Robotic Survey and Mapping of Mines

Applied Science Project
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Introduction

The techniques demonstrated in this project introduce innovate and efficient methods for gathering data about abandoned and working mines. Resulting information accrued using this technology returns model data that is significantly denser and truer to real mine conditions than conventional survey and geophysical techniques. Consequently, the resulting model data allows for accurate analysis of void volumes, measurements and verification of backfill, evaluation of mine deterioration, and the location and extent of mining operations.

Carnegie Mellon University (CMU) developed and demonstrated scientific methods for the mapping of underground mines using the application of scanning sensors, survey methods, and robotic technologies. During the 1 year program these 3 core technologies were fused together in order to produce an integrated autonomous mapping system which was tested over miles within coal mines. The system was refined throughout the project culminating with 3 days of a mapping demonstration within a working coal mine.

This body of work demonstrates the superiority and effectiveness of using robotic methods for generating 3-D mine models and 2-D maps. Results from this work characterize and show:

- Autonomy using a preexisting map to guide a robot autonomously through a mine.
- Robotic survey automation to efficiently and reliably gather miles of 3-D data.
- The attributes of using radar sensing in a mine to map and supplement lidar data.
- Model accuracy comparing generated 3-D models to preexisting maps.

Wheeling Jesuit University's National Technology Transfer Center (NTTC) worked with CMU on the project. They arranged access with CONSOL Energy, Inc. to a working coal mine for the mapping demonstration, provided insight into the mining industry relative to the technologies, and had significant input into the technology transfer plan.

Equipment:

The project was conducted using an automated surveying instrument and the CaveCrawler robot equipped with a suite of sensors including lidar, radar, and camera.

Robot - CaveCrawler Figure 1, is a 4 wheel drive, tetherless, battery operated body averaging robot that was developed for operations modeling subterranean environments. CaveCrawler weighs 400 lbs is 46 inches wide, 68 inches long and 28 inches tall. In relatively flat terrain the batteries give the robot a range of about 2 miles.

CaveCrawler is operated locally by a wireless joystick, wireless Ethernet, or autonomously using no external communications. On board computing supports low level commands, sensor interfaces, data logging, communications, and autonomy.

Figure 1 CaveCrawler Robot in the Research Mine

Lidar – laser ranging data is the primary sensor for gathering model data and enabling autonomous navigation. CaveCrawler has 2 spinning lidar units mounted symmetrically on either end of the robot. In Figure 1 they are the blue devices on the ends. Each unit collects a hemisphere of 3-D measurement data. The symmetry of the sensors allows CaveCrawler to operate in either direction surrounded with a sphere of mapping data. Each lidar unit has a planar field of view of 180 ° with an angular resolution of 0.25 °, a range resolution of 10 mm , and a scanning range up to 80 m in ideal conditions. Range, not accuracy is affected by the surfaces being mapped and in coal 40 meter ranges are typical. By spinning the lidar units with rotary drives the hemisphere of data is collected. The speed of rotation is varied from slow for stationary high resolution modeling scans to fast for autonomous navigation. Hundreds of thousands of measurements are recorded from the units during scans. All measurements are then referenced relative to the robot's coordinate frame and are post processed to absolute coordinates based on robot position. Navigation software on the robot uses scan data to identify intersections, drive down the center of entries, drive around obstacles, and determine when an area is blocked and to determine speed and orientation.

Radar - The sensor in Figure 2 is a 77GHz-millimetre wave radar unit that provides a full 360 degrees planar scan at 2.5 revolutions per second. The radar system is able to send signal power in each 0.25m cell up to 200m every sensor beamwidth. The radar measurement is reliable in all environmental conditions including smoke, and dust. The radar also has the advantage of penetrating through low density objects such as mine curtains. These characteristics make radar ideal when looking for ways to navigate and model in smoke filled mines or when navigating or searching in areas where mine curtains exist.

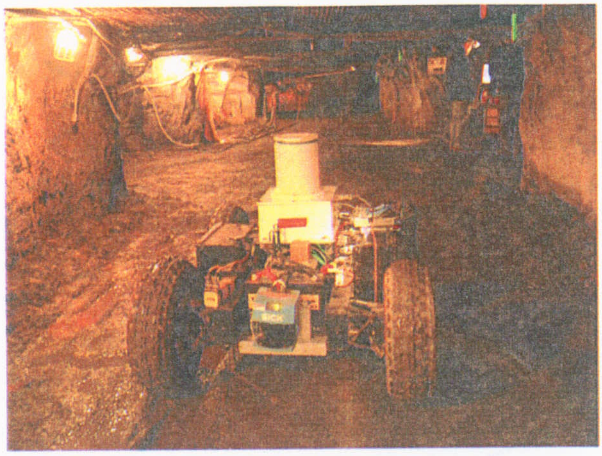

Figure 2: CaveCrawler with the radar sensor

Camera - The robot's imaging system Figure3 consists of a high quality digital still camera and light source mounted on to a motorized turret. This 1-DOF actuation provides the robot with the ability to collect information from a panoramic view of the environment. The current configuration mounts an 8 megapixel camera with a fisheye lens. This provides a 183 degree field of view for each image at 3,264 x 2,448 resolution, of which roughly 50% is usable. The light source consists of two, tangentially mounted 40 watt helical florescent light bulbs to illuminate the scene evenly across the field of view. Images are set for optimal exposure at 20 feet in absolute darkness with only the onboard light source using a lens aperture of f/3.5 and shutter speed of 0.5 seconds. Typical mine images from 1 robot location is shown in Figures 4. Images are stored on the robots hard drive.

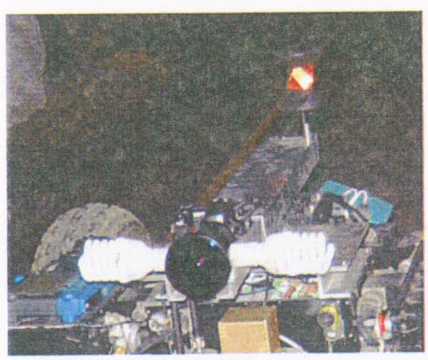

Figure 3: Camera with turret mounted on CaveCrawler

Figure 4: Forward, right, rear, and left camera images captured from CaveCrawler

Additional Robot Sensing – CaveCrawler is also equipped with other sensing that supplements both the robot operation and data collection. Inertial measurement unit (IMU) provides roll, pitch and yaw plus 3 axes of acceleration. The motor controllers provide wheel velocity which is used to compute odometry . A combination voltage and temperature sensor provides voltage conditions from the batteries while the temperature sensor collects the air temperature. The computing interface allows for interfaces to other sensors and Cave Crawler has supported gas sensors, thermal camera (Figure 5), and video cameras.

Figure 5: Thermal camera on CaveCrawler at the Loveridge Mine with thermal image of miners

Automated Surveying Equipment – A robotic survey instrument was used to track the position of the robot and to tie into existing survey reference points. A robotic survey instrument has the appearance and function of a surveyor's total station which includes electronic reading of the horizontal and vertical angles integrated with an electronic distance measuring laser and data collection system. The robotic portion of the instrument adds horizontal and vertical servo motors and a signal return feature that tracks a survey prism thus automating the aiming of the survey instrument.

Figure 6: Automated survey instrument tracking CaveCrawler in the Research Mine

Methods and Results:

A series of modeling experiments were conducted in coal mines over the course of the project in order to characterize project performance. The laboratory work at the university was used to refine methodologies and calibrate sensors for the field work. Processing of the models and analysis of the data was conducted. Four key areas were addressed during this project: autonomy with a preexisting map, robotic survey, radar performance, and model accuracy.

Calibrations

The lidar and radar are the primary sensors used for modeling and navigation. The calibration for these sensors took place at the CMU laboratory Figure 7. With CaveCrawler sitting on a flat floor the spinning lidar units were measured to establish height and mounting positions onboard the robot. The robot was positioned close to the center of a large rectangular room and scans were taken. The resulting 3-D model was then compared to the physical measurements of the room. Small errors that produce slight warpage of the resulting model were resolved and the corrections needed to adjust the model were integrated into subsequent models during post processing. A similar process was used to verify the measurement performance of the 2-D radar. The radar measurements were within the manufacturer's specifications.

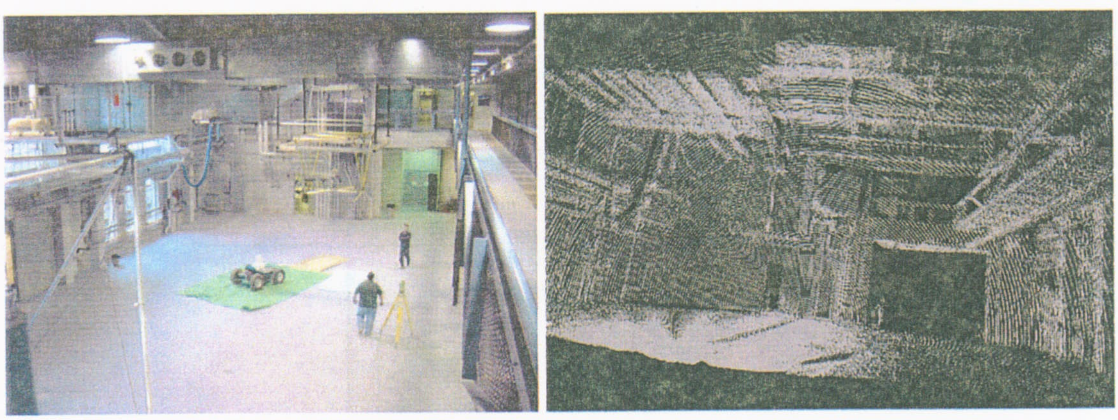

Figure 7: Calibration of sensors in CMU highbay and the associated rear laser scan.

Autonomy with preexisting map

Reliable autonomy is the key to robots operating successfully in abandoned or working mines. CMU had previously developed ways of driving, sensing, identifying and locating intersections in a mine for the purpose of exploration. Software that links the robot autonomy with preexisting maps is an incremental step to autonomy without maps.

The navigation scheme employed on Cave Crawler is a behavior-based system where simple steering routines are managed by higher-order control logic. Based upon 2D navigation schemes, Cave Crawler extends these prior 2D schemes to 3D to take advantage of its 3D LIDAR . At moderate speeds (human walking pace) this simple reactive 3D navigation scheme has shown to be robust.

Higher-order navigation is based upon a topological command structure. The robot is provided with pairings of <distance, action> commands prior to the start of the survey. A typical command list, for example, would have the robot drive straight for 90 meters, turn left, continue for another 30 meters, turn right, and etc. Scanning locations are therefore defined as waypoints (i.e. specific increments) along this path. In addition, both the topological commands and waypoint increments can be dynamically altered during the robot's traverse

For this project preexisting maps of the Research Mine and Loveridge Mine were electronically imported and intersections and corridors were defined as a topological representation. The process starts with digitizing the mine map, defining the intersections and finally creating the topological representation Figure 8. Given the topological representation, a user defined set of waypoints and the onboard navigation allowed the robot to autonomously follow the defined path without human interaction.

