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ROBOTICS TECHNOLOGY IN MINE DISASTER RECONNAISSANCE, RESCUE AND RECOVERY

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ABSTRACT

It is almost a given that post-disaster mine conditions will have compromised the mine ventilation system, resulting in a hazardous atmosphere in portions of the mine, and often complicated travel through debris fields and roof falls. Robotic technologies provide the opportunity to gather valuable information to assist decision making or lessen exposure to dangerous conditions. MSHA's Mine Emergency Operations Division (MEO) has utilized a fully permissible mine robot, the V2, for a number of years, constantly updating the unit as new technologies became available. The National Institute for Occupational Safety and Health, as part of the MINER Act Extramural Contract Program, examined the need for additional robotic units and ultimately funded three different types of prototype technologies: two robots, the Snake Robot and the Gemini-Scout, and a mine rescue robotic assist vehicle known as the "Mule". The Snake Robot is designed to be lowered through a borehole and to conduct surveillance (gas monitoring, video and audio) in the immediate vicinity, while the Gemini-Scout, designed to be deployed in the mine opening, serves as a more mobile and agile exploratory tool as compared to the MSHA V2 robot. The Mule was developed in response to needs expressed by mine rescue teams for a versatile remotely operated support vehicle and it will move from prototype to MEO utilization in the near future. This paper describes the development of the robot prototypes and discusses their limitations in the prototype stage, possible enhancements and potential applications, as well as the utilization of the Mule.

INTRODUCTION

The conditions in a coal mine may be dramatically altered after a mine fire or explosion. For example, the ventilation system may not be functioning correctly as control devices may be compromised or damaged beyond repair. The visibility in the mine opening may be limited due to accumulated smoke and dust. Roof support systems may be damaged or no longer functional. Equipment and materials may be strewn about the mine opening. Debris fields, blocked openings, roof falls, flooded areas, gas accumulations and active burning make it very difficult or impossible for those managing the post-event emergency to permit mine rescue teams to enter the mine to conduct search and rescue operations.

With the evolution of robots and robotic assist technology there has been a proliferation of purpose-built units for the military, police and law enforcement agencies, urban search and rescue and those contending with hazardous environmental conditions. In each case, the technology used is designed to limit human exposure to the unsafe conditions or to provide access to areas under difficult conditions. For example, a specially-designed marine robot has been deployed into the damaged core of the Japan’s Fukushima Daiichi Nuclear Power Plant to assess the conditions of the containment vessels, where melted fuel is believed to have accumulated. Human access to the area is prohibited due to dangerously elevated levels of radioactivity [1]. Multiple robots were deployed in Amatrice, Italy, to assist in the response after the 6.2-magnitude earthquake devastated the town. The robots were used to explore two medieval churches that were severely damaged and deemed too dangerous for human entry [2]. Tactical robots are regularly used by police and law enforcement agencies when the conditions of the emergency place intervening officers directly in harm's way [3].

The Mine Health and Safety Administration (MSHA) commissioned Remotec, Inc. of Oak Ridge, TN to build a mine-worthy version of their ANDROS Wolverine Robot. It was believed that robotic technology would offer significant potential to reduce mine rescue team members exposure to hazardous post-event mine conditions and would provide key information and data to assist in planning and implementing search and rescue operations while exploring ahead of the mine rescue team. Remotec had a readily usable platform in their inventory that was designed, built and tested for challenging applications. The robot was modified to meet MSHA’s specifications for underground usability and intrinsic safety and on February 25, 2004, the V2 variant of this robot was granted approval as having met Part 18, Title 30 CFR. (Approval No. 18-A040002-0), by the MSHA Approval and Certification Center [4]. This robot is deemed to be permissible for use anywhere in an underground coal mine and is the only robot in the United States to be granted this approval (figure 1).

Figure 1. MSHA's V2 Robot [4].

