A Campaign in Autonomous Mine Mapping

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***Abstract*— Unknown, unexplored and abandoned subterranean voids threaten mining operations, surface developments and the environment. Hazards within these spaces preclude human access to create and verify extensive maps or to characterize and analyze the environment. To that end, we have developed a mobile robot capable of autonomously exploring and mapping abandoned mines. To operate without communications in a harsh environment with little chance of rescue, this robot must have a robust electro-mechanical platform, a reliable software system, and a dependable means of failure recovery. Presented are the mechanisms, algorithms, and analysis tools that enable autonomous mine exploration and mapping along with extensive experimental results from eight successful deployments into the abandoned Mathies coal mine near Pittsburgh, PA.**

I. Introduction

Subterranean voids, specifically those presented by abandoned mines, are a hazard to their surroundings. Mining operations that encroach upon these spaces risk inundation by water or hazardous gases. Surface structures must cope with issues of subsidence and collapse. In coal mines, the exposed strata continuously generate sulfurous, acidic byproducts that poison the surrounding streams and ponds. The first step in combating these risks is to catalog the existence, extent, and characteristics of these voids. Tens or even hundreds of thousands of abandoned mines exist in the United States alone[1]. Many of these mines were never mapped, and the maps that can be found are often unreadable or inaccurate.

Currently, the identification and verification of the extent of abandoned mines relies entirely on what maps are available and on indirect methods of observation such as ground-penetrating radar, in-seam seismography, or other geophysical techniques[2]. Degraded structural integrity, pockets of lethal or explosive gases, fire, flooding, and other hazards often render these spaces inaccessible to human surveyors. Hardened against these conditions and ultimately expendable, robots are well-suited for operation in these dangerous areas. Carnegie Mellon has developed a mobile robot (Fig. 1) that can autonomously navigate and map dry or partially flooded mine corridors.

Groundhog is a 700 kg custom-built platform with an embedded computer, laser range finders, explosive gas sensors, and low-light digital video system. It is operated by a suite of software modules that handle everything from low-level actuation to navigation and exploration. This document describes the system, with emphasis on the perception, navigation and exploration software that enables Groundhog to autonomously operate in subterranean voids. Groundhog returns with data that is postprocessed into high-quality two-dimensional maps of its traverse as well as data that can be used to generate a full three-dimensional model of the mine. Presented herein are the results from a campaign of eight successful deployments of Groundhog into the abandoned Mathies mine.

Fig. 1. Groundhog: a rugged platform designed to traverse the rough, unpredictable terrain of mine corridors, able to overcome obstacles such as fallen roof timbers, partial sidewall or roof collapses, rail tracks and deep mud. Shown here at the north portal to the Mathies mine.

II. Platform

A. Chassis

Groundhog is a rugged platform designed specifically to traverse the rough, unpredictable terrain of mine corridors. Common obstacles include fallen roof timbers, partial sidewall or roof collapses, rail tracks and deep mud. The chassis began as the union of two commercial ATV front-ends, allowing four-wheeled Ackermann steering for maneuvering in tight corridors. The original ATV frame has been reinforced and steel guards have been added to protect wire conduits and hydraulic hoses. The locomotion system is electric over hydraulic, with an electric motor powering hydraulic actuators for driving and steering. Critical components such as the CPU, hydraulic pump motor, and actuation electronics are housed in an MSHA-approved explosion-proof enclosure[1]. For safety and simplicity, Groundhog is limited to one speed, approximately 10 cm/s, while operating autonomously. A more

[1]Despite their namesake, this class of enclosures is not meant to completely contain an explosion, but to release its energy in a controlled manner so as not to ignite a potentially explosive mine atmosphere.

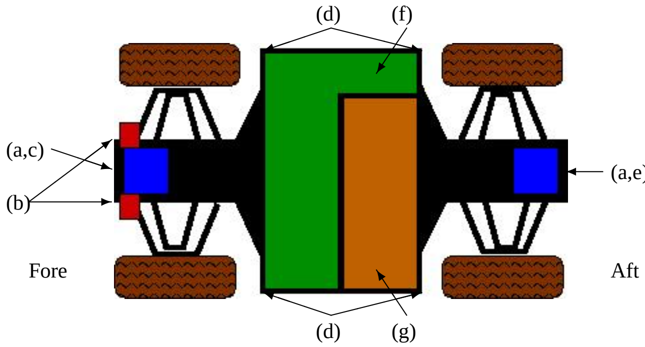

Fig. 2. Groundhog Layout: (a) Laser Range Finders (b) Gas Sensors (c) Low-Light Camera (d) Sinkage Sensors (e) Wireless Ethernet (f) Batteries (g) Main Electronics Enclosure (CPU, Tilt, Gyro, Control Circuitry)

complete overview of the system configuration may be found in [3].