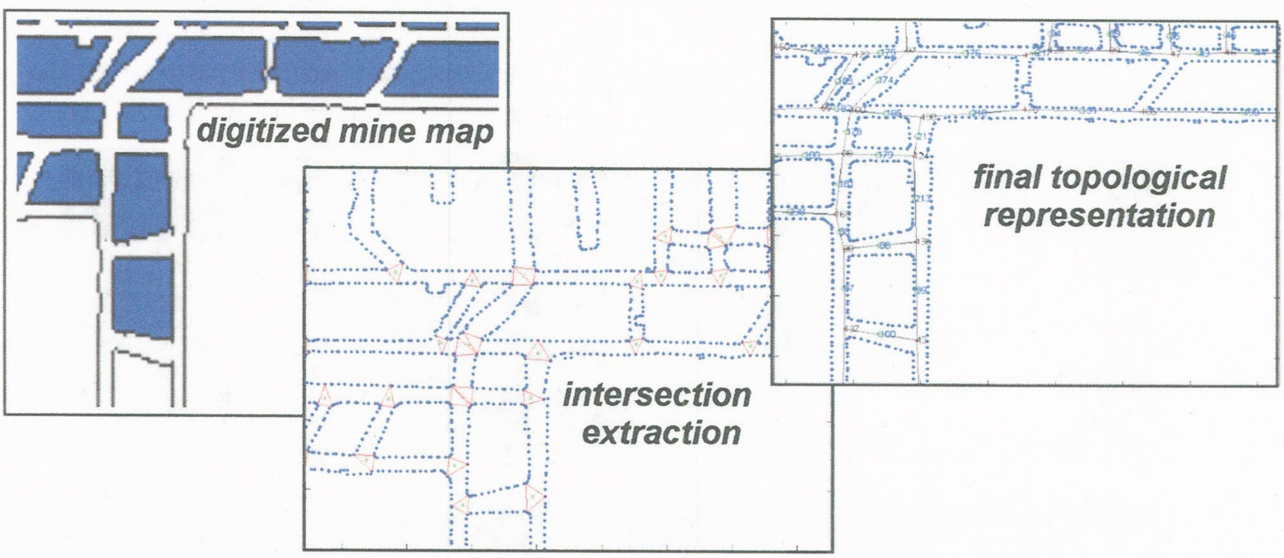

Figure 8: From digitized mine map to topological representation of the Research Mine.

The direct import of the digital maps and conversions requires review and hand work to fill in map lines. In Figure 9 the missing lines from the direct import of a section within the Loveridge Mine are evident. Old maps that are stretched, improperly scaled, or simply not updated add to errors for topological representation. Active mines today keep up to date maps which are accurate and reliable for applying autonomy and the topological representation. In abandoned mines with poor or non existent maps a simple autonomous exploration mode such as drive straight from the portal until you reach a T or dead end and return is implemented. Using the model returned from the initial exploration run the next leg of exploration is implemented. This iterative process described enables full coverage autonomous exploration and development of topological representation.

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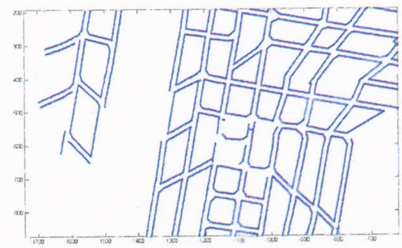


Figure 9: Digitized import of the Loveridge Mine map reveals broken and missing lines

3-D autonomy was successfully demonstrated in traversing 1800 ft portal to portal with no human interaction at the Research Mine Figure 10. The robot traversed the entire red and blue path from portal to portal during testing in December. Subsequently autonomy was broken into 2 legs; the red path to take the robot to an experimental area and the blue path to exit the mine. The 2 leg approach was used for entry and exit during additional Research Mine visits.

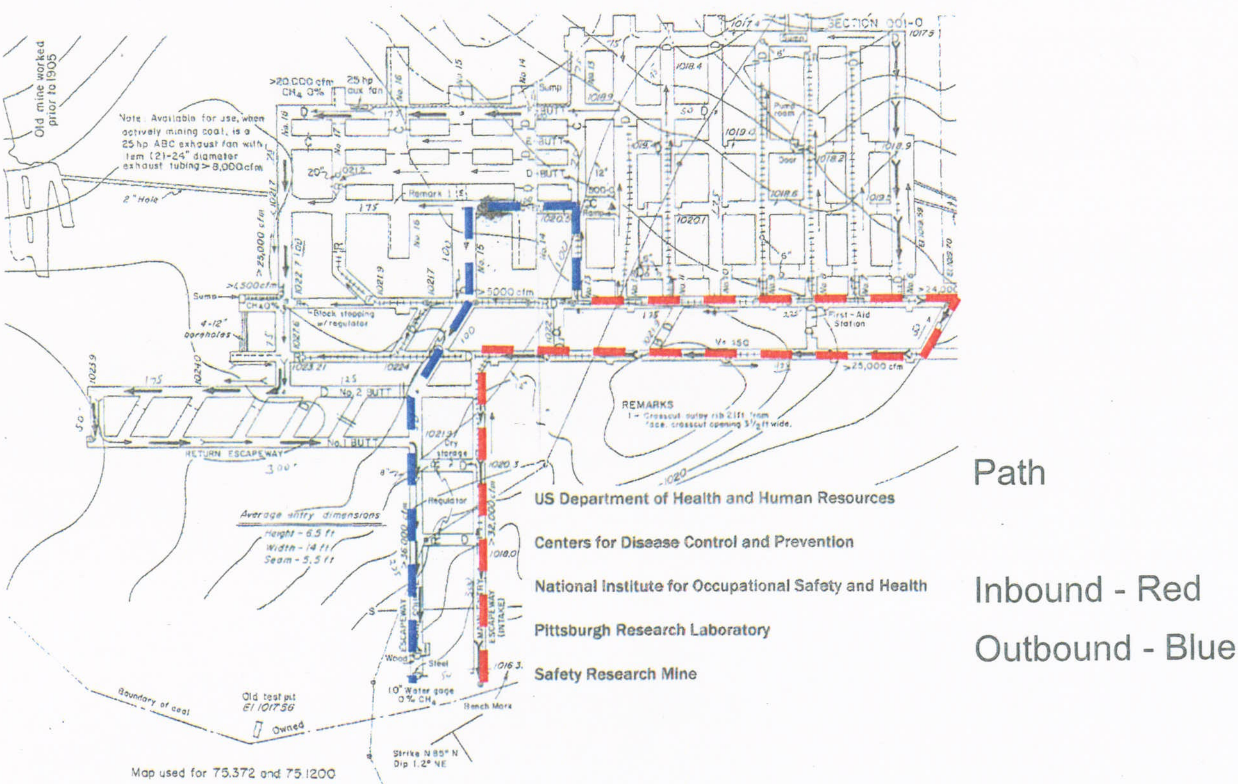


Figure 10: 3-D autonomous route shown on Research Mine map.

Robotic Survey

Gathering and integrating large volumes of data into accurate models requires significant amounts of post processing. Locating the robot with survey positions within the mine resulted in better positional accuracy and less post processing errors. To obtain a sensor coverage capable of reconstructing mine surfaces to within centimeters of accuracy, the robot moves, stops and thoroughly scans the mine interior in continuous repetition. During each scan, the robot moves its survey prism to four locations and queries the survey instrument to measure each prism position. After obtaining these measurements, the robot resets the prism position to a specified start position and moves to the next scan location. This cyclic operation transpires in clockwork fashion until the robot has completed its survey, is halted by error or is stopped by human intervention.

Prior to this project a human operator using a robotic surveying instrument capable of automatically tracking a prism on the robot was used to locate the robot in the mine. At each robot location the surveyor acquired the measurement and communicated completion to a robot operator who would then drive the robot to the next incremental location. The next iteration had the surveying instrument automated to collect measurement readings and the robot moving automatically. In this mode of operation once the prism is lost the surveying instrument stops tracking and must be restarted. Post processing required matching time stamped survey measurements of the robots position to individual scan locations.

During this project software was written to coordinate communications with the survey instrument and the robot computer. A laptop computer connected to a wireless Ethernet radio controlled the survey instrument. By enabling communication and control automatically between the robot and surveying instrument it is possible to tell the surveying instrument where to look to reacquire the prism and continue logging position data. Also the survey data is now directly stored on the robot.

Table 1 summarizes performance results recorded from actual field data in three modes of operation: H for human-only, HR for mixed human-robot and R for robot-only. All three data sets utilized the same equipment (i.e. robot and surveying instrument), followed the same procedure of moving and scanning. This data is occurring in different yet comparable subterranean environments. Human-only data required a team of two people to manually operate the survey instrument and puppeteer the robot. Human-robot data required one person to operate the survey instrument while the robot autonomously navigated, scanned and signaled the human to take survey measurements. Robot-only required a human to monitor the surveying process, but the operation was conducted without direct human interaction.

Table 1 is composed of the following information: The sample size for each of these results is denoted by the Size column and is in units of robot stations (i.e. the number of scan-transition cycles). To accurately portray performance characteristics, stations where errors occurred were removed from statistical computations. In this work, errors are considered to be stations where one or more of the survey readings were corrupted or the cycle time was larger than two standard deviations from the sample mean. Average error is reported in the Err/Size column. The error-free averages (fist number) and standard deviation (highlighted second number) of the scan and transition times (in seconds) are reported in columns S-Time and T-Time, respectively. The estimated period (in seconds) for scan-transition cycles are shown in the Period column.

Table 1. Survey Performance Comparison

Mode	Size	Err/Size	S-Time (s)	T-Time (s)	Period
H	116	0.086	73.08±15.14	54.48±18.17	127.56
HR	160	0.044	75.71±0.59	23.26±0.05	98.97
R	106	0.035	76.86±7.79	23.27±0.05	100.13

Table 2. Survey Factors Comparison

Factor	Human	Human-Robot	Robot	Optimized
Prism placement	M	A	A	A*
Communication	M	M	A	A
Survey instrument	M	M	A	A
Station selection	M	A	A	A
Mobilization	M	A	A	A*
Error recovery	M	M	M	A

Automate Robot *Optimize

Automate Survey

Table 2 Survey Factors Comparison shows factors that are either manual or automated at the various stages of development. Finally optimization was introduced in order to decrease the cycle times for prism placement and mobilization. At each station the prism is spun to 4 positions on the robot turret. Before for each station the turret was rotated back to the same starting position. Now the turret starts each station with its last position changing rotation direction. Before the robot could reach a new station before the turret reinitialized and now the robot simply moves without having to rotate the turret. Results of the station cycle optimization are reflected in table 3 summary of performance.