The V2, can travel through an underground mine in conditions that might be unsafe for mine rescue team members to pass through. The robot is approximately 50 inches tall, 29 inches wide and 58 inches long and with the added safety equipment weighs over 1,200 pounds. It is propelled by explosion-proof motors that drive rubber tracks and is equipped with navigation and surveillance cameras, lighting, atmospheric detectors, night vision capability, two-way voice communication, and a manipulator arm [5]. The V2 is operated remotely from a safe location, has the capability of exploring up to 3,500 feet, and can communicate vital information about the conditions in the mine over a fiber optic cable. The operator can view real time information including video, and concentrations of combustible and toxic gasses. This information can also be directly transmitted to the MSHA Command Center. The V2, though highly functional and versatile, does have its limitations for use in the underground environment. The unit is tall, heavy and has a sizeable foot print (11.7 square feet). These characteristics preclude its use in tight areas, collapsed zones and areas of low mine roof. Furthermore, the fiber optic cable can easily become damaged or broken if the cable becomes hung up while turning on debris or falls under the unit tracks. The V2 unit has been deployed underground during mine emergencies with varying levels of success.

In 2006, the Mine Improvement and New Emergency Response Act of 2006, also known as the MINER Act, was signed into law. Under this legislation, the National Institute for Occupational Safety and Health (NIOSH) was charged to create an Office of Mine Safety and Health (Office). The purpose of the Office is to enhance the development of new mine safety technology and technological applications and to expedite the commercial availability and implementation of such technology in mining environments. The Office was granted the authority to award competitive grants to institutions and private entities to encourage the development and manufacture of mine safety equipment and to award contracts to educational institutions or private laboratories for the performance of product testing or related work with respect to new mine technology and equipment [6]. Under this authority, NIOSH initiated work to develop smaller, more versatile robotic technology to assist mine rescue teams in post-event mine exploration and evaluation.

GEMINI-SCOUT MINE RESCUE VEHICLE DEVELOPMENT AND TESTING

Under an Interagency Agreement (IAA), Sandia National Laboratories' (Sandia) Intelligent Systems, Robotics and Cybernetics group in Albuquerque, NM, was tasked by NIOSH to develop a mine rescue version of their Gemini unmanned vehicle (also known as the Gemini-Scout Mine Rescue (GSMR) vehicle). The GSMR vehicle was designed for maximum mobility to enable the vehicle to overcome a wide variety of obstacles and terrains, such as rubble, water, mud, and track [7]. The primary mission of this vehicle is to act as a scout to assist mine rescue teams to move safely and efficiently through hazardous underground environments.

The design criteria for the GSMR included the following:

- Ability to move at 4 to 5 miles per hour in the mine opening;
- Maintain mobility through a debris field that includes mud and standing water (up to 18 inches deep);
- Function in a wireless environment using line-of-sight technology or tethered using fiber optic cabling;
- Operate with battery power for up to 4 hours (and ability for rapid battery recharge);
- Detect oxygen, methane, carbon monoxide and measure temperature;
- Enable two-way voice communication; and
- Provide 100 feet of lateral illumination for color and infrared video.

Construction of the robot was completed followed by rigorous testing and evaluation conducted by Sandia and then by NIOSH. Figure 2 shows the GSMR vehicle as delivered to NIOSH. The GSMR vehicles have extreme ground mobility, PC-Based control interface, pan-zoom-tilt color and IR cameras with lighting, a 2-way radio, gas and temperature sensors and available I/Os for adding payloads and sensors. Rigorous testing at NIOSH damaged several components and identified several technical problems. Follow-up work with Sandia was conducted to update, refurbish and improve the units and provide in-depth training and technical support. This work included altering the software to ensure that the vehicle would power down when a high concentration of methane gas was encountered and adding a spooling device to the rear of the robot that would hold up to a kilometer of fiber optic cable (figure 3). Recognizing that the GSMR could be deployed in an emergency by MSHA's Mine Emergency Operations Branch (MEO), in-mine training and testing was expanded to include the MEO mine rescue experts, escalating that effort to a high-level final technical evaluation. Once the upgrade and refurbishment work was completed, Sandia returned two of the GSMR vehicles to NIOSH and retained the third vehicle for testing system upgrades and troubleshooting if problems developed.

