

Mine Rescue Robots Requirements

Outcomes from an industry workshop

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Abstract—Mine rescue robotics is an area of research and development that has had some attention in the past, but has been bypassed in development by urban search and rescue, where the conditions could arguably be classified as less extreme. The safety situation in South African underground mines is such that work in rescue robotics can be justified. At a recent industry gathering, a workshop was convened to explore the applications where robotics could be of assistance in current operations, and then to determine the requirements specifications of the three most promising deployment scenarios. This paper records the outcome of that workshop session, and expands the outcomes in the context of existing research and development in South Africa and internationally. The paper identifies three definite robot deployments in South Africa as a) box hole deployment (vertical tunnels), b) flying drone reconnaissance and c) proto (rescue) team assistance. These represent applications where there is a market need, and defines the required capabilities for such robots. In some cases, the requirements would need research and development in order to meet the criteria, such as the flying drone reconnaissance. In others, the technology could be considered ready for implementation in a specifically designed machine, such as for proto team assistance. It is significant to note that there is no single robotic platform design that could meet all the application requirements identified, and it is likely that a suite of robots would be required to meet the variety of mining rescue robotic needs.

Keywords—mine rescue, mining robotics, rescue robotics, underground robotics.

I. INTRODUCTION

This paper documents the process and outcomes of an industry interaction that produced a list of requirements and deployment possibilities for mining rescue robotics. The process formed part of a Melrose Training conference titled: Mine Emergency Preparedness and Rescue Innovation (MEPRI). It was presented in Johannesburg, South Africa, in June 2013. 21 delegates attended the workshop and represented a number of companies including mining houses head offices, proto team¹ members at operations and operations

personal, equipment suppliers and policy makers in unions and government.

Safety in South African mines is below international benchmarks, and while significant work is underway to address this imbalance, this implies that there is a greater need for rescue response than international counterparts, yet South Africa does not have a rescue robotics capability, and tends to shy away from the use of new technology in any mining practices, this is true less so in the rescue process where the Mines Rescue Services do an exceptional job training and equipping the proto teams.

The outcomes were arrived at by following a three step process. Initially a background presentation was given to the delegates. Then a general brain storming session was convened, during which many deployment scenarios and tasks possibilities were recorded. The outcomes of the session were then analyzed and grouped into feasible deployments that were most likely to be implemented in the mining scenario, with a reasonable chance of short term implementation. This was achieved through group discussion. The three most promising scenarios were then further brainstormed in three groups to determine the requirements in more details. These were then presented to the larger group for comment and discussion.

II. MEPRI CONFERENCE PROCESS.

Initially, a presentation was given to the delegates on the history of mine rescue robotics. Examples of developed robots for various mining applications was given, as well as examples of where those robots were deployed was produced. The presentation then went on to describe current work in the development of mine rescue robotics. This content is partially reproduced in section III of this document.

Day 2 of the conference included 2 brainstorming sessions. In the first, the participants were briefed on the goal before splitting to three smaller groups to identify as many deployment scenarios as they could think of where a robot could have been used to make a task easier or safer, either from past experience or from possible scenarios that could feasibly occur. Three groups then presented their findings for discussion. This is presented in Section IV.

The various deployments reported on in session 1 were discussed, and grouped by application. The best three deployments in terms of feasibility and uptake were selected

¹ A Proto team is a team of volunteer mine personal that act as a rescue team as and when the need arises. They undergo additional training, often in their own time, to fulfil the requirements.



Figure 1. CSIRO's Numbat.

for further discussion in session 2. The requirements of these three were then explored, expanded and recorded, presented here in Section V.

III. BACKGROUND PRESENTATION

This is a summary of the rescue robotics presentation that was given to the participants of the conference. It illustrated the history of mining robotics research, and gives an idea of the current South African capabilities in the area. To date there has been no routine deployment of mine rescue robots internationally. Below follows a discussion about some of the robots that have been developed, deployed, and in many cases, lost in the process of a rescue or recovery operation. This is an important consideration as the robot needs to be viewed as disposable, with recovery for redeployment obviously the favorable outcome, it is never a certainty.

A. Robots from the past

This is a record of completed robots from the past. It presents an idea of the broad range of development in the field of Mine Rescue Robotics. It excludes the work directed at the Robocup Rescue competitions, which have many overlapping technology requirements.