Table 3. Summary of Performance

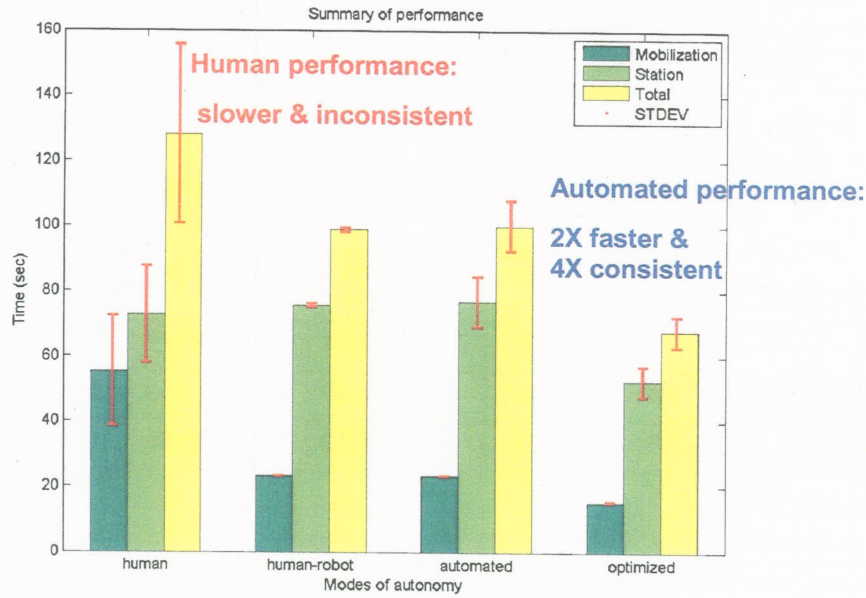


Figure 11. Performance results of the surveying process during this project.

Radar performance

CaveCrawler equipped with the radar unit was used to evaluate performance looking through a mine curtain. The following test was set up at the Research Mine. Figure 11 shows the robot set up to the right of a chosen mine intersection. A mine curtain was placed across the mine corridor to the left. A miner then walked around traversing further from the curtain and back and forth across the corridor. Additionally lidar scans and photographs were gathered for comparison with the radar results.

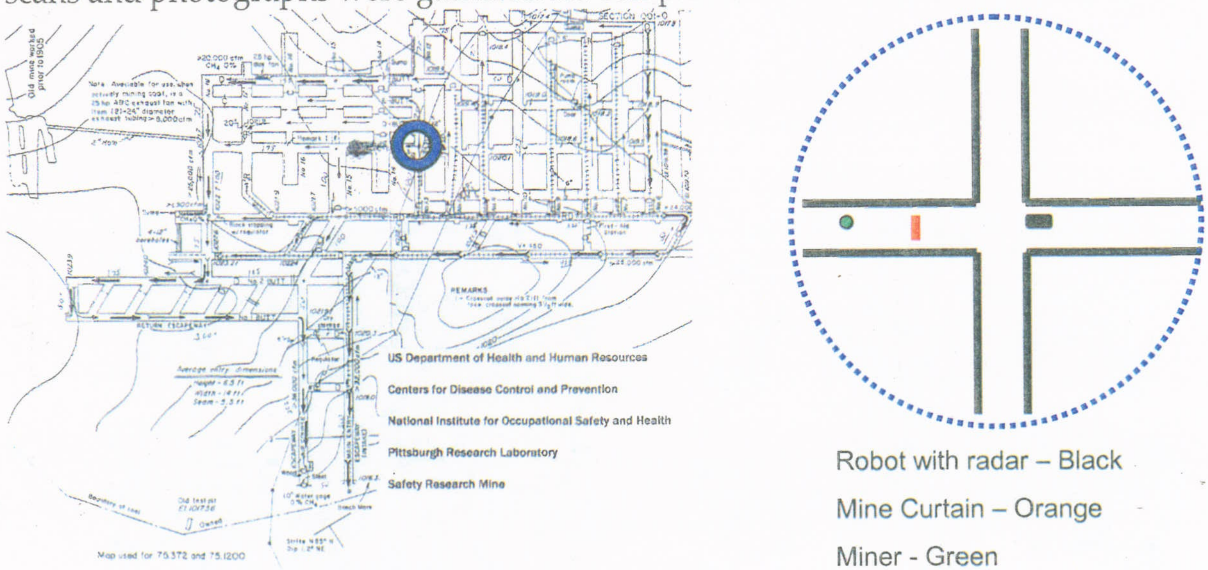


Figure 12: Mine map and diagram showing the radar curtain test setup in the Research Mine

The scan in Figure 13 shows the representation of the radar scan with the corridors, the mine curtain and the miner. In observing the radar data live one can clearly see the miner walking around behind the mine curtain. A movie playback is included in the radar section of the electronic data provided with this report.

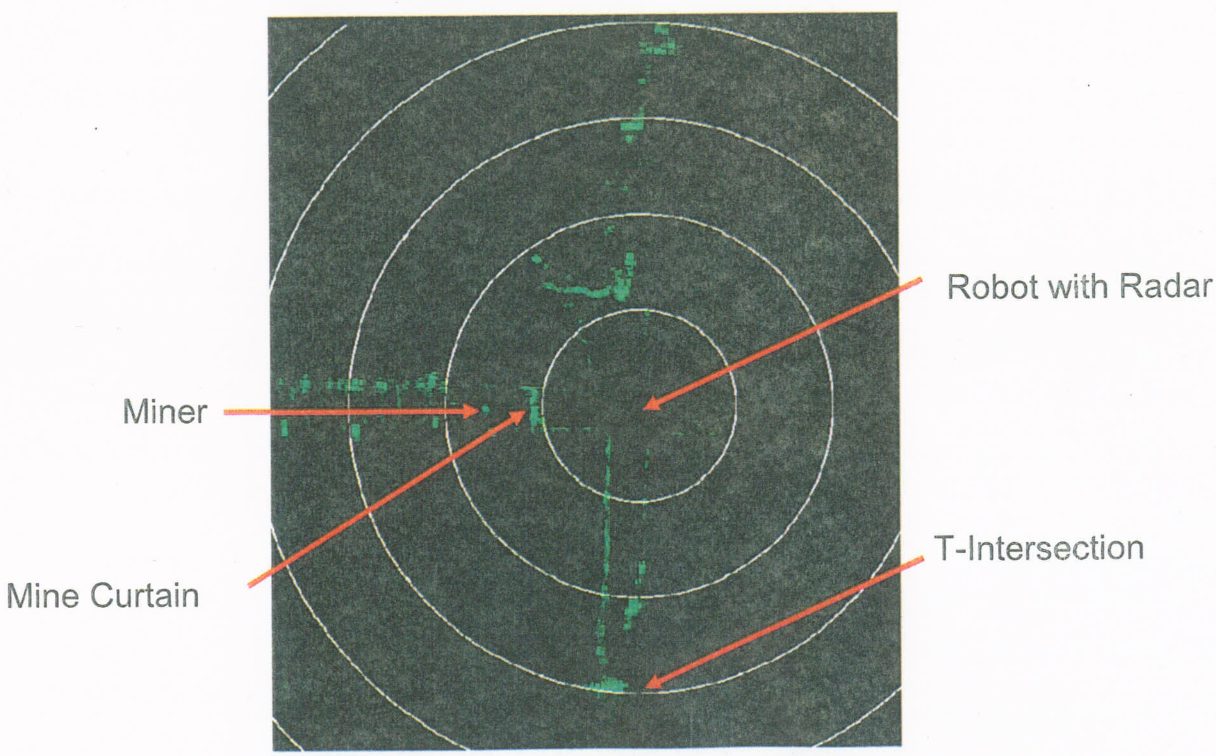


Figure 13: Snapshot of the radar data from the curtain test

The laser scan and photographs in Figure 14 clearly shows the mine curtain in place with no data beyond while the radar Figure 13 shows the curtain and the walls beyond. The comparison of the lidar and radar data clearly defines the existence of the mine curtain.

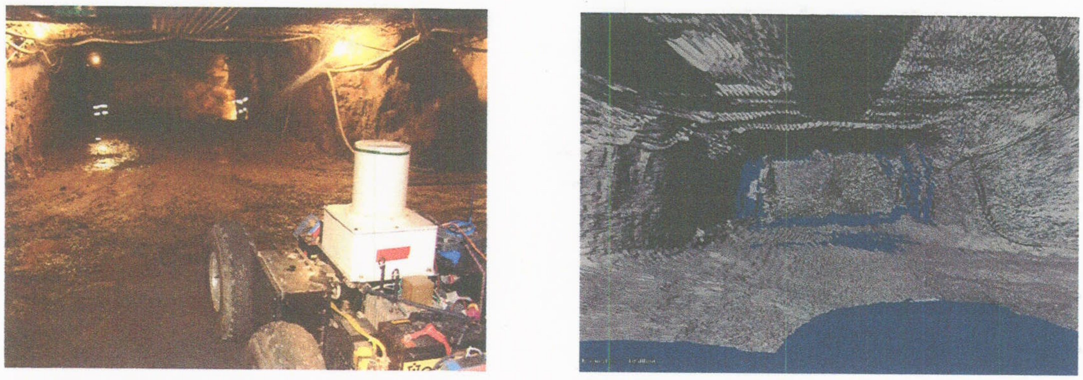


Figure 14: Photograph of CaveCrawler with radar and mine curtain plus corresponding lidar model

Radar data was also gathered while driving in mines. In areas where mine curtains exist the radar clearly senses past the mine curtains to the walls. Radar data was gathered at both the Research Mine and at Loveridge Mine. Collected radar data from 1 section of the Research Mine was oriented into a rough 2-D map as shown in Figure 15. The radar data shown was aligned using only the odometry and inertial information from the robot. Development of additional post-processing techniques will lead to better radar based maps and alignment of this data.

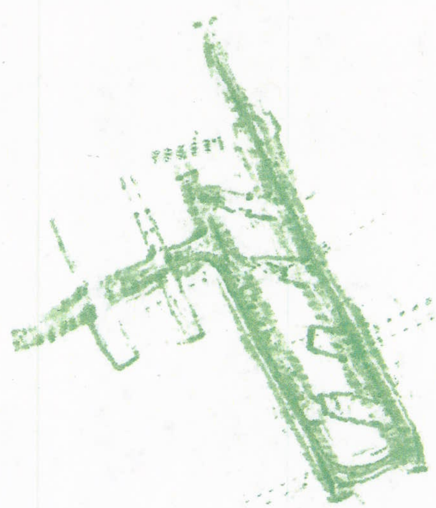


Figure 15: Integration of radar and robot data to form a 2-D mine map of the Research Mine

Model Accuracy

Model accuracy – Models and maps are the product delivered from our robot investigations in mines. Known landmarks, data runs that loop, and positional accuracy of the robot all influences the quality of the resulting models.