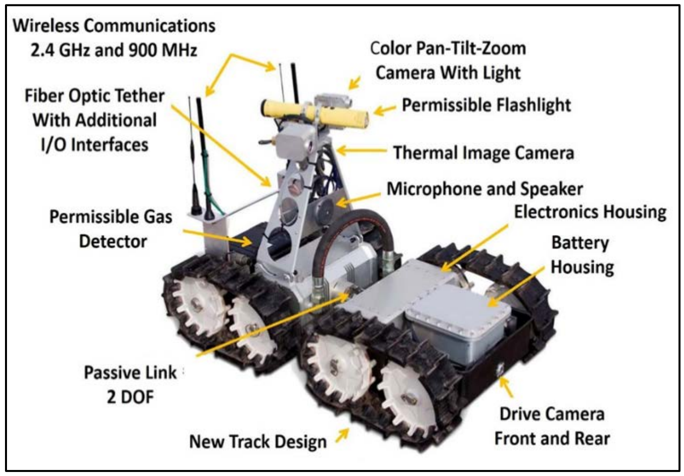

Figure 2. Gemini-Scout Mine Rescue Vehicle [7].

Figure 3. GSMR Vehicle in use in the underground mine.

After completing the Sandia training the MEO team took control of the GSMR units for a 30-day field test, additional issues were discovered with the weight associated with the nickel-metal hydride batteries and the reliability of the track drive motors. It was decided to change onboard battery chemistry from nickel-metal hydride to lithium-ion batteries to reduce weight and to limit battery failures. In addition, recommendations were made for improving the lighting on the unit by switching from the permissible flashlight to a LED light panel and to ruggedize the fiber optic spooling system to make it more mine-worthy. At the time of the completion of this paper, a new IAA was being negotiated to conduct the follow-up improvement work. It should be noted that this vehicle is not permissible, though many of the features were designed with permissibility in mind.

NOTABLE GSMR VEHICLE ACHIEVEMENTS

During testing of the prototype GSMR vehicles the following were achieved:

- The ability to communicate with the robot from the Operator's Console via radio frequency transmissions in an operating underground coal mine for a distance of over 500 feet. This was accomplished in a straight-line mine entry containing significant floor undulations. Testing at the NIOSH mine yielded communication distances over 1,100 feet in a mostly flat straight-line entry.
- The GSMR vehicle was able to navigate over and through various obstructions made of cribbing block, stopping blocks, rib and roof material, brattice cloth, rock dust and pooled water (up to 18 inches deep) (figure 4).
- MEO was able to operate the GSMR vehicle for a distance over 2,600 feet from the operator's console using the fiber

optic cable. The GSMR vehicle was driven around corners of coal pillars during this excursion.

- MEO was able to link the GSMR vehicle output with the MSHA Command Center and operate the robot remotely from the surface while the robot was in the underground mine (figure 5).
- It was demonstrated that the GSMR vehicle can be operated and maneuvered remotely by only using the onboard cameras.

Figure 4. GSMR vehicle driving over a pile of stopping blocks.

Figure 5. MEO officials operating the GSMR vehicle from the MSHA Command Center.

SARCOS SNAKE ROBOT DEVELOPMENT AND TESTING

Following a large-scale mine fire or explosion, boreholes are often drilled from the surface to the mine opening to determine the conditions of the workings. Underground information is typically collected using camera-based technology and sampling of the gases in the mine atmosphere. This information unfortunately only represents the immediate area near each borehole or other mine access points (i.e. shafts or slopes). It was thought that a borehole deployable exploration robot would provide the exact capability needed to assess the mine conditions beyond each mine access point, expanding and improving the data needed by mine rescue operation decision makers. To address this need, NIOSH awarded a contract to Sarcos in Salt Lake City, UT to design and construct a borehole deployable robot for post-event mine exploration operation by modifying their existing tandem track snake robot technology. The design constraints for the borehole robot included:

- The ability to move at 1 to 2 miles per hour in the mine opening,
- Maintain mobility through a debris field which includes mud and standing water,
- Operate tethered with cabling of sufficient strength to be lowered vertically 2,000 feet through a borehole,
- Sized to fit inside a 4-inch diameter borehole,
- Onboard technology to detect oxygen, methane, carbon monoxide and measure temperature,
- Enable two-way voice communication,
- Receive power for accessories through either onboard batteries or a tether cable, and
- Provide 200 feet minimum lateral illumination to support color and infrared video.