1) Numbat

The numbat (Figure 1) was developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in the late 1990's for use in coal mine emergency applications [1]. It was a remote control tool for enhanced situational awareness for rescue team assistance. It is



Figure 2. Gemini Scout from SANDIA.



Figure 3. CMU Groundhog.

still used in mining research project at CSIRO, and has never been operationally deployed in a rescue.

2) Gemini scout

The Gemini scout (Figure 2) was developed by Sandia Laboratories for the National Institute for Occupational Safety and Health (NIOSH) [2]. It is a coal mine specific development that is 2 feet (0.6m) tall and 4 feet long. It is intrinsically safe, and thus allowed to operate in fiery environments of the mines [3]. Continuous gas monitoring information is wirelessly fed back to the operator along with colour imagery, and stereo camera depth information. The articulated body and rubber tracks enable it to tackle very rough terrain. 3 units were manufactured and it has never been operationally deployed.

3) Ground Hog

The Ground Hog (Figure 3) was developed by Carnegie Mellon University (CMU) between 2003 and 2005 where it had great success in autonomous mapping of abandoned underground mines [4]. The focus of the group appears to have waned, with the subsequent cave crawler model of the robot shifting to a rescue focus [5], before the end of the series of publications on the work. Current focus appears to be on mining technology development with Anglo American and has not been publically published.

4) V2

The wolverine robot (Figure 4) was acquired by the Mine Health and Safety Administration (MHSA) in the USA in 2001 from Remotec as an adaptation of the ANDROS wolverine



Figure 4. Wolverine from MHSC.



Figure 5. CAESAR from UKZN

robot [6]. It is an adapted military robot that has been made mine permissible. Total cost was approximated to be \$265 000. It is remotely operated by a fiber optic tether and has 3TV cameras with remote display for the operator. Weighing in at approximately 500kg, it is not quickly deployed.

The wolverine was developed by MHSA has been deployed in actual mine disasters (the Sago mine disaster [7]), albeit unsuccessfully. Remototec continues to work in this area although funding remains a challenge [8].

B. Current research.

This section records the current research in potential mine rescue robotics, with a focus on South African capabilities and outputs. It does not represent an exhaustive list of activities, but seeks to illustrate that there is capability in South Africa to take the outcomes of the workshop and produce viable prototypes, assuming sufficient funding is made available, and a consortium is created that can contribute the various technologies needed.

1) UKZN CEASAR.

The University of Kwa-Zulu Natal's Constructible Arms Elevating Search And Rescue (CAESAR in Figure 5) robot [9] was developed by the MR2G group in response to a fire fighting robot need [10]. AI allows for the detection of danger and victims with the use of communication, gas, and image analysis of the unstable environments. UKZN also have some



Figure 6. UCT Ratel at RoboCup Rescue 2013.



Figure 7. CSIR Mine Safety Platform.

work on unmanned aerial vehicles for in mine reconnaissance, although this is as yet unpublished.

2) UCT Ratel.

The UCT robot, RATEL [11] was developed for the Robocup® rescue 2013 competition held in Mexico (Figure 6). The Robots and Agents lab [12] focuses on the development of rescue robots, swarm robots and autonomous underwater vehicles. The Ratel is a lightweight platform with wireless remote controlled flippers for mobility, and a lightweight robotic arm for manipulation tasks. It was designed and built for completing the series of tasks for the Robocup Rescue competition.

3) CSIR mine safety platform.

The CSIR has developed a prototype mine safety platform [13] Figure 7, specifically with the intention of developing towards a narrow stope gold mining robot solution [14]. The Monster [15] was developed to navigate the steep rough terrain of the deep level gold mines in South Africa, but to date has only been tested in the simulated test facility [16]. The first robot prototype is for enhanced safety in the mining areas by assisting with the entry inspection process.

4) Gemini-Scout

The Gemini Scout is still a viable proposition with the license now held by Black-I Robotics in Boston USA [17]. Combined with the company's other robotic platforms and accessories the robot may still be deployed underground in a production or rescue scenario.

IV. BRAINSTORMING OUTCOMES

This section records the outcomes of the conference sessions.

A. Session 1. General deployment scenarios.

In the first brainstorm session the participants were split into three groups, all with the same brief, as articulated above in Section II. The groups tended to dwell on a specific type of application in their discussions, expanding the tasks that it could achieve until that lead to a further or alternative platform designs or configurations.