Just as data collection requires automation for reasons of efficiency and accuracy, data processing is tedious and error-prone without the proper autonomous tools to manage the volumes of data logged from robot sensors. Model synthesis requires that all data be synchronized, fused and spatially registered into a global coordinate system. As such, data synchronization begins online while the robot is collecting data. The Cave Crawler system is constructed with a modular software architecture that specifically monitors and regulates data flow. Every sensor and input device is time stamped and logged. Handling data in this manner allows for complete offline playback of the data and provides a timeline to organize streaming data into discrete model-building blocks

Once data is blocked into time segments, these blocks are aligned and registered into a model. LIDAR data streams and survey measurements, for example, are blocked into point clouds and robot position/pose data, respectively. Point clouds are filtered for outliers and globally registered using the surveyed position and pose estimates as the starting point for multi-view surface matching and global Iterative Closest Point (ICP) algorithms. Figure 16 shows a 2D map generated from 172 scans of varying views that were autonomously registered from these algorithms. Following scan registration, updated position and pose information (obtained through the registration process) corrects orientation for all robot sensors. This step allows data from each sensor to be globally registered and thereby visually represented on a 3D model.

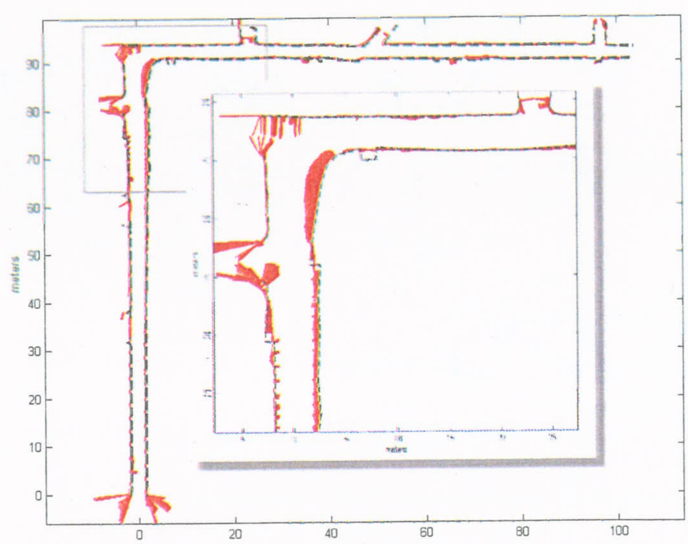


Figure 16: Map Comparisons. The original mine map is represented by the dashed line. Differences between the prior and robot-generated maps are signified by the colored area surrounding the dashed line. The robot-generated map remains consistent to the

"idealized" mine map; however, locations where mine interior has changed are distinguishable.

In additional evaluations, the reported accuracy of this process has been shown to be within 8cm of surface measurements acquired by alternative profiling technologies such as human survey and stationary laser profiling systems. Figure 16, for example, shows the difference between a decades-old human-surveyed mine map and one generated through robotic survey over a traverse of 183 meters. In areas where concrete walls exist, which define a flat and easily comparable surface, the prior map and robot survey are within 7.24cm of each other. Natural surfaces, such as the rock wall, are within 15cm of each other; however, the human survey tends to "idealize" walls whereas as robotic survey captures the true interior surface. Topologically, intersections align exactly to locations specified on the prior map. The notable differences are caused by alterations in the environment. As shown in magnified portion of Figure 16, equipment and structural modifications dramatically alter the subterranean surface, which suggest yet another interesting application for this technology: the ability to produce temporal subterranean maps that monitor change over time.

Visualization and analysis tools are show in Figure 17. The left portion of Figure 17 shows a multi-view registration utility that colors individual point clouds inside of a 3D model. This colored model assists in quickly assessing potential problems that may have occurred during the automated registration process. The right portion of Figure 17 shows a tool for extracting area and volumetric measurements from model information. Such tools are invaluable for data interaction and can also be automated to produce sectional views and record measurements over long stretches of model.

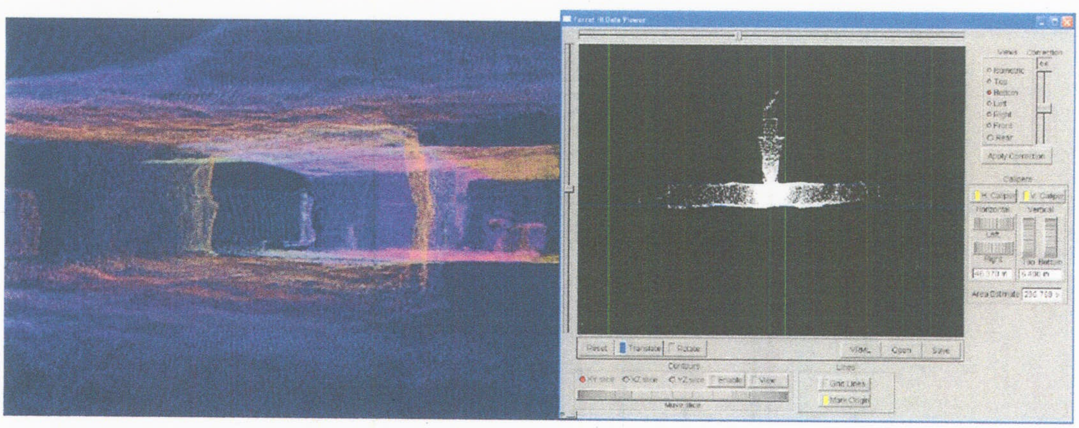


Figure 17: 3D Data Manipulation. (Left) A limestone mine model is visualized by coloring each individual scan with a random color. This model can be flown-through, meshed or cut into cross sections as needed. (Right) Analytical tools provide measurements from subterranean models in the form of cross sections, area and volume calculations.

The modeling techniques described were applied during this project in order to build survey locked and scan matched maps. The resulting maps were used to compare the data gathered in the mines to the provided maps. Qualitative comparisons of the mapping accuracy are shown using the field work examples.

The data presented in this paper is just a fraction of the data collected and analyzed. Conservatively there were over 10 linear miles of mapping data collected over the course of the project. More than 8 miles of the data were collected in the mines. Table 4 summarizes the field work.

Table 4: Summary of Field Work

DATE	DAY	LOCATION	PURPOSE
September 20, 2006	Wednesday	Research Mine	2-D navigation
October 4, 2006	Wednesday	Research Mine	2-D and 3-D navigation
October 18, 2006	Wednesday	Research Mine	3-D navigation
December 8, 2006	Friday	Research Mine	Autonomous survey
February 16, 2007	Friday	Research Mine	Radar system
March 14, 2007	Wednesday	Research Mine	Preparation for readiness review
March 15, 2007	Thursday	Research Mine	Readiness dry run
March 30, 2007	Friday	Research Mine	Readiness dry run
April 5, 2007	Thursday	Research Mine	Readiness review
June 20, 2007	Wednesday	Research Mine	Preparation for Loveridge Mine
June 27-29, 2007	Wed to Fri	Loveridge Mine	Demonstration
August 13, 2007	Monday	Research Mine	Autonomy and Imagery

The methods and equipment were demonstrated to OSM personnel during the March 30 and April 5 readiness reviews at the Research Mine. The photograph and corresponding laser scan (Figure 18) show the readiness review visitors in the Research Mine.

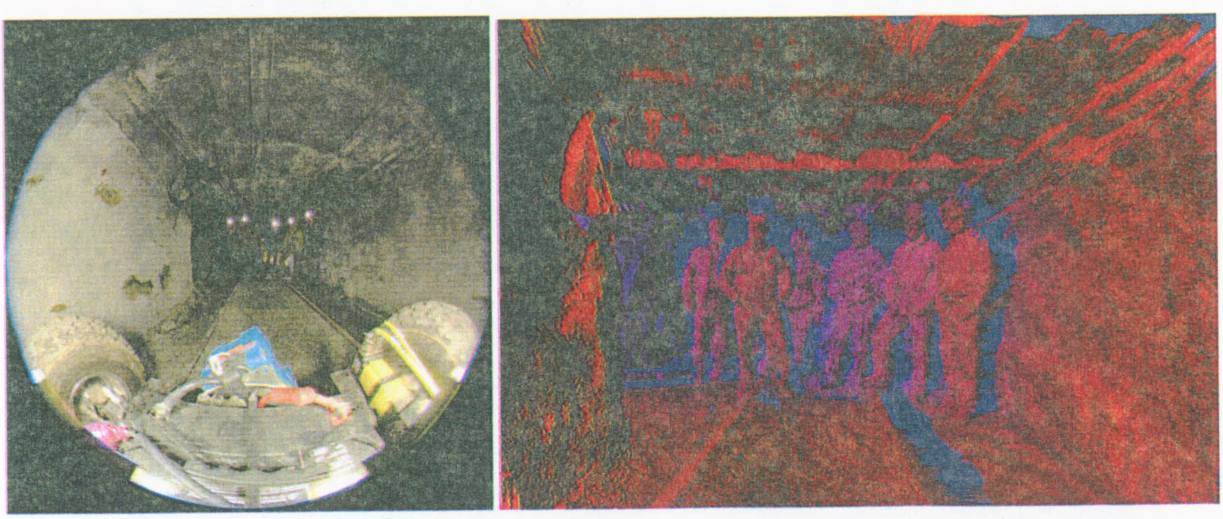


Figure 18: Photograph and Scan at Readiness Demonstration. (Left) This photograph shows six review visitors and was taken from the CaveCrawler system. Poor lighting conditions and the miner's lamps, however, make it difficult to see these visitors. (Right) This is a laser scan of the six reviewers. Lighting conditions do not affect these results and the visitors are clearly visible.

Similar tests were repeated for each of the two readiness review visits. Autonomy with a map, laser scanning and photographic capabilities of the system, survey locked mapping, radar curtain tests, and radar mapping runs were all demonstrated.

Following the readiness review NTTC, CONSOL Energy, Inc., and CMU came to an agreement to enable use of the Loveridge Mine to conduct the demonstration test. The Loveridge Mine is located in northern West Virginia near Fairmont and produces coal from the Pittsburgh 8 Seam using one longwall system and four continuous mining machines. CaveCrawler was repaired and prepared for the demonstration. A software feature was added following the readiness review allowing live thumbnail review of the on board camera images in the field to verify proper camera settings. Final calibrations and a preparation visit to the Research Mine were conducted prior to traveling for the test. During the miner's holiday June 27-29 Cave Crawler was deployed at the Loveridge Mine.

All of the elements demonstrated at the Research Mine except the radar curtain test were successfully repeated during the mine visit. Training, transportation logistics, active mine repair work and the realities of working in an active mine factored in to what was possible to achieve during the visit. CaveCrawler successfully performed long sections of survey locked data collection, autonomous operation, and radar runs in the mine.

Deploying CaveCrawler started with a 1000 ft descent on a mine elevator and an eight mile trip by rail to the working area.

