510 Packbot [20]

The capabilities and limitations of this robot is listed in Table 1. It is mobile over rock and move through snow, mud and other tough terrain. *Packbot* withstands being thrown out a window, tumbling down stairs and submersion in water.

Capabilities	Limitations
Length = 88.9cm; Width = 52.1cm; Height = 17.8m; Weight = 10.8kg. Climbs: 60°; Moves < 9.3 km/hr Operator: See environment & Knows position; on-screen view from multiple high resolution cameras, 3-D graphics showing robot's orientation. Lifting capacity: 2.27-6.8kg (small manipulator) & 4.54-13.61kg (3-link manipulator) Two way audio communication: All weather conditions Camera with laser-range finding & day/night/low-light vision capability	Video & sound monitoring limited Battery: 4 hrs of continuous runtime Robot arm can only extend to 2m. The gripper can only hold things the size of about 10cm.

Table 1: Capabilities and limitations of the iRobot 510 Packbot

The robot also does route clearance and ordinate lift system that digs around, moves and carries objects. Improvements on arm extension and holding capacity can still be done.

5.2 iRobot 710 Warrior

The iRobot 710 Warrior is designed for operation in dangerous environments and detection of chemicals. More than 3500 of these robots shown in Figure 4 have been delivered to military and defence stations.

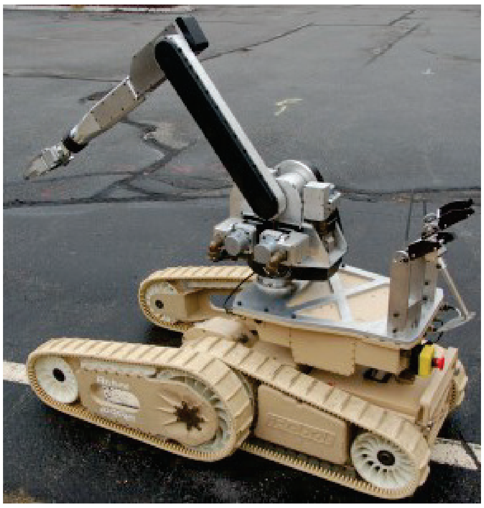

Figure 4: iRobot 710 Warrior [21]

The *Warrior* moves easily in tough terrains and suitable for indoor as well as outdoor use. It has a wireless range of only 800 meters and a limited battery life as illustrated in Table 2.

Capabilities	Limitations
Climbs stairs & slopes of 45° inclines Wireless connections Robot's 2-link heavy-lift manipulator's arm has an extension of 192.2 cm Lift loads <100 kg-turrets Obstacle avoidance sensors Field-, sustainment- and depot maintenance capability	Wireless range < 800m The time in operation limited due to battery life.

Table 2: Capabilities and limitations of the iRobot 710 Warrior

Gripper cameras can quickly disconnect from chassis and disconnect gripper-payloads, but communication ability needs improvement for deep level mining application.

5.3 The Big Dog

This robot shown in Figure 5 was specifically designed to go anywhere a human or animal can go [22]. This robot can walk, run and climb in rough terrains while carrying heavy loads.

Figure 5: The Big Dog [22]

The Big Dog can move through a variety of terrains, which include rubble, mud, snow and shallow water. Various sensors allow this robot to control a variety of movements as listed in Table 3.

Capabilities	Limitations
Multi-jointed legs: Absorbs shock & recycle Energy: Step-by-step movement On-board computer: Controls variety of sensors, locomotion & balance the legs Locomotion sensors: Control joint positioning, joint force, ground contact, ground contact & Additional sensors: measures robots internal state Move: 6.44km/h & travels 20.6km without stopping or refueling. Carrying capacity=154.2kg; Length=91.44cm; Tall=76.2cm Temperature range of hydraulic seals in legs is between -70°C and 260°C	Maximum range=12 miles if it doesn't carry maximum payload Cannot pick up loads or dig with absence of cameras No visual capability Use gasoline for fuel

Table 3: Capabilities and limitations of The Big Dog

The Big Dog is not operational at night. Only follows person using laser range under limited conditions and doesn't respond to verbal commands. The gasoline may cause ventilation problems in deep level mining.

