Position Measurement for Automated Mining Machinery

Anthony Stentz, Mark Ollis, Steve Scheding, Herman Herman, Chris Fromme,
Jorgen Pedersen, Tim Hegadorn, Robert McCall, John Bares, and Rich Moore.
Robotics Institute
Carnegie Mellon University
Pittsburgh PA 15213

Abstract

Underground coal mining is an industry well suited for robotic automation. Human operators are severely hampered in dark, dusty, and cramped mines, and productivity suffers. Even a slight improvement in productivity can amount to thousands of dollars of additional revenue per machine per day. Automation to date has relied on infrastructure to guide the equipment. The industry finds this approach unsuitable, and it has not taken root. Our approach uses machine-mounted video cameras to guide the equipment. It utilizes natural infrastructure and equipment commonly used in mines. We have demonstrated that our approach meets the requirements for cutting straight entries and mining the proper amount of coal per cycle. The technology is rapidly approaching beta form and will be deployed in several mines in the coming months.

1. Introduction

The mining of soft materials, such as coal, is a large industry. Worldwide, a total of 435 million tons of coal are produced per year. Much of the coal is deposited in seams underground, located too deep to remove from the surface. The two primary processes for mining coal underground are longwall mining and room and pillar mining. Longwall mining employs a system of rail-mounted shearers that rapidly cuts the coal and deposits it on a conveyer for removal from the mine. Hydraulic roof supports protect the shearers as they move along the rail. After a complete pass along the face, the shearer, rails, conveyer, and roof supports are advanced, and the roof collapses behind.

Room and pillar mining uses an ensemble of machines to cut a lattice network (Figure 1). Unlike in longwall mining, only some of the coal is removed; the square pillars are left behind to support the roof. The coal is mined by a continuous miner, a track-driven machine with a rotating cutter head for shearing coal from the face (Figure 2). The machine drives into the coal face with cutter head raised, then shears down to the floor to remove a block of coal. The coal is gathered onto an on-board conveyer which carries it to the tail of the machine. The tail deposits it either in a shuttle car or on a mobile conveyer belt. The coal is transported to a more permanent conveyer and out of the mine.

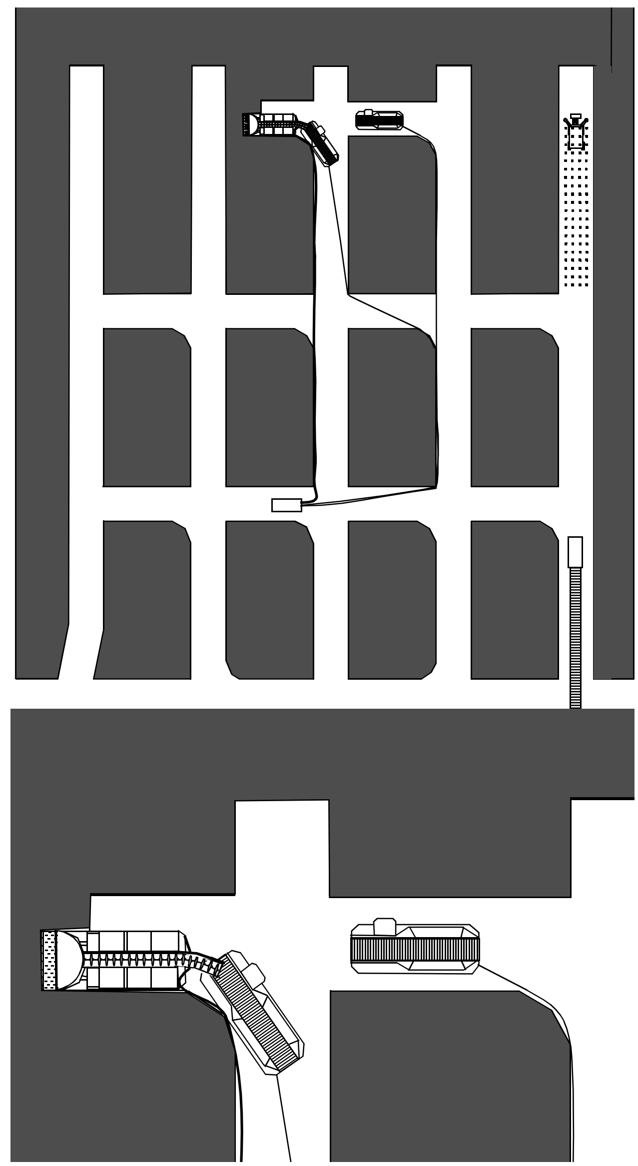

Figure 1: Room and Pillar Mining. Top shows continuous miner, shuttle cars, roof bolter, and conveyor. Bottom shows continuous miner and shuttle cars.

After cutting a section of coal roughly equal to the length of the machine, the continuous miner retreats and a roof bolting machine installs bolts to compress the roof strata and reduce the chance of roof fall.