Outcomes are classified here as done by Murphy in [18]. However, borehole deployment was not mentioned in the sessions, possibly as the deep nature of the South African

underground mines mean that the likelihood of successfully deploying a borehole solution is low. Thus only void Entry and surface entry classifications are discussed.

Void entry, or vertical entry, as would be used in box hole and ore pass² inspection and rescue events was identified by Murphy as the least likely scenario, however in South African conditions, this was identified as a very large need do to the prevalence of the vertical structures, and the dangerous nature of the environment, as well as the inspection requirements for tipping areas into the vertical tunnels.

The final deployment classification is surface entry, where the robot moves horizontally on the floor (footwall in mining terminology) from the deployment site to the inspection site. This is by far the most used deployment method to date, and all the robots discussed above fall into this category.

B. Requirement specifications.

This is a list of the brainstorm outputs. They have been grouped into similar deployments and the characteristics combined.

Some common characteristics across all scenarios were.

- Intrinsically safe/flame proof
- Waterproof (IP65)
- Streaming video to operator/s
- Gas sampling of environment

Follows is a list of applications and key capabilities for each application:

1) blocked chute (Kapsule robot)

- 360 degree camera pan tilt
- Camera zoom with onboard LED lighting
- Inspection as well as rescue applications
- Ability to compute voids
- Ore Pass inspection
- Box hole inspection
- Absolute position determination
- Explosive delivery to site
- Absolute

2) Reconnaissance

- Flying drone machine
- 2kg payload (explosives perhaps)
- Inspection as well as rescue applications
- Short flight times
- Quick data processing and feedback
- Face inspection

3) Explosive deployment to blocked boxhole

- Rocket to deliver explosives to underside of blockage
- Remotely positioned/ triggered
- Disposable

4) Methane sensing

- See through walls to a void
- Analyze gasses in the void (methane pocket)
- Track driven (for traction)

5) Toxic environment sensing

- Remote sensing drone – in and out quickly
- Prevent human contamination
- Chemical spills/pipe leaks identification
- Disposable in case of severe contamination
- Would be made of different material for toxic environment

6) Rescue robot

- Wet bulb dry bulb measurement – determine human survival likelihood.
- Supplies delivery
- Thermal camera to ID people
- 2 way communication
- Light – can be carried and quickly deployed
- Airflow measurement

7) Non categorised deployments/characteristics

- See through walls to ID survivors (sonar?)
- ID wall thickness (for getting close to old workings)
- Hanging wall failure detection
- Roof bolt failure detection.
- Remote sensing of rock type.
- One platform that can fly, float and drive – can get anywhere in the mine, including a flooded tunnel.
- Compute volumes (box-hole/stope) assist with surveying
- Locomotion with feet, not just tracks/wheels
- Fall of ground inspection
- Use in a maintenance mode (not just rescue)
- Not autonomous – remote controlled or semi-autonomous.
- Confined space entry
- Change detection – moving ground over time – take continuous measurements over time to detect and highlight slow changes.
- Foam delivery (fire fighting application ED)
- Hot spot detection –for coal environment –thermal camera.
- +50 degree c environment

The scenarios were then discussed after each group presented their outcomes.

Choices were made based on:

- Technical risk, i.e. the amount of new technology development that would be needed.
- Financial considerations: the cost of the research and development that would be needed to create a product, as well as the cost of the product in relation to the benefit it would produce.

² A box hole or ore-pass is the vertical tunnel in an underground mine through which ore is dumped so that it can get to the bottom of the mineshaft for hoisting in the ore cage. A box hole is typically shorter (10-30 meters) and an ore pass is typically between levels, up to 200m in length.

- The impact that the product would have on the operations, both financially and from an improved safety perspective.