5.4 RiSE: The Amazing Climbing Robot

The design goal of the RiSE shown in Figure 6 was to create a bio-inspired robot that can walk on land and climb surfaces.

Figure 6: RISE: The amazing climbing robot [23]

This robot can be used for surveillance and monitoring operations in deep mining. Its size and ability allows it to be useful for entering surfaces difficult to reach as listed in Table 4.

Capabilities	Limitations
Climb vertical terrain Changing posture: conform to surface Communicates: Operator commands	Needs charging station (Recharge itself) Slow movement

Table 4: Capabilities and limitations of the RiSE robot

Dimensions are suited for purpose used in deep level mining. The robot's speed needs to be improved for faster responds and feedback.

5.5 RHex

This is an autonomous hexapod robot shown in Figure 7, with compliant legs and only one actuator per leg. It is currently the only robot that can perform such a wide variety of activities as a single autonomous robot.

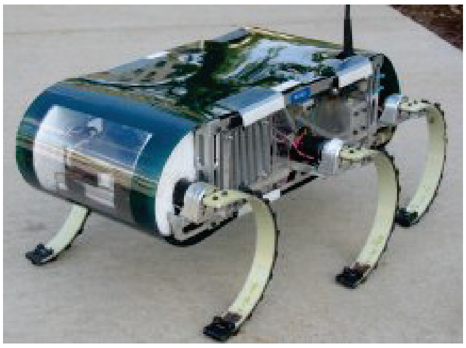

Figure 7: RHex hexapod robot [24]

The Rhex's use of legs instead of wheels or tracks allows for a variety of behaviours. Passive compliance in the legs overcomes limitations of under-actuation and helps simplify mechanical design, yielding robustness and sprawled posture creates passive stabilization of lateral motion. The capabilities and limitations of this robot technology are listed in Table 5.

Capabilities	Limitations
Climbs: stairs & slopes up to 45 degrees Run for 45 minutes (covering < 4.8km) Moves over rough terrain Autonomously follow a line on the ground without any operator control Performs simultaneous localization & mapping by using artificial landmarks scattered over natural terrain	Remote control <150m (distance)

Table 5: Capabilities and limitations of the Rhex robot

To recover nominal body orientation the robot can flip itself over. The flexibility of its legged design leaves significant room for additional behaviours. Its high mobility over natural terrain opens up new possibilities for specific application domains for which components to achieve autonomy are still in their infancy. Commercialization of the RHex platform requires significant platform development as well as further behavioural research to improve its performance

5.6 The Remotec ANDROS F6A

This robot is viewed as the most versatile heavy duty robot available. One of the best heavy duty robots on which responders worldwide rely to help assure a safe, successful outcome for their most challenging missions. The Remotec is shown in Figure 8.

Figure 8: The Remotec ANDROS F6A [25]

The capabilities and limitations of this robot technology are listed in Table 6. The Remotec ANDROS can move in wet and dry conditions because it has a sealed weather resistant enclosure. Also, for precision the manipulator's speed can be varied.

Capabilities	Limitations
Height=143.5cm; Width=73.7cm; Length= 132.1cm; Weight=220kg Joystick: Easy navigation, video- & audio output, heavy duty, portable & water resistant. 2-way audio system (weatherproof speaker & microphone). Colour camera: Low-light switching Extra-low-light colour pan/tilt/zoom (full 360° continuous-pan 180° tilt). Gripper & continuous rotate 61cm camera extender. Multiple-mission tool & sensors. Automatic arm positioning.	Manipulator arm: Only extend up to 61cm Wireless & radio control only functional to distances < 1.9km.

Table 6: Capabilities and limitations of the Remotec ANDROS

This robot has potential for a variety of applications, but is currently only used in the military.

5.7 Petman (The Protection Ensemble Test Mannequin)

This robot shown in Figure 9 is an anthropomorphic robot designed to test the chemical protection clothing in the military. Walking robots based on passive-dynamic principles can have human-like efficiency and actuation requirements. However, movements are mostly in sagital plane and in straight line, being extremely difficult to turn, go back, seat. The motion is mostly symmetrical. A sequence of tests and performance measures must be done to decide on the feasibility of their use in the mining discipline. Therefore, time studies and continuous improvements must be done for such implementation.