Figure 6 shows technology incorporated into the Snake Robot as delivered to NIOSH. The specifications of the robot include: overall length – 63.5 inches, body length – 54.6 inches, diameter – 4.01 inches, weight – 27 pounds and for mobility 11 degrees of freedom [8].

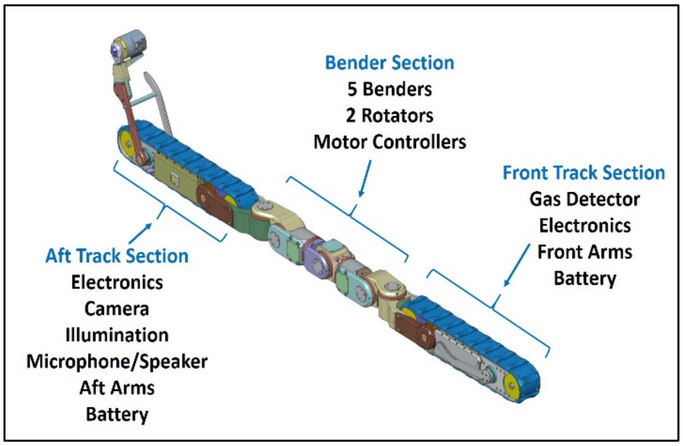

Figure 6. Snake Robot [8].

In addition to extensive lab testing, robot performance was also evaluated in the NIOSH test mine in Bruceton, PA. The evaluations were conducted using Sarcos experts operating the robot under numerous test scenarios including operation of the robot through a borehole (figures 6 and 7). In each case, the skilled operators were able to navigate the robot through in-mine obstacle courses and challenges that were designed to simulate post disaster debris and to test the robot's capabilities.

Figure 7. Snake Robot being lowered into the NIOSH mine through a borehole.

After completion of the contract, it was decided that additional work was needed to address deficiencies (repair optical connection in reel enclosure, replacement of out-of-date sensors and update the Operator Control interface) that were discovered during the in-mine evaluations. In-mine training and testing for the MEO mine rescue experts was added to the Sarcos work scope. It was believed that this new work would confirm the Snake Robot's ability to operate in the underground mine environment.

Figure 8. Snake Robot traversing a stopping block debris field. Note, the lighting for this image was provided by the robot's onboard LEDs.

Follow-up work with Sarcos was designed to address the discovered deficiencies described above, install new batteries if needed, update the user's manual, provide hands-on training and technical assistance during the conduct of the field evaluations in collaboration with MSHA Mine Emergency Operations (MEO) personnel. Once the robot was delivered to NIOSH and the training was completed, the robot was turned over to the MEO team for 30 days of field testing. Feedback provided to NIOSH indicated a potential software or hardware problem in the middle section of the robot as it enters a mine opening from a vertical position and the MEO suggested an improvement to the design of the way the tether enters the robot chassis. The current design led to failure of the fiber optic cable at that connector.

At the time of the completion of this paper, a final contract was being negotiated to conduct the follow-up improvement work. As with the GSMR vehicle, this robot is not permissible, though many of the features were designed with permissibility in mind.

NOTABLE SNAKE ROBOT ACHIEVEMENTS

During testing of the prototype Snake Robot the following were achieved:

- Successful deployment of the robot through a borehole.
- Demonstrated the ability to drive the robot through 12-inch deep ponded water. This was done with some difficulty and the robot operator was positioned nearby the robot.
- The ability to navigate over and through various obstructions made of cribbing block, stopping blocks, rib and roof material, brattice cloth, and rock dust.
- The ability to configure and position the robot to look through a mandoor in a stopping.
- The ability to sense methane gas in the mine atmosphere. This was confirmed by placing calibration gas in the vicinity of the robot.
- The ability to operate and maneuver the vehicle by only using the onboard lighting and camera system at lateral distances up to 100 feet from the borehole entry point.
- The ability to climb steep slopes. Note: the front claws were particularly helpful when climbing up steep slopes and over objects.
- Built-in functionality including: self-righting capability, the ability to take a humplike stance for climbing, the capacity to offset the front track from the rear track for stability, the ability to increase or decrease the robot's footprint for stability, maneuverability and traction and to reconfigure the robot to sit-up to look over or into obstacles.