This resulted in the follow three scenarios/platforms

1. Void inspection – vertically deployed robot for inspecting box-holes and ore-passes from the top access point, not only during emergency situations where a victim is trapped in a hole, but for when they become blocked during production. The platform would also be used for regular inspection of both the loading area, which currently needs to be regularly inspected, and the length of the vertical tunnel, which is not currently inspected along its length. This would enable the tracking of wear and prediction of scaling, and potential blockage, and enable the prevention of the blockages that currently give rise to dangerous situations for the miners, and production stoppages.
2. Surface Reconnaissance. This robot platform is a conglomeration of the surface entry applications as listed above. It is specified as a reconfigurable robust robot platform (RRR or R³) for measurement and observation. The various sensors that can be mounted onto the platform would enable the redeployment for a variety of different applications, including rescue situations, in entering the danger area ahead of a proto team, to surveying of dangerous areas, to large repetitive surveys, such as in a tunnel where many datasets are required close together. The number of possible deployment scenarios is limited only by ones imagination.
3. Flying Drone. The final platform that was chose had a dual application potential. For quick scouting of an area that needed inspection, either in an emergency situation, or for hazard identification. This would be a function of the sensor payload that the drone would be able to carry. The second application was in the inspection and unblocking of blocked box-holes and ore-passes. Thus similar to scenario 1, but inspecting from the underside of the blockage to determine the blockage position, and then delivering an explosive package to the blockage in an attempt to dislodge the stuck material.

V. REQUIREMENT SPECIFICATIONS

This is a summary of the rescue robotics brain storming outputs, as well as some additions and clarifications for the three deployments that were chosen as most likely to succeed. This is taking into account the technical risk of the deployment, the likely cost of the solution, and likelihood of the operations adopting the tool in their working environment.

It is assumed that for all these deployments there following will apply.

- Intrinsically safe/flame proof/mine permissible
- Streaming video/data to operator consul in real time. With on board lighting.

- At best semi-autonomous behavior, i.e. operator always in the loop. Remote control preferred. NOT autonomous.
- Thermal camera for victim identification – and to determine the likelihood of the miner being still alive if in a rescue situation. And hazard identification. It would identify a fire, as well as a leaking pressure vessel (or pipe), where there would be a temperature drop with the expanding gas.

A. Void Inspection: Ore-Pass/Box-hole deployment

- Temperature reading (wet bulb/dry bulb) to be able to determine the likelihood of a rescuer surviving entry as well as victim survival.
- Deployment distance of 500m from deployment site
- Gas monitoring (CO₂, Methane, CO, Oxygen)
- Bidirectional microphone comms
- 360 degree visibility with camera (Pan Tilt Zoom)
- Minimum operators (it was commented that current trend of a minimum of 3 operators per current USAR research findings is too many. One to oversee the operation, one to drive the robot, and one to monitor the payload and its data.)

B. Surface Reconnaissance with R³

- 3km deployment range
- Deployment 17km from storage location
- At least walking speed as a maximum

Possible sensor payloads include:

- Laser scanner for 3d mapping
- Toxic air quality measurement
- Thermal cameras for victim/hazard identification
- Wet bulb dry bulb measurement
- Gold grade sensing – such as the LIBS sensor on the Mars curiosity robot
- Closure sensing over time (repeated measurements of wall to ceiling height in the same place over many days to determine the rate of closure)
- Hanging wall stability sensor, such as in [19]
- Rescue package for miner (oxygen/sustenance)

C. Flying Drone

- 100-200m range from deployment
- Man packable
- Speed from hover to 5km/hr.
- Interchangeable battery for rapid redeployment (this is significant in an intrinsically safe design)
- 360 degree awareness/void mapping
- Disposable cost

VI. CONCLUSIONS

This is a summary of the rescue robotics brain storming outputs. It highlights the best three possible robotic applications for South African mines currently, and defines the requirements specifications for the robot deployments. It is significant to note that there are three very different scenarios discussed, that require three different robotic platforms to meet the deployment needs. It is also significant to note that the

outcomes only partially resemble the rescue robotic work that is being conducted in the rest of the world. South Africa has unique requirements that require unique solutions.

The requirements represent a suit of robots that could be deployed in a mine. The alternative deployments of these platforms with slight modifications is not discussed, but it is not unwarranted to say that these three applications should be explored further to identify the single one with the broadest scope of deployment, and thus the biggest impact. This application would be the best one for immediate development and deployment. The expansion of the requirement specifications discussed would then be expanded to represent an engineering requirement specification that would guide a design team.

It is the intention of the authors institution to pursue this aspiration of designing and building a suite of not only rescue robots, but mining robots generally. The next steps are to create a consortium of technology providers, end users of the product that can both ensure the development of a useable product, and provide a testing location, and the eventual supplier and supporter of the product to the end user. Interested parties are invited to contact the author for discussion on forming a consortium to this end.

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