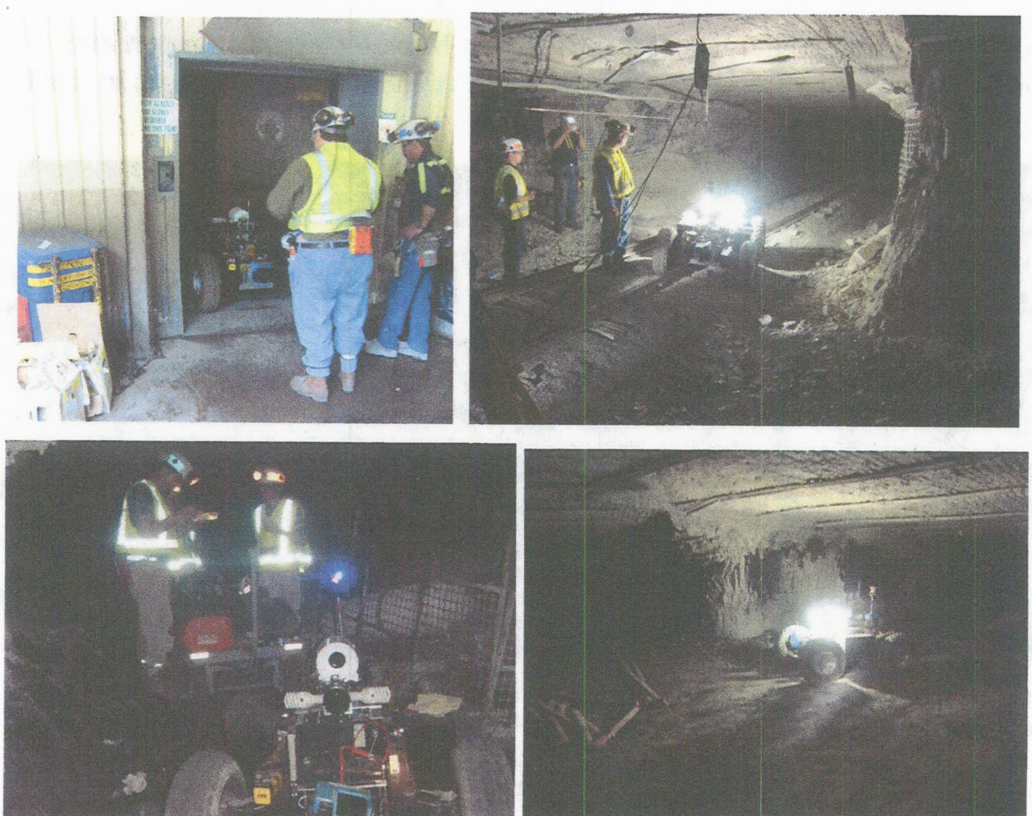


Figure 19: Photographs from the Loveridge Mine Demonstration

At the Loveridge Mine day 1 and a portion of day 2 were used to collect the data highlighted in Figure 20 location 1 . Survey locked data with autonomous operation was used to traverse and model this area. Day 2 concluded with the continuous driving autonomous run shown in Figure 20 location 2. Survey locked and autonomous radar runs were conducted on day 3 as shown in Figure 20 location 3. The orange highlighted area shows the survey locked work with autonomy and the green highlighted area shows the autonomous run with radar. Table 5 summarizes the amount of data collected and the distance covered demonstrating the different techniques at the mine.

Table 5. Summary of the operations and statistics from the Loveridge Mine

Location	Technique	Data Points	Dist. (ft)
1	Survey locked with lidar– Autonomous operation – Camera and thermal camera	161,867,453	1639
1	Autonomous operation (orange) Reverse Traverse	60,130	550
2	Autonomous operation with lidar portions of the loop	134,878	1206
2	Autonomous operation with lidar complete loop	71,590	1060
3	Survey locked with lidar – Autonomous operation (orange)	114,861,897	1160
3	Autonomous operation (orange) Reverse Traverse	52,786	660
3	Autonomous operation with lidar and radar (green)	119,242	1350
	Totals	**277,167,976**	**7625**

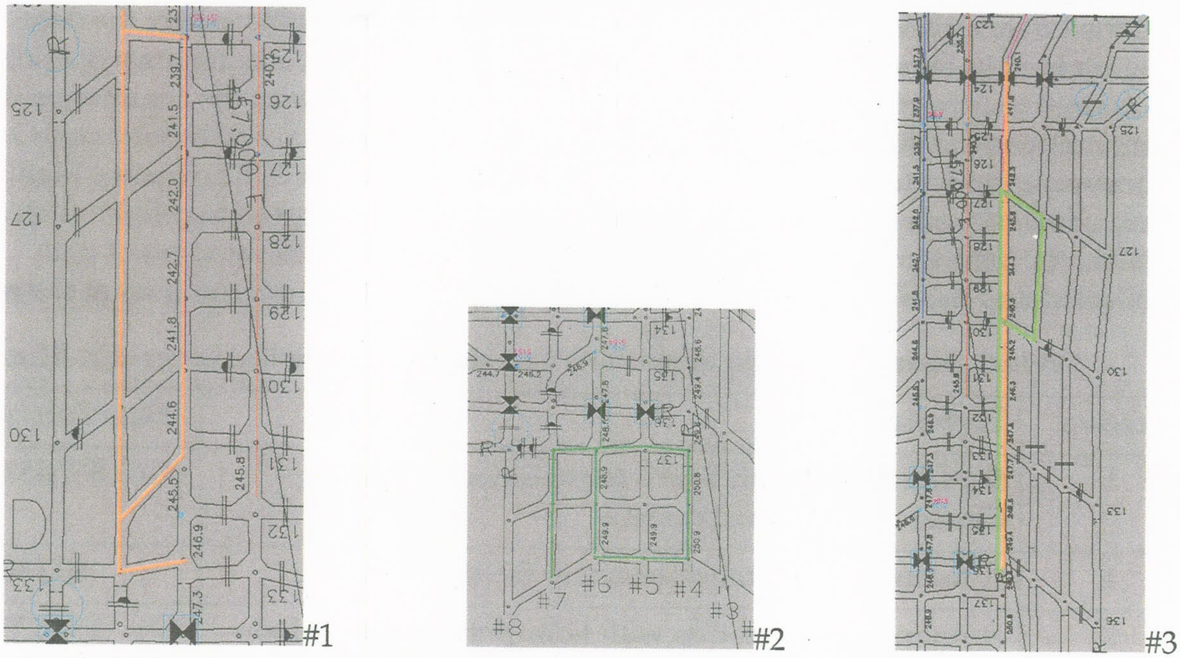
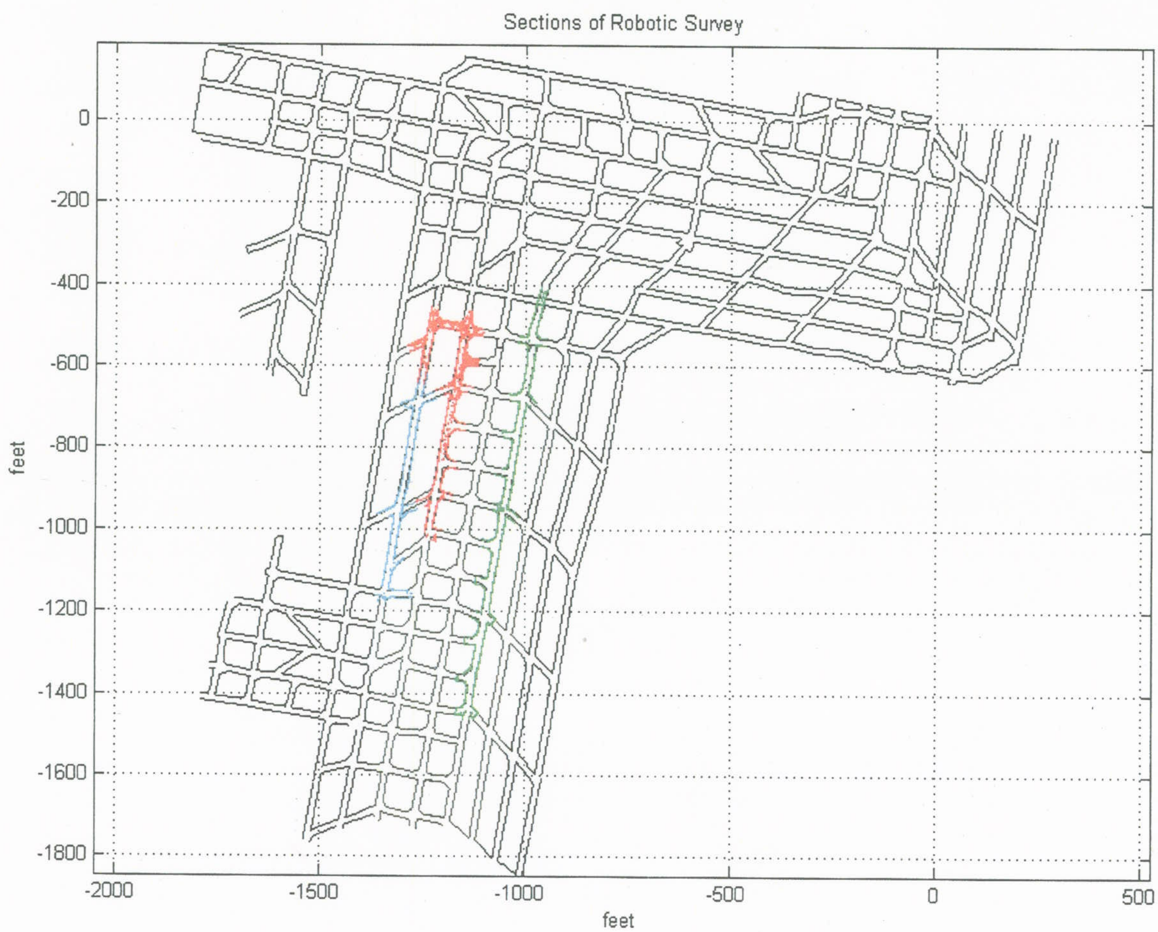


Figure 20: Model Locations. This colored portions of the Loveridge Mine map indicate where robot data collection occurred.