B. Perception

Groundhog's sensor layout is depicted in Fig.2. The laser scanners are manufactured by SICK (model LMS-200) and serve as the primary mapping and navigation sensors. The lasers scan 180-degree arcs in front of and behind the robot and are tilted through 60 degrees to generate three-dimensional scans of the local terrain for obstacle avoidance and path planning. The nearly complete symmetry of the configuration allows Groundhog to change its direction of travel without the need to turn around, which may be impossible given the width of a deteriorating mine corridor.

C. Communications

Among Groundhog's electronics is a commercially available 802.11b access point with bandwidth and fragmentation thresholds set to maximize signal integrity for communication with the surface, when possible. To avoid communication lockups as the signal degrades, data is transmitted exclusively using UDP. Under normal circumstances, the robot reports basic state information and can accept a small number of simple commands, including the command to egress from the mine. In situations where the autonomous navigation system malfunctions, it is possible to view laser scans and attitude information from the robot and issue velocity commands to teleoperate the machine into, or more likely out of, a mine.

III. Autonomous Navigation

Groundhog follows a canonical Sense, Plan, Act cycle[6]:

- **Sensing:** From a static pose, the currently active sensor (depends on direction of travel) takes a three-dimensional scan of the environment. The world is then discretized into 10cm squares upon which a local gradient map is generated.
- **Planning:** The gradient map is processed as in [4] to ascertain a set of suitable goal locations, ordered by distance, and to derive a cost grid for path planning. The A* algorithm[5] is used to compute the best path to the farthest reachable goal.
- **Action:** The path returned by the planner is executed by the robot. Odometry and scan matching provide feedback to the motion controller and allow Groundhog to follow the designated route. Once the goal has been reached, the robot stops and repeats the cycle.

The Sense, Plan, Act paradigm is a well established control model for many robotic systems in indoor environments[7]. Given Groundhog's limited on-board processing[2], this cycle takes approximately 90 seconds and requires a relatively static environment. This is a reasonable assumption in abandoned mines, whose most dynamic features are drops of water and resettling piles of rubble.

The bulk of the implementation, along with the statistical methods and formulation behind it, is thoroughly described in [4]. Some details are recounted here in brief; the rest of the section describes the modifications and enhancements made to the system as motivated by lessons learned in field experiments.

A. Sensing: Terrain Maps

The autonomous cycle begins by acquiring a 3D scan of the terrain forward of the robot, obtained by tilting the active laser scanner from 20 degrees above horizontal to 40 degrees below horizontal. This model is projected into a $2\frac{1}{2}$D terrain map where the gray level of each cell in the map reflects its traversability; lighter cells are easier to traverse than darker cells. See Fig.3 for an example 3D scan and its corresponding terrain map.

The terrain map is obtained by first discretizing the world into 10 cm square cells in the $\langle x, y \rangle$ plane, then by analyzing all point measurements $\langle x, y, z \rangle$ that fall into each cell. Within each cell, $\{x_{\min}; x_{\max}\} \times \{y_{\min}; y_{\max}\}$, the algorithm first determines the minimum and maximum z-values, denoted $\underline{z}$ and $\bar{z}$ respectively. The difference $\bar{z} - \underline{z}$ is called the navigational coefficient and loosely corresponds to the ruggedness of the terrain. Points for which $\bar{z} - \underline{z}$ significantly exceeds the height of the vehicle are ignored as parts of the ceiling. For each cell, the differences between its $\underline{z}$ and $\bar{z}$ values and those of its immediate neighbors are computed and incorporated into the cell's navigational coefficient. This step estimates the traversability across cells of the map.