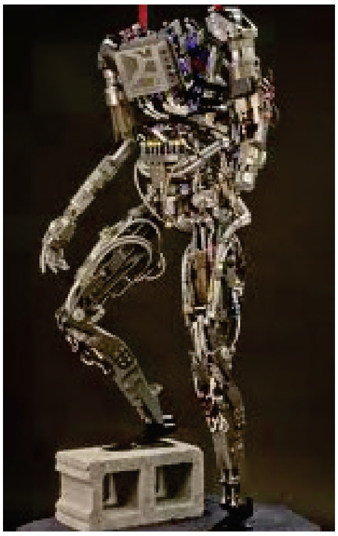

Figure 9: Petman (The Protection Ensemble Test Mannequin) [26]

Petman can balance itself and move freely about the environment. Simulate body physiology by controlling temperature, humidity and sweating. This humanoid has structure of average human and can do simple activities such as walk and crawl. However, this robot is still in the development stage.

6. EVALUATION OF DIFFERENT ROBOT TECHNOLOGIES

As outlined in section two, the different robot technologies will be evaluated through a four step lift cycle. The four steps outlined are: installation and setup, optimization and usage, maintenance and disposal. The first section of the life cycle of a robot that was identified was the installation and setup. Installation and setup is important to deep level mining activities as this environment has a high level of uncertainty and robots must be able to adapt to these constraints. The installation and setup constraints are discussed in Table 7.

Existing Robot Technologies	Dimensions	Communication capabilities	Geological stability	Functionality	Energy usage	Charging station
iRobot 510 Packbot	Very Good	Very Good	Very Good	Very Good	Average	Yes
iRobot 710 Warrior	Very Good	Average	Very Good	Good	Bad	Yes
Big Dog	Good	Very Bad	Good	Good	Very Bad	No
RiSE	Very Good	Good	Very Good	Average	Average	Yes
Rhex	Very Good	Good	Good	Very Good	Good	Yes
Remotec ANDROS F6A	Average	Good	Bad	Bad	Bad	No
Petman	Bad	Bad	Good	Good	Bad	No

Table 7: Evaluation of the different robots according to the installation and setup constraints

The iRobot 510 has good all round capabilities that could work within the deep mining environment in terms of installation and setup. Due to its small size, stability and very good communication capabilities it will be able to adapt to the harsh environment. However, its energy usage is still a concern. Robots that work within the deep level mining environment are exposed to a number of hazards, including rock falls and backfills. They must provide feedback to the mine operators through a number of sensors carried onboard; these sensors consume large amounts of power, putting strain on the battery and thus limiting their usage.

Table 8 shows an evaluation of optimization and usage constraints.

Existing Robot Technologies	Robustness	Communication capabilities	Geological stability	Sensor ability	Autonomous operation ability
iRobot 510 Packbot	Very Good	Very Good	Very Good	Very Good	Bad
iRobot 710 Warrior	Good	Average	Very Good	Good	Bad
Big Dog	Very Good	Very Bad	Good	Good	Bad
RiSE	Very Good	Good	Very Good	Very good	Average
Rhex	Very Good	Good	Good	Very Good	Good
Remotec ANDROS F6A	Average	Good	Bad	Good	Bad
Petman	Bad	Bad	Good	Bad	Average

Table 8: Evaluation of the different robots according to the optimization and usage constraints

The iRobot 510 again has good all round capabilities however it does not perform well under autonomous operation which is an important characteristic. I would be optimal to combine the iRobot's abilities with the RiSE autonomous operations and maybe expand on it. It remains a major challenge to inspect, maintain and recover robots which are involved in deep mining operations. The robots used should therefore have a long service life and be adaptive to protect its own existence. Table 9 evaluates the different robots with reference to maintenance constraints.