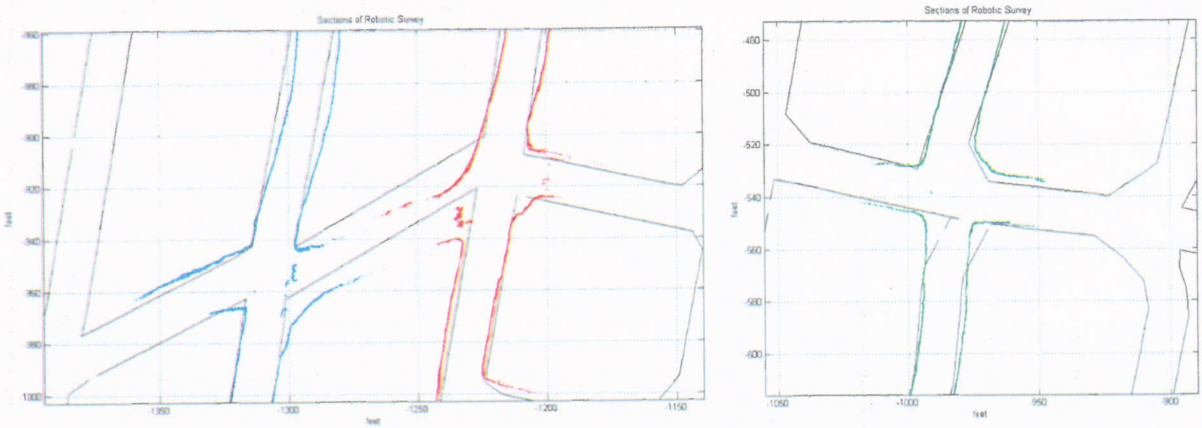
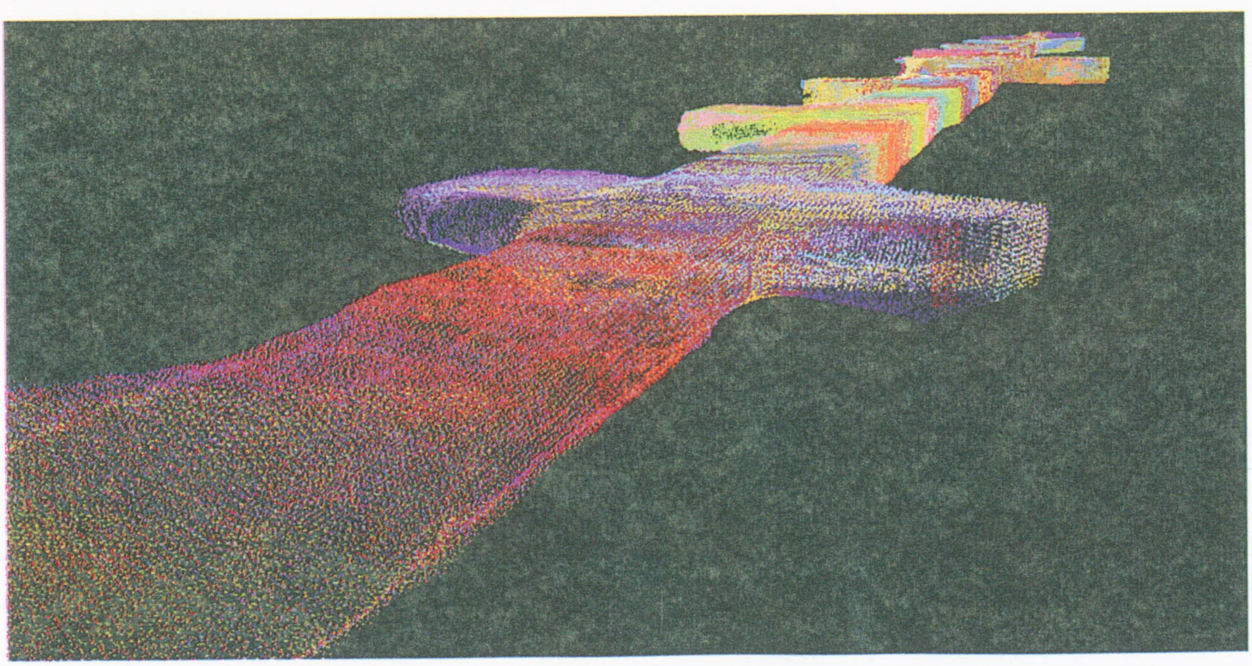


Figure 21: Comparison of Robotic Survey Maps to Mine Map. (Top) The robotic survey maps acquired during the Loveridge mine experiments are superimposed on an existing mine map. Each day of operation is represented by different color map. As shown, the robotically generated maps correlate precisely with existing mine map at the macro level. (Bottom left) At the micro level, discrepancies between the idealized mine map and the robot map become clear. Notice the blue and red lines of the robot's map bend and sway indicating the true geometry of the mine corridor. The mine map, however, exhibits straight and idealized lines that do not match the mine's geometry. (Bottom right) The shape of this intersection in the mine map differs from the robotic survey findings, which could be an error in the mine map or a change in the mine's geometry since the construction of the map.

As shown in Figure 21, mine maps generated from the automated surveying process are of higher accuracy compared to maps built from traditional surveying methods. Intersections and corridor walls identified by the mine map correlate to those mapped in automated survey; however, automated survey surpasses the quality of traditional survey as automated survey captures the true geometry of the mine. Figure 21 shows multiple examples where the idealized lines of the mine map do not accurately portray the interior surface contours of the mine.



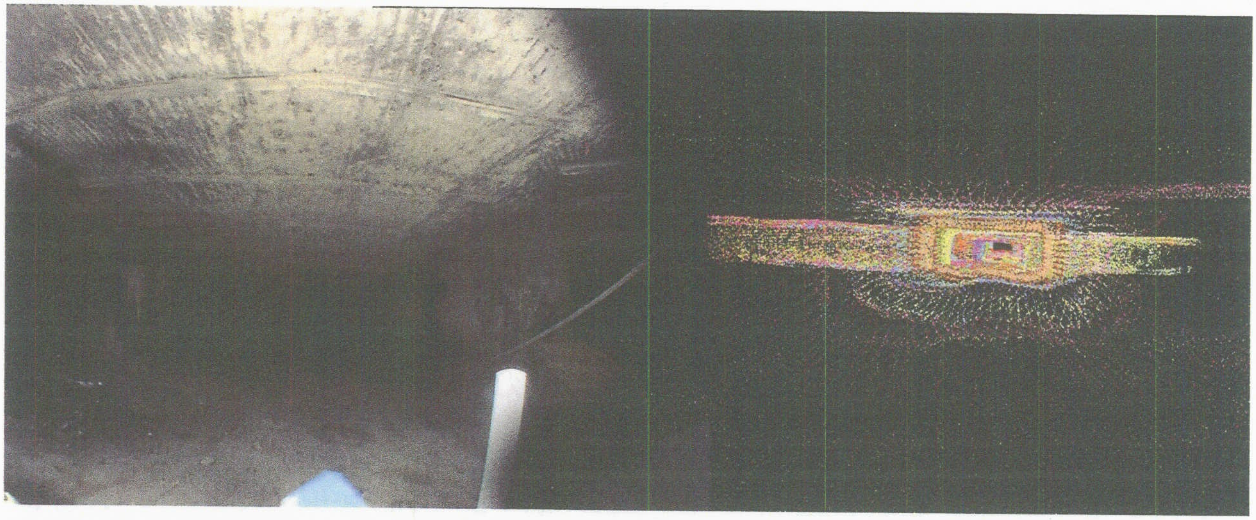


Figure 22: Three Dimensional Models. (Top) This image is taken from the 3D model of the section of mine colored green in Figure 21. (Bottom) This image shows a photograph and model view from the same perspective at the section of mine colored blue in Figure 21 .

In addition to superior maps, automated survey captures the full 3D description of the mine. As presented in Figure 22, the 3D models from each section provide an immersive view of the mine that is metrically accurate.

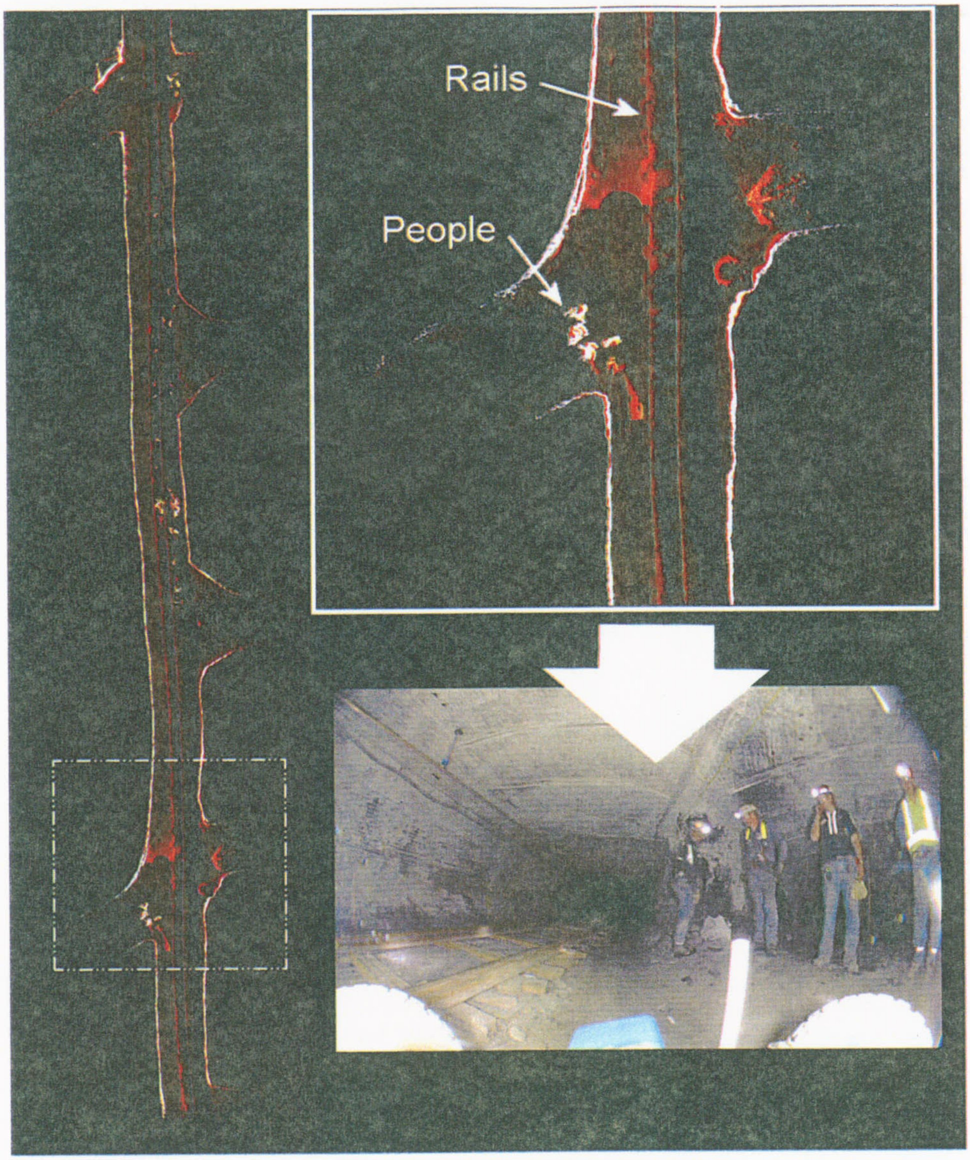


Figure 23: Gradient Maps. Gradient maps visualize relative changes in the mine's surface interior. This gradient map shows the section of mine colored red in Figure 21. Notice in the magnified section of the map that the rail tracks and people are clearly visible.

The utility of 3D models span numerous applications. In Figure 23, a gradient map shows local changes in the mine's interior surface. This type of map is excellent for identifying objects in the mine such as a mantrip, tracks, and people.