If no information is available for a given cell, the terrain values of nearby cells are interpolated to produce estimates for $\underline{\tilde{z}}$ and $\tilde{\bar{z}}$. This interpolation is crucial for navigation in partially submerged areas of the mine where laser readings will often reflect off the surface of water when the incident angle is large, leaving substantial holes in the terrain map. It approximates the surface level of the water, but no information concerning the depth or the nature of the underlying structure is available. Thus, these interpolated areas are potentially dangerous and their navigational coefficients are biased accordingly. The terrain map is subsequently convolved with a narrow radial kernel that simulates a repellent potential field and converts

[2]Groundhog is operated by a 300 MHz PC/104 form-factor embedded computer with 256 MB of RAM

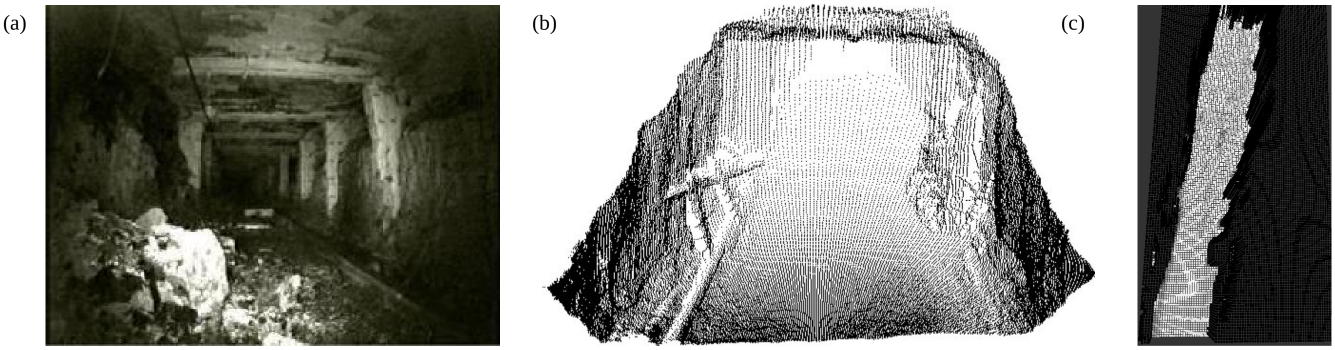

Fig. 3. From Mine Corridor to Cost Map: (a) An image, deep in the mine, taken by Groundhog's low-light camera. (b) A 3D point cloud obtained by the laser scanner in a similar corridor. (c) The corresponding traversability map where brighter spots are easier to traverse.

the terrain map into a navigational cost map. The number of cells for which there are no readings is recorded as an indication of how much of the local area is covered by water. This information is used to decide whether the robot should plan over the complete space or to bias its attention to one side of the corridor, as described below.

B. Planning: Configuration Space Maps and Goal Selection

The terrain map is used to construct a collection of maps that describe the robot's configuration space, or C-space[6]. The C-space is the three-dimensional space of poses that the vehicle can assume, consisting of the $\langle x, y \rangle$ location along with the vehicle's orientation, θ. The C-space maps are obtained by convolving the terrain map with oriented kernels that describe the robot's footprint. Fig.4 shows some of these kernels. The highest kernel value is placed in the wheel area of the vehicle, with comparatively small values assigned to the non-contact area in between, where the vehicle's clearance is approximately 30 cm. The result of this transformation is a collection of C-space maps, each of which represents a different vehicle orientation.

The reasoning behind this selection of kernels is a function of the environment. Notwithstanding fallen rocks or timbers, the most prevalent ground features in abandoned mines are railroad tracks, once used to haul personnel into and coal out of the mine. It is acceptable, often preferable, to navigate with a track between the wheels, but excessive interaction with these tracks causes the robot to consume more energy and can even damage the robot catastrophically by puncturing or unseating a tire. By assigning higher costs to the wheel areas, the intent is to make crossing the tracks a more expensive proposition than following them.

Many large mine corridors contain two sets of railroad tracks, side by side. The safest area to navigate is directly over either of the two tracks. However, between the sets there can exist significant dips in which the robot may get stuck. Hence, it is imperative to keep the robot focused on one side of the corridor when water prevents it from perceiving the ground structure. If the rate of data loss due to water surface reflection exceeds a predefined threshold, the planner applies another filter to the C-space map before proceeding to path selection. This additional step constrains the C-space maps in an effort to bias the robot's path to one side of the corridor and keep within a predetermined distance of the mine wall.