MINE RESCUE TEAM ASSIST VEHICLE (AKA THE "MULE") DEVELOPMENT AND TESTING

When emergencies and catastrophic events occur in the underground mining industry, mine rescue team members place themselves at a higher level of risk while responding to such emergencies and face not only the compromised mine environment but also demanding and grueling manual labor. NIOSH, recognizing this need, began to develop the concept of operations for a mine rescue team assist vehicle (also known as the Mule). Before machine design specifications were developed, mine rescue and recovery personnel were consulted to determine the needs of the mine rescue community. Discussions with mine rescue team representatives from the mining industry and state and federal agencies were held to determine their preferences on how the robotic equipment could best be used to improve the mine rescue efforts. The following is a generalized list of design features and considerations that resulted from the discussions.

- The machine must be able to maneuver in an area where the mine floor conditions are poor and it should have sufficient ground clearance to traverse over debris and obstructions. The unit must be able to navigate through at least 18 inches of standing water, work through muddy or soft mine floor conditions, have a low center of gravity and be stable on uneven grades. A track driven machine is preferred because of superior capability over wheel drive machine.
- The machine should be able to move at a brisk walking pace.
- The machine must be compact in size, not only for access beyond the Fresh Air Base but also for doing work in obstructed mine entries and for moving to and from the Fresh Air Base especially when in-mine access is limited. It was suggested that the vehicle be less than 4 feet wide and should weigh between 2,000 to 4,000 pounds. The machine should be small enough to be transported into the mine using the mine elevator and through the mine on a mine flat car.
- The machine should not have sharp edges or appendages which could catch on hanging debris or mesh.
- The machine should have the ability to be moved on rails.
- The machine must have a cargo capacity of at least 1,000 pounds to transport needed materials and supplies or possibly injured miners. It was suggested the machine be equipped to pull lightweight trailers and that the trailer(s) be configured to transport injured miners.
- The machine should have a loader bucket attachment to move debris or carry supplies
- A hydraulic power take-off unit should be provided to power a chainsaw, drill or other tools that may be used in the recovery effort.
- Remote control of the machine with a range of 600 feet from the operator is most desired. A backup control system is needed in case of primary control system failure.
- The vehicle should be equipped with video cameras and gas measurement capabilities including carbon monoxide, methane and oxygen with data transmission capabilities to a remote operator station.
- The machine should have onboard lighting to aid the video cameras as well as to illuminate the work areas.
- Major machine components should be readily changeable and accessible in the event of a machine breakdown or parts failure.

- The machine should be as quiet as possible so that rescue team communication is not disrupted.

NIOSH awarded a contract to Rohmac, Inc. of Mount Storm, WV to build a diesel powered mine rescue team assist vehicle. Diesel power was selected over an electric motor design because the electric version would require several complete sets of batteries and additional personnel to manage battery use, transport and recharging. The vehicle was to be built using the MICROTRAXX™ compact track driven machine platform that has been proven and used in the mining industry for many years. Many customized versions of this equipment have been built to perform specific support tasks ranging from a loader for cleaning mine entries or haulers built to carry section fans and power centers, to a cutter for cutting shelter holes. Many designs have provision for multiple attachments that can be quickly changed to perform a variety of tasks with one base machine. Radio remote control has been used on MICROTRAXX™ machines for over fifteen years. This allows the machine to work in places that may be unfit for personnel, such as confined spaces, while the operator is located in a safe area. The controls used on this equipment have been tested to a range of nearly 600 feet in open air line-of-sight [9].

The priority design constraints for the Mule were focused on building a machine that was compact, yet mine-worthy enough to operate in the post-event mine environment, to have the ability to attach and operate a variety of mine tool implements and be remote controlled to allow operators to remain a safe distance from the machine. Communications and video equipment were requested to provide the machine with forward exploration capability and allow it to record the immediate mine environment conditions. The primary machine functions were to move away post-event debris and to transport materials, rescue team members and injured miners. The overall intention of this effort was to design and develop a machine to support mine rescue and recovery operations while reducing the risk of exposure to the rescuers.