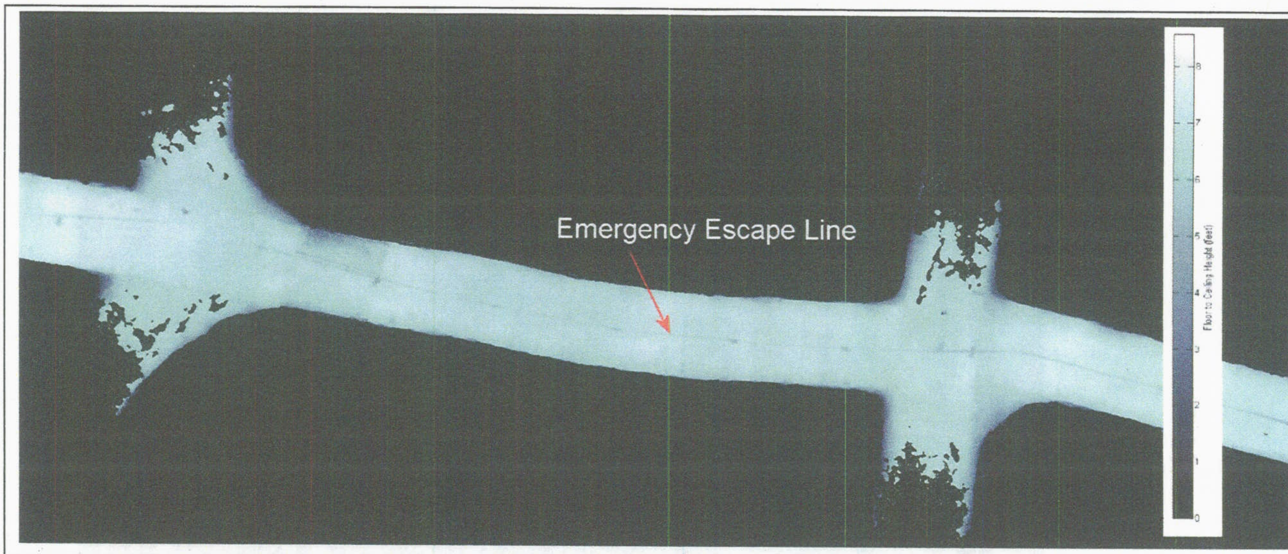


Figure 24: Height Maps. This maps show the difference in height between the floor and ceiling of the mine. According to the map, the nominal height is between 7 and 8 feet. Also note the clarity by which the emergency escape line can be seen.

These 3D models can also be used to accurately measure the floor-to-ceiling heights in the mine. In Figure 24, the nominal height of this section of mine is documented to be between 7 and 8 feet. Darker areas represent locations in the mine where low-hanging objects or tall objects on the floor reduce the distance between the floor and the roof. As show here, the emergency escape line is such an object, which makes it visible in this plot.

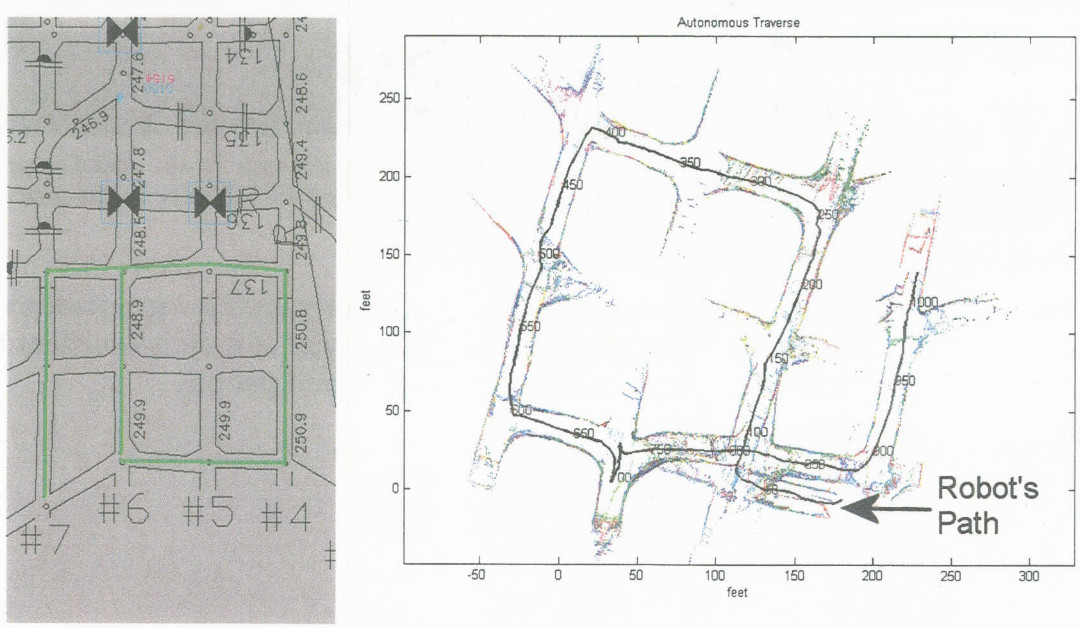


Figure 25: Map production from autonomous navigation.

In addition to robot survey, the CaveCrawler system autonomously navigated sections of the Loveridge mine as shown in Figure 25. Unlike robotic survey, the robot computes its relative position in the mine from on-board sensory data. This process is known as *dead reckoning* and is susceptible to drift error due to the absence of absolute external position information. The right portion of Figure 25 shows this drift as the overlap portion of the traverse do not align. Figure 26 shows this drift more concisely as through visualization of the robot's path.

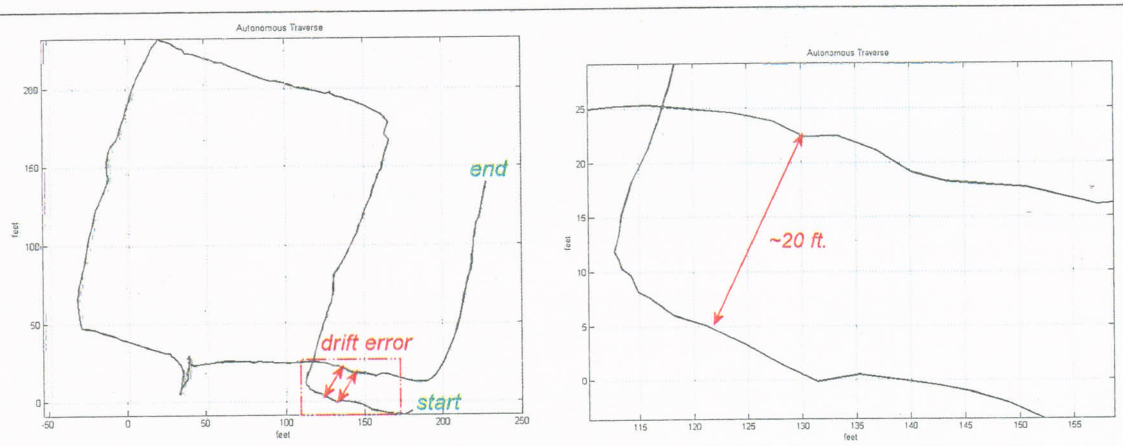


Figure 26: Drift error from localized map construction.

In Figure 26, the boxed area of the robots traverse would nearly overlap if the robot's position would have been perfect. Through *dead reckoning*, approximately 20 feet of drift was determined to occur after 825 ft of traverse. Sources of dead reckoning error come from noisy odometric sensors and error in 2D scan matching.

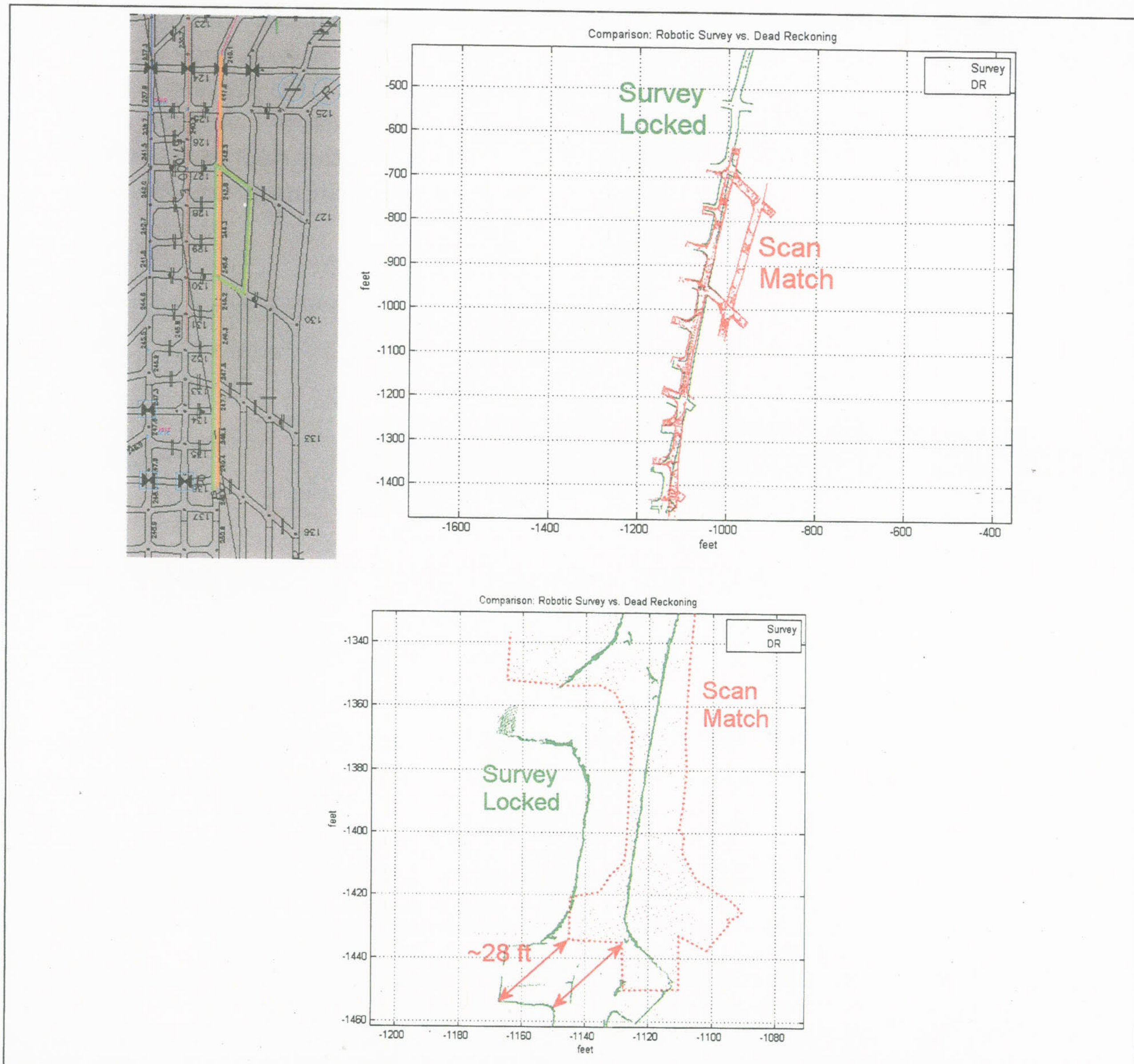


Figure 27: Drift error from localized map construction.