The A* algorithm[5] is then applied to the resulting C-space maps. The A* search is initiated with a set of goal points in decreasing order of distance from the robot. These goals are selected based on prior pose information to maximize motion down the center of the current corridor and are constructed to coincide with non-obstacle areas of the C-space maps. If there is a wall bias to be considered, the goals are reselected to lie within the restricted C-space corresponding to the preferred side of the corridor.

If the robot is unable to find a path to any of the goals generated, it concludes that the corridor is unnavigable and begins exiting the mine.

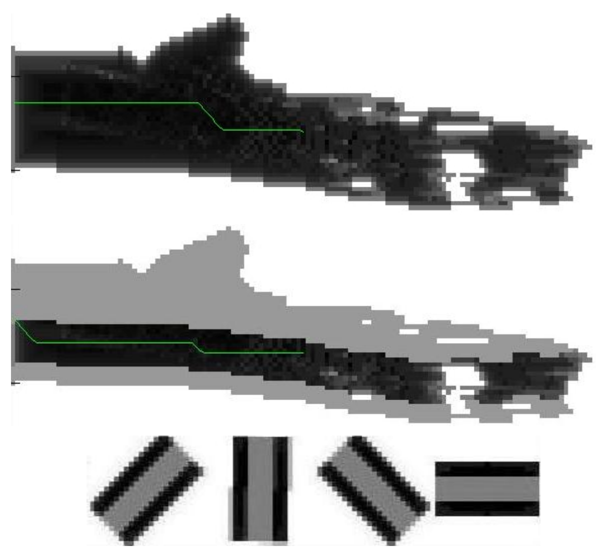

Fig. 4. Cost Map to Paths: White areas have higher cost; paths are in green. Top: An unbiased path through the center of the corridor. Middle: A path biased to the right side of the corridor. Bottom: Example convolution Filters

C. Action: 2D Scan matching

The path returned by the planning module is executed by visual servoing. As in [8], [9], an incremental scan matching technique registers scans acquired using a forward-pointed laser range finder while the vehicle is in motion. This algorithm aligns scans by iteratively identifying nearby points in pairs of consecutive range scans, then calculating the relative displacement and orientation of these scans by minimizing the quadratic distance of these pairs of points[11]. This approach leads to the recovery of two quantities: locally consistent maps and an estimate of the robot's pose. This pose estimate is used to correct the substantial drift in the robot's odometric pose estimation and allows the robot to more closely traverse its selected path.

IV. Operational Safeguarding and Failure Recovery

Under controlled conditions, an emergency stop switch and CPU restart button are sufficient mechanisms to safely and reliably operate the robot. However, in a field deployment, the hazardous nature of abandoned mines prohibits physical interaction. To ensure the robot's consistent and safe return from the mine, it must be able to respond to environmental hazards and recover from system failures.

Groundhog has five[3] basic modes of operation.

- **Exploration.** The robot explores inward using 3D path planning and obstacle avoidance.
- **Normal Return.** The robot proceeds out of the mine using 3D path planning as in the exploration mode.
- **Aggressive Return.** The robot temporarily degrades to simple 2D corridor following using the rear laser when 3D planning fails to find a path out of the mine.
- **Hazard Idle.** If the robot encounters an explosive atmosphere, all external devices are powered down and the system idles until the condition passes or power is depleted.
- **Teleoperation.** While the robot is in wireless ethernet range, it is possible to interrupt the autonomous cycle and operate the vehicle remotely.

Fig.5 illustrates the transitions between these states in response to three problem classes: Component Failure, Software Failure, and Environmental Hazards.

A. Component Failures

Many hardware failures are catastrophic and will result in the permanent loss of the robot. There are, however, several simple hardware failures that may be successfully mitigated, listed in Table I.

TABLE I
COMPONENT FAILURE RISKS AND MITIGATIONS.