When the Mule was delivered to NIOSH, testing was conducted at the West Virginia University Academy for Mine Training and Energy Technologies, also known as Dolls Run, in Core, WV (figure 9). The MEO team participated in the testing of the vehicle at Dolls Run and operated the Mule while under a breathing apparatus to simulate mine emergency conditions and to test the ease of operation of the vehicle. Testing consisted of operating the vehicle remotely using radio frequency signals, driving the vehicle in an entry filled with theatrical smoke, turning the vehicle around in tight spaces with and without a trailer in tow and driving over a crib block obstacle (figure 10). Debris was also moved using the onboard bucket and grappling arm.

Figure 9. Mule with an MSHA MEO operator at the Dolls Run Facility.

An evaluation of the Mule after testing revealed a few shortcomings including refinement needed to operate the vehicle using the tether, and improvement of a pad based operator's control unit. It was decided that these items would be addressed under a follow-up contract that included pursuing MSHA permissibility certification.

Figure 10. Mule with a trailer in tow inside the Dolls Run Facility.

NOTABLE MULE ACCOMPLISHMENTS

During testing of the prototype Mule, the following were achieved:

- The utility of the bucket and grappling arm was demonstrated. The unit was capable of plowing debris out of the travel way or could pick up problematic pieces of debris.
- The unit was operated using radio frequency control and thus the operator could stand behind of the unit and away from harm.
- The onboard video and lighting capability enable the operator to see ahead of the vehicle.
- It was demonstrated that the Mule could be turned around in a conventionally sized mine entry and in an intersection with a trailer in tow.
- The Mule was able to drive over and through a debris pile made up of cribbing blocks.

DISCUSSION

Subsequent to the promulgation of the MINER Act, NIOSH researchers set out on a course to develop smaller, more versatile prototype robotic technology to assist mine rescue teams in post-event mine exploration and evaluation. This task is being accomplished through the design, development and testing of three distinctly different prototype robotic vehicles. The GSMR vehicle and the Snake Robot are designed to explore areas ahead of the Fresh Air Base where conditions could be too dangerous for mine rescue teams.

The GSMR vehicle has demonstrated long-range capability that makes it particularly useful for missions that require inspection of a large number of entries. The Snake Robot has a more limited range of 100-200 feet laterally from the insertion point and because of its size can be deployed in 5-6 inches diameter cased boreholes. This robot also has the ability to work in tight places. Both technologies have the ability to navigate through standing water of depths up to 12 inches for the Snake Robot and 18 inches for the GSMR vehicle.

Rigorous and demanding testing has revealed shortcomings and that have led to equipment failures and modifications. This was expected given that each technology must be considered in the prototype stage for the underground mine environment, with its own unique MSHA permissibility requirements for full utilization in an emergency situation. NIOSH made additional requests of the developers for modifications as the utility of the units evolved and the needs of the rescue team members became more defined. These additional modifications did in the end improve functionality. Both the GSMR and Snake Robot as developed for this mining application fill an important niche, but the full development costs to move beyond the prototype stage for units that will never be commercially available, because of the limited application, makes their future uncertain. Developing both units for permissibility would involve trade-offs that would negate many of the properties that make them attractive for use in a mine emergency situation, such as speed or size. NIOSH is currently evaluating that future path.

The Mule is designed to be a rescue team assist vehicle and its mission was readily defined. The selection of the MICROTRAXX™ platform for this vehicle appears to be an ideal choice given its versatility and pre-existing commercial viability within the mining industry. The designers feel that the Mule could also be used on tether for exploration in advance of the Fresh Air Base given its video and gas sensing capabilities. NIOSH is currently funding the submittal of the Mule through the MSHA Approval and Certification Center for permissibility approval, anticipating its acceptance by mine rescue teams nationwide.

DISCLAIMER

The findings and conclusions in this paper are those of the authors and do not necessarily represent the official position of NIOSH and the Centers for Disease Control and Prevention (CDC). Mention of any company or product name does not constitute endorsement by NIOSH or the CDC.

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