Figure 27 shows a comparison between dead reckoning map generation and survey-locked modeling. Again, dead reckoning shows the accumulation of drift over time. In this figure, over the course of 900 ft of traverse, the robot accumulated roughly 28 ft of drift when the 2D maps are compared. Terrain, quality of inertial and mapping sensors, placement of sensors, loop closures and density of data collected effect the magnitude of the drift error

Dead reckoning drift is a normal occurrence in robotic systems. While drift is undesirable for modeling, it does not affect the robot's ability to understand its location in the mine. As discussed in previous sections of this report, CaveCralwer looks for features in the environment such as intersections to pinpoint its position. As such, autonomous robotic survey is the method of choice for efficient data collection, precision modeling results, and superior mine maps. On the other hand, autonomous robot navigation is ideal for quick glances and reconnaissance when time is the critical factor.

Technology Transfer/Commercialization Plan

Background

Accurate mapping of active and abandoned underground mines can improve the safety of miners, increase the economic return of mining operations, provide subsurface information for surface construction projects, and confirm the effectiveness of backfill efforts.

Preliminary testing and commercial application of the underground robotic mapping system has been conducted by CMU and Workhorse Technologies, LLC. These tests include mapping of active and abandoned coal mines, mapping of abandoned metal and non-metal mines, and verification of flyash backfill in an abandoned limestone mine. These preliminary applications of the technology indicate that robotic mapping provides information about underground voids of a fidelity, density, and utility not possible using any other method.

Potential Applications

Discussions with mine operators and federal and state mine regulators, combined with the results of these tests, indicate that there are applications that can be addressed immediately and others which will require additional development and testing. Additional mid and long term applications have also been identified that can be accomplished with a combination of further development, testing, approval and certification, and regulatory changes. Brief descriptions of these applications are provided below:

Immediate Applications

The most obvious and direct application of this technology is to verify the accuracy of existing underground maps and to gather information for post-accident investigation. Incorrect maps have led to several mining disasters in the past including the Quecreek inundation and the Martin County impoundment failure. The robotic mapping system, at its current state of development, has demonstrated the ability to autonomously map underground mine workings. This ability has been demonstrated and Workhorse Technologies, LLC is currently positioned to offer commercial services.

The map verification application can be applied to both abandoned and active mines. In the abandoned mine application, a portal to the workings would be opened and the robot would enter, operate autonomously, and exit the mine with the mapping data.

The data is used to create a model to compare with existing maps. No personnel would have to enter the abandoned workings.

In the active mine application, the robot would be used to create models of the active mine outby of the last crosscut. Because the system has not been approved by MSHA, the system is limited to operating in outby areas at this time. However, there are still advantages to having accurate 3-D models of the workings. These advantages include:

- Models that allow the mine operator to monitor the condition of the mine. A baseline model would be developed and subsequent models can be compared to the baseline to determine roof, floor, and rib changes over time. This comparison can be automated to highlight the changed areas.
- Accurate models also provide mine engineers a powerful tool to determine power and piping routing, equipment clearances, and new section development. Accurate 3-D models also allow the operator to very accurately calculate the volume of coal removed from entries and crosscuts. As the accuracy of the model is proven, the requirement for manual surveying may be reduced or eliminated.
- These models also have great value as training materials for future miners, mine inspectors, and mine rescue teams. Accurate 3D mine models could also assist in future mine designs and provide research data for geologist and mine researches.

Mid-term Applications

Midterm applications include real-time mapping at the working face and exploration of sealed areas for future development. Both of these applications would require additional development and require that the sensors be certified by the MSHA Approval and Certification Center for use inby the last crosscut.

The advantages to real-time mapping include insuring that the mining is occurring as planned and providing management real-time progress reports. When developing a new section of the mine it is important to ensure that the entries are being cut straight and parallel to other entries. Real-time mapping would allow a very accurate comparison of the actual development to the planned development. This information could be sent to the mine's engineering staff at the end of each shift or, if the mine's communication infrastructure has sufficient bandwidth, directly to the surface in real time. The data could then be overlaid on computer aided design maps for comparison of planned verses actual development.

The second midterm application is the exploration of inaccessible areas of the mine such as sealed areas or old abandoned workings. There are times that the mine operator needs or wants to explore a sealed area of the mine for future development. A mine operator may wish to cut a new slope, run a pipeline through old workings, or need to evaluate the condition of old workings. Currently, after all the regulatory requirements are met, the operator must deploy trained mine rescue teams to explore the abandoned area. This puts personnel at risk by entering areas where roof/rib and atmospheric conditions are unknown. The robotic system could enter these areas, collect the necessary information, and exit without endangering any personnel. This information would allow the operator to determine the area's potential for development and provide necessary engineering data for the development design.

A third mid-term application is the use of the robotic system for mine recovery or reopening. After a major mine emergency or long-term closure, a recovery or reopening plan must be developed. There is often little information on the condition of the mine and trained mine rescue teams are used to explore the workings to determine what needs to be done for safe reopening. The robotic system could be used to provide the necessary information prior to deployment of the rescue teams. This would greatly enhance the safety of the recovery effort.

Long-term Applications

The underground robotic mapping tests have demonstrated that a robotic system can autonomously navigate through an underground mine environment. This ability could be developed and expanded to include routine mine operations and be utilized in emergency situations.

Routine operations such as collecting atmospheric and infrastructure information along intakes, returns, bleeders, escapeways, and beltlines could be done robotically. Currently, personnel are required to walk these areas on a routine basis, collect atmospheric data at specified points, and inspect the condition of the passageways. These routine inspections consume a large amount of manpower and require miners to traverse remote sections of the mine. A robotic system could be outfitted with the required sensors and programmed to travel the specified areas continuously collecting data on roof, rib, and floor conditions while stopping and collecting atmospheric data at specified points. A robot equipped with an infrared system could be employed along beltways to spot hot bearings or other areas where unwanted friction is causing high temperatures. These routine applications would require design changes to the existing robot system, changes to current regulations, and modification to the mine's air flow control stoppings to allow robotic access.

A second long-term but potentially significant application of the underground robotic system is its application in mine emergencies. An autonomous system could travel in front of mine rescue teams collecting information on atmospheric conditions, fire or explosion potential, and other possible obstacles. Having this information available to the mine rescue teams would greatly enhance the safety of the team members while significantly speeding up the exploration process. Preliminary testing of a system that can operate in a smoke filled environment has been completed but significant design and testing would be required for successful deployment.

Milestones to Commercialization

Milestones to commercialization of the underground robotic mapping system include:

- Approval and certification of the robot's power and drive system. As mentioned above, in order to work inby the first crosscut of an active mine and/or explore areas where the atmosphere is unknown and may be explosive, the robot's motive system must be certified and approved by MSHA to be explosion proof. In its current configuration the batteries, inverters, and motors would have to be redesigned, repackaged, or replaced to meet this requirement. An alternative would be to place the sensors and computers on an existing certified mine vehicle.

- Approval and certification of the sensors. The current sensors are not currently certified. This will require working with the sensor manufacturers and MSHA's Approval and Certification Center to modify the sensors to meet MSHA's requirements.

- Mine infrastructure. Typical coal mines have many impediments that will interfere with an autonomous robot's ability to traverse many parts of the mine. These impediments primarily consist of airflow control stoppings, curtains, and overcasts. A stopping is typically constructed of concrete blocks that form a wall across a crosscut to direct airflow and isolate areas such as intakes, returns, beltways, and bleeders. Typically some of the stoppings have a small man-door to allow worker passage from one area to another. Curtains serve the same function as stoppings on a temporary basis. Overcasts are sealed bridges that allow air to be directed overtop of a crossing entry to supply air to a section of the mine. Overcasts typically have stairs allowing workers to go up and over the overcasts. Future robots will have to be adapted to overcome these restrictions.

Commercialization Roadmap

A successful commercialization of this technology must include a clear understanding of the mine operator's need to improve the efficiency of the mine. To do this, the results of the testing will be presented to coal mine operators. These presentations will highlight the testing results and potential uses of the technology and provide a forum for mine operators to express their interest in the various applications.

Key, near term, applications will be identified based on the mine operator's input. The certification and approval requirements will then be determined with input from MSHA's Approval and Certification Center. Certification of the components will then be pursued and a mine will be selected for operational testing. The operational testing will provide a basis for any required modifications and provide data on the improvement in mine efficiencies.

Once robotic mining systems are in place in operational mines, Government could facilitate commercialization by incorporating mine modeling into training, accident response, and post-accident investigations.

Summary

This work demonstrates the superiority and effectiveness of using robotic methods for generating mine models. The project realized new levels of efficiency for survey locked operations; demonstrated 3-D autonomy using a digitized mine map to guide a robot; analyzed the attributes of radar sensing to supplement mine mapping; characterized model accuracy for the demonstrated techniques. Goals for producing models and gathering miles of data collection were achieved. Multiple visualization techniques for presenting model data were presented. A technology transfer plan to cast the future and bring these techniques into the mining industry was produced. Each field deployment, post analysis and reporting of data reveals that robotic mapping can deliver useful results for mines. There are many applications beyond the scope of this project for applying these technologies within the mining community.

Acknowledgements

We appreciate the Office of Surface Mining for this opportunity to demonstrate and showcase the robotic survey and mapping of mines technology. Thanks to the National Institute for Safety and Health for providing access to the safety research mine at the Pittsburgh Testing Laboratory in Bruceton, PA. We appreciate Wheeling Jesuit University's National Technology Transfer Center and specifically Paul Myles for his support of this work. Thanks to CONSOL Energy, Inc. for enabling access and providing support at the Loveridge Mine in West Virginia for the demonstration task. We appreciate Zachary Omohundro, Joshua Anhalt, Uland Wong, and Michelle Gittleman at CMU for their efforts in support of this project. .

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Electronic Data Files

The attached DVD contains images, maps, models, presentations, movies, and this report. Following is the folder structure:

Readiness Test Data – Bruceton Research Mine

- Mine photographs
- Data plots
- Curtain test
- Models
- Radar Movies
- Robot Photos

First Robotic Survey Data – Bruceton Research Mine

- Plots
- Sectional Models
- Movies

Final Demonstration – Loveridge Mine

- Location 1
- Location 2
- Location 3
- Map Overlays
- Images
- Models

Movies

- Bruceton Research Mine
- Loveridge Mine

Utilities

- TechSmith Codec – needed to watch certain movies
- VRML view – a utility for viewing (.wrl) models

Report

- This report