Risk	Mitigation
CPU Lockup	Reset Watchdog Timer
Lasers Not Responding	Power Cycle Lasers
Front Laser Failure	Initiate Egress
Gas Sensors Not Responding	Initiate Egress
Wireless Bridge Not Responding	Power Cycle Bridge

[3]A sixth mode in which the robot would drive backward blindly in a final effort to exit the mine was rejected on grounds operational of safety

B. Software Failures

Groundhog's software system is managed by a master process that executes all the software modules on system startup and monitors them for failure. On initial startup (before entering a mine), the master process sets a persistent flag in the file system that is detected on any subsequent reboot and immediately initiates exit from the mine.

If a software module is terminated unexpectedly, the event is logged, the entire software system is reinitialized, and egress is initiated. If the software system cannot be restarted, the CPU is rebooted with the hope that restarting the system will resolve the failure. For lack of a better alternative, this reboot cycle will persist until the failure is resolved or power is exahusted.

V. Field Campaign

A. Location

As an uncertified[4] vehicle, special consideration was given to the choice of mine for field experiments. In close coordination with MSHA and PA-DEP, the Mathies mine (Fig.6) was selected given the following requirements:

[4]MSHA nominally requires strict and rigorous safety testing before permitting any device to operate in a mine.

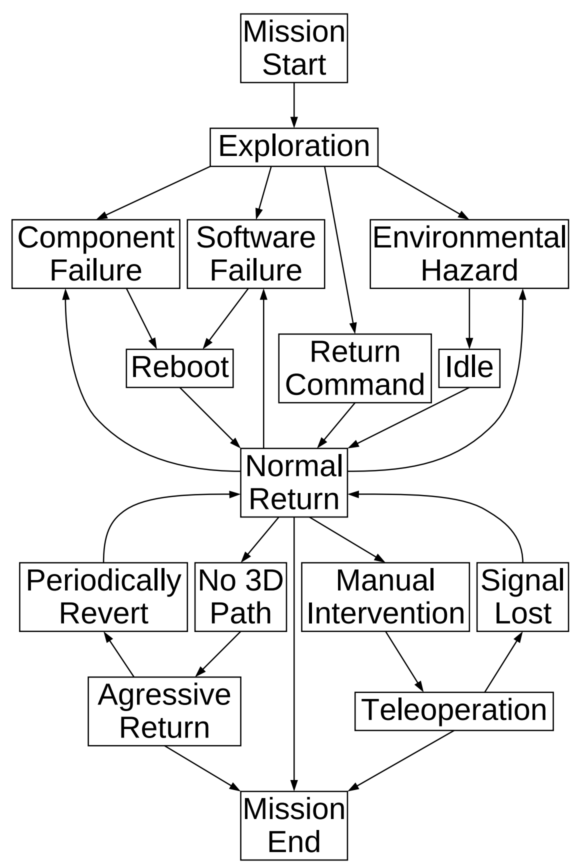

Fig. 5. Groundhog's State Transition Graph. Nodes with multiple outgoing edges branch depending on the type and severity of the problem.

- Historically benign environmental characteristics: good natural air flow, minimal explosion hazard.
- Abandoned comparatively recently, with a prior map to compare results.
- Exploration and mapping provides useful results for MSHA and PA-DEP.

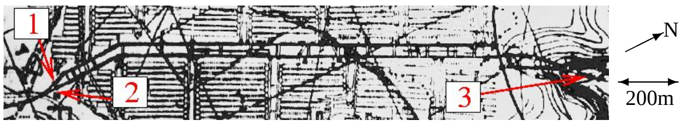

Fig. 6. The prior map of Mathies, with the three portals labeled. The corridors of interest run horizontally from left to right. Note the inaccuracy in the map on the right side (the corridors are misaligned). The image represents approximately 1200 meters from left to right.

After working closely with these agencies and with the mine owner, we were granted access to the Mathies mine, which until 2000, had been used as a coal haulage route to move freshly mined coal through a small mountain rather than over it. Since the mine was abandoned, acidic runoff from Mathies and other nearby mines has been building up on one side of the mountain, and PA-DEP has been charged with pumping the runoff to a treatment facility on the other. PA-DEP is interested in running a pipeline through the old Mathies mine to avoid the expense of laying pipe and pumping the water over or around the mountain. Under this premise, we were granted an experimental variance to autonomously explore the Mathies mine in order to evaluate its condition.