Existing Robot Technologies	Operation life Capacity	Self-Healing Capability	Geological stability	Func-tionality
iRobot 510 Packbot	Very Good	Bad	Very Good	Very Good
iRobot 710 Warrior	Very Good	Bad	Very Good	Good
Big Dog	Very Good	Bad	Good	Good
RiSE	Good	Bad	Very Good	Average
Rhex	Very Good	Bad	Good	Very Good
Remotec ANDROS F6A	Good	Bad	Bad	Bad
Petman	Bad	Bad	Average	Good

Table 9: Evaluation of the different robots according to the maintenance constraints

The self-healing capability of robots has not be developed as of yet and needs further investigation. Operational life capacity of the iRobot series is very good as is for the other robots, expect for the Petman which has very complex movement systems, and is still in the development stage. The robot technology platform must allow for new improvements and upgrades to be incorporated easily into the robot. The design should be of a modular form to facilitate new upgrades in form of software and hardware; this will also increase the operational life of the robot. If the robot does need to be disposed of, it should be easy and also recyclable. The evaluation of the different robot technologies with respect to disposal and redesign is listed in Table 10.

Existing Robot Technologies	Dimensions	Opportunity to improvements ability	Functional ity	Ease of disposal
iRobot 510 Packbot	Very Good	Very good	Very Good	Average
iRobot 710 Warrior	Very Good	Very Good	Good	Average
Big Dog	Good	Very good	Good	Average
RiSE	Very Good	Good	Average	Average
Rhex	Very Good	Good	Very Good	Average
Remotec ANDROS F6A	Average	Good	Bad	Bad
Petman	Average	Good	Good	Bad

Table 10: Evaluation of the different robots according to the disposal and redesign constraints

The big dog has many opportunities to incorporate new technologies and improvements as does the iRobot, RiSE and Rhex. The ease of disposal is also an area where all robots do not perform well, the Petman and Remotec even worse due to the complex components used.

7. POSSIBLE SOLUTIONS AND RECOMMENDATIONS

The design process is best described metaphorically as a system of spaces, rather than a predefined series of orderly steps. The spaces demarcate different sorts of related activities that together form the continuum of innovation [1]. After contacting specialists in the field and a thorough literature study, it was possible to understand the opportunities better. Thereby, it was possible to collaborate in order to start generate ideas. The evaluation of the robot technologies helped to identify constraints and special features. These could be considered for the robot technology concept as illustrated in Figure 10. Currently, there are no robotic platforms with all the necessary technologies to mine 5 km deep. Recommendations are made on how to combine the strengths of each robot into a platform. The robot technologies must be able to communicate and be equipped with sensors to be used for various applications. The sensors can help management to monitor rockfall hazard risk and fragmentation. Ultimately, the control unit and specialist team can use this feedback (data) in a 3D-virtual room on ground level to make strategic and operational decisions.

Figure 10: Possible future opportunities for robot platform

Developments in wireless electricity by wiTricity [8] at MIT may be a solution to supply power. Robots can be developed from self healing materials like shape memory alloys and shape memory polymers to allow recovery when deformation is caused by temperature and stress applied. 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) [2]. 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. High frequency rock breaking, due to the fatigue phenomenon also shows promising results [2].Various sensors can be integrated with robot technologies to help monitor the rockfall hazard risk. The range of sensor functions can include micro-seismic, acoustic, closure and differential movement, infrared, support loading, and seismic velocity. Similar technologies than the

GOM ATOS Camera technologies can also be fixed on the platform to capture and convert mine layout into CAD-drawings. Different types of sensors are available for light, motion, temperature and pressure. Infrared sensors have much better coverage of an area. Infrared technologies can be used to monitor gas leak detection, water leak detection, and pipe and cable detection [18]. Sensing of radio activity emitted can allow for the early detection of the amount of gold mined [19].

8. CONCLUSION

The constraints of robots associated in deep-level mining environments are identified. Thereafter, various existing robot technologies are analyzed to categorize functional attributes of each robot. These were assessed with regard to the constraints, establishing a basis for selection of a feasible robot technology platform. Recommendations are made on how to improve the existing robot technology to compensate for specific conditions. It is concluded that it is vital to improve existing robot technologies in order to mine at deeper levels. In collaboration with technology- and mining companies a mechanized mining concept was developed from these evaluations.

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