As highlighted in Fig. 6, there are three portals into Mathies[5]. On the left side of the map, two portals lay next to each other, separated by approximately 10 meters. These two portals lead to two separate corridors that run roughly parallel to each other for approximately 900 meters. There they join together into one larger corridor and proceed another 200 meters to the single portal at the other end, near the treatment facility.

B. Conditions

Portals 1 and 2 are dry, with a single set of railroad tracks running the length each and a small drainage ditch to one side. Portal 3 is at a lower elevation and thus contains a significant portion of the residue and runoff from the mine. The resulting terrain is dominated by 10-20 cm of orange, sulfurous mud[6] interwoven with small areas of slowly flowing water. As previously mentioned, this area of the mine has two tracks on raised beds, with a steep-walled drainage trench that can be as deep as 50 cm. The discovery of this trench necessitated wall-biased navigation as described above.

C. Operations

Groundhog's inaugural mission into Mathies took place on May 30, 2003[7] and is documented in [3]. The robot entered Portal 1 with the goal of autonomously traversing the entire mine from end to end. Instead, Groundhog encountered a fallen roof timber (see Fig.7) 308 meters into the mine and decided to turn back. Subsequent system failures stranded the robot approximately 160 meters from the portal, and on-site inspectors received permission to suit up and walk into the mine to recover the robot. The lessons learned from that first deployment led to the development of the fault-tolerance paradigm described above.

Fig. 7. Fallen roof timber 308 meters inside portal 1 (Photograph Courtesy PA-DEP)

Groundhog was redeployed into Mathies seven times over the course of October 2003. With the new failure recovery measures in place, the extents of Portals 1 and 2 were explored and mapped without incident. The partially submerged corridor inside Portal 3 interfered with terrain estimation and neccessitated the algorthmic developments detailed in Section III. Groundhog's final mission, on October 30, successfully explored portal 3 for 200 meters to a fork in the corridor, and an additional 30 meters into the right side before encountering a fallen cable. The cable blocked the path of the machine and it began to exit the mine. On the way out, the robot became lodged in a drainage ditch 40 meters from the portal. Unable to find a return path by 3D planning, the system reverted to "Aggressive Return" and subsequently crashed. The failure recovery system reinitialized the software system, and once restarted, the autonomous cycle was interrupted and the vehicle was teleoperated out of the mine.

D. Results

Table II summarizes the Mathies campaign. Groundhog successfully mapped 800 of the possible 2100 meters[8] of mine corridor, autonomously traversing in excess of 2 kilometers in the process. The results of these eight deployments are displayed in Fig.8, showing the generated 2D maps and 3D scans of the mine.

The roof-falls encountered in portals 1 and 2 have been deemed impassable, so no further exploration is planned for these entries. It is suspected that there is more information to

[5]Throughout the paper, the portals will be referenced as numbered in the figure.

[6]In the mining community, this mud is called "Yellow Boy" and is a primary pollutant of nearby bodies of water

[7]Known as "Groundhog Day" at CMU

[8]The mine is roughly 950 meters per corridor, plus 200 meters after the fork near Portal 3.

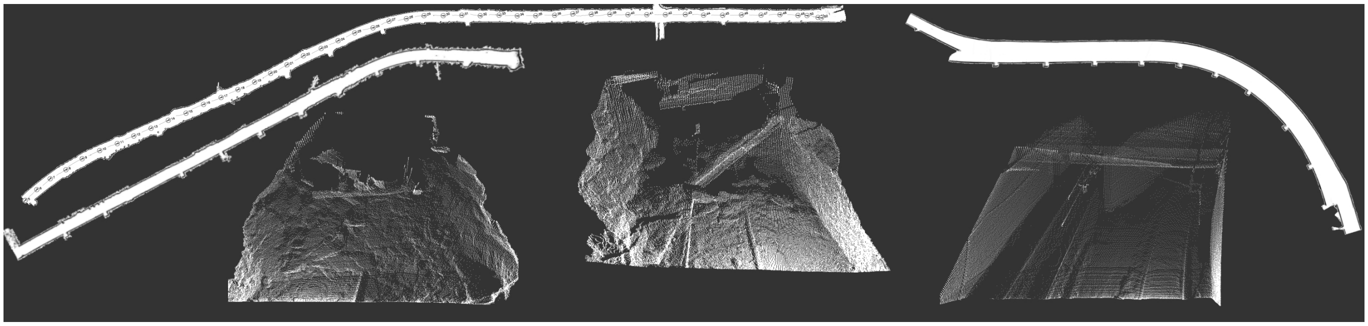

Fig. 8. Results from the Mathies Mine: The 2D maps are approximately scaled and aligned to match the orientation in Fig.6. The 3D scans are, from left to right, The roof-fall encountered 140 meters into portal 2, the fallen timber encountered 308 meters into portal 1, and the fork in the corridor encountered 200 meters into portal 3.

TABLE II
SUMMARY OF FIELD DEPLOYMENTS OF GROUNDHOG INTO THE MATHIES MINE DURING MAY AND OCTOBER 2003.

Mission	Date	Port	Goal	Comp	Return Caused By	Duration	Egress	Comments/Results
1	05/30	1	500 m	308 m	Roof-Fall	2 hr, 35 min	No	Robot Stranded
2	10/01	2	100 m	100 m	Mission Complete	48 min	Yes	Complete Success
3	10/01	1	100 m	100 m	Mission Complete	43 min	Yes	Complete Success
4	10/01	3	100 m	60 m	Submergence	30 min	Yes	Slid Into Drainage Trench
5	10/08	2	500 m	140 m	Roof-Fall	1 hr, 21 min	Yes	Hard Drive Failure
6	10/22	3	100 m	20 m	Software Problems	20 min	Yes	Navigation Malfunction
7	10/22	3	100 m	10 m	Software Problems	9 min	Yes	Navigation Malfunction
8	10/30	3	330 m	230 m	Fallen Cable	2 hr 20 min	Yes	Teleoperated Out

be gained by further exploration of portal 3. Groundhog's last mission reached a fork in the tracks 200 meters inside portal 3 and began exploring the right-hand corridor, corresponding to portal 1 at the far end. The fallen cable that caused Groundhog to turn back may be circumvented with careful planning, after which up to 600 meters of corridor may be open for additional exploration and mapping. The left-hand corridor remains completely unexplored, and may also be open for several hundred meters.

VI. SUMMARY

We have described a mobile system, Groundhog, for the robotic mapping of dry and partially submerged mines. Over eight missions, Groundhog has met the hazards and challenges of an abandoned mine and returned seven of those eight times without physical intervention. Groundhog has logged over 10 hours of autonomous operation and has autonomously traversed in excess of two kilometers in an abandoned mine. Groundhog is a robust, reliable system capable of collecting data and generating maps of hazardous environments where no human should go.

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REFERENCES

[1] J.J. Belwood and R.J. Waugh. Bats and mines: Abandoned does not always mean empty. *Bats*, 9(3), 1991.

[2] USGS CMG InfoBank Definitions http://walrus.wr.usgs.gov/infobank/programs/html/main/definitions.html

[3] C. Baker, Z. Omohundro, S. Thayer, W. Whittaker, M. Montemerlo, and S. Thrun. A case study in robotic mapping of abandoned mines. *FSR-03*.

[4] D. Ferguson, A. Morris, D. Hähnel, et. al. An Autonomous Robotic System for Mapping Abandoned Mines. *NIPS-2003*

[5] S. Russel and P. Novig (1995) *Artificial Intelligence, A Modern Approach* Englewood Cliffs, New Jersey

[6] J.-C. Latombe. *Robot Motion Planning*. Kluwer, 1991.

[7] G. Oriolo, G. Ulivi, M. Vendittelli Real-Time Map Building and Navigation for Autonomous Robots in Unstructures Environments *IEEE T-SMC*, June 1998.

[8] J.-S. Gutmann and K. Konolige. Incremental mapping of large cyclic environments. *CIRA-00*.

[9] D. Hähnel, D. Schulz, and W. Burgard. Map building with mobile robots in populated environments. *IROS-02*.

[10] D. Hähnel, D. Fox, W. Burgard, and S. Thrun. A highly efficient Fast-SLAM algorithm for generating cyclic maps of large-scale environments from raw laser range measurements. *IROS-03*.

[11] P. Besl and N. McKay. A method for registration of 3d shapes. *PAMI* 14(2), 1992.

[12] M. Bosse, P. Newman, M. Soika, W. Feiten, J. Leonard, and S. Teller. An atlas framework for scalable mapping. *ICRA-03*.