It is important to note that the continuous mining machine is crucial to both types of underground mining. In longwall mining, the machine is used to develop the entries in the section that house the conveyers, provide ventilation, and enable the longwall equipment to be emplaced. The typical speed for continuous miners is slow (typically on the order of 30 meters of advance per 12 hour shift), and they constitute the bottleneck in longwall mining.

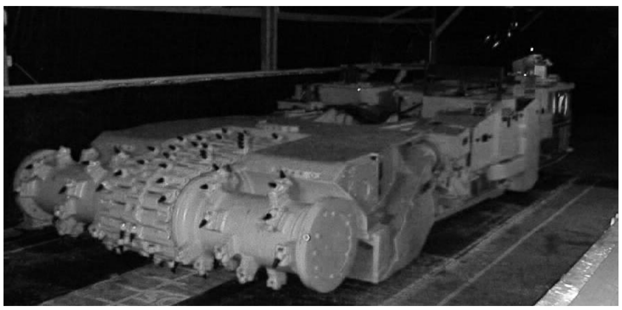

Figure 2: Continuous mining machine in simulated mine.

2. Motivation for Mining Automation

Coal mines are dark, dirty, wet, and cramped. The entries are not much larger than the machines that cut them. Often the seams are so low that the operator cannot stand upright. As the miner cuts coal, dust fills the air. To be safe, the operator typically stands behind the machine and runs it via a button box. Visibility is poor, the operator fatigues, production slows, and mistakes are made.

Automation promises to add value to underground mining in a number of ways:

Increased productivity: operators take breaks during the course of a shift and slow down as they fatigue. Both lead to lost productivity. Automation can operate the equipment a peak rates for an entire shift. Even a 1% improvement in productivity can mean thousands of dollars of additional revenue per machine per day.

Lower operational costs: maintenance is a significant portion of total mining cost. The machines require regular maintenance, including a complete re-build according to a fixed schedule, leading to lost production. Automation can ensure that a machine is operated within its performance envelope, thus minimizing everyday wear and tear and lengthening uptime. Labor is another significant cost. Automation can reduce labor costs by enabling each worker to oversee several machines.

Fewer errors: mining requires some precision. If the heading of an entry deviates significantly, additional roof bolts are required. In the extreme case, the entry must be re-cut. Both result in lost revenues. Automation can add precision to the mining operation.

Greater safety: the key to safety is to locate the operator away from the face, where roof fall, explosions, and machine accidents are most likely to occur. Automation eliminates the need to observe the machine's actions up close, thereby enabling the operator to monitor the machine from a longer, and safer distance.

3. Automation Strategy

Automation has been slow to take root in underground mining. Previous approaches, primarily in hard rock mining, require beacons, light tubes, or other infrastructure to guide the equipment[1][3]. This additional infrastructure is undesirable, since it can be damaged by the machines or dislodged as the ribs and roof shift. Furthermore, new infrastructure is needed as the mine is extended. Our approach is to capitalize on the natural structure of the mine itself, coupled with equipment widely used in mines at present.

Since the continuous miner is used both in longwall and room and pillar mining, we selected it first for automation. The mine plan completely specifies the geometry of the entries to be cut; therefore, measurement of the miner's position and orientation in the mine, coupled with control of the tracks and boom, is sufficient (in theory) to implement the plan.

The exact thickness of the seam, however, is generally unknown, making boom control difficult. Two approaches have been pursued for detecting the boundary between coal/rock in situ[6]: 1) *proactive:* surface-penetrating sensors such as radar and gamma detectors; 2) *reactive:* infrared cameras to detect heat generated as rock is struck. Boom control is outside the scope of this work.

The remaining state parameters of the machine are its position (3) and orientation (3). Of these six, the three most important are heading, lateral offset from a heading reference line, and distance travelled along this reference line. We refer to measurement and control of the first two as *heading control* and the third as *sump depth control*.

Heading control ensures that entries are cut straight and properly dimensioned to accommodate longwall equipment and conveyer systems. The required specification is +/- 10 cm lateral error from a surveyor's reference markings.

Sump depth control ensures that the machine cuts the proper amount of coal per sump/shear cycle. This is important for matching the capacity of shuttle cars that haul the coal to the conveyer. The required specification is +/- 2% of distance travelled.

This paper discusses heading control and sump depth control in depth. Initially, we plan to release these technologies as operator aids, providing the operator with a measure of error from a desired setting. Later, we will release the technologies as semi-autonomous control systems, closing the control loop by computer with human supervision.

Finally, as we develop the capability to measure more of the machine's parameters, we will automate larger portions of the machine's cycle, maximizing machine and worker productivity.

4. Heading control

The purpose of the heading control system is to measure heading and lateral offset of a mining machine. The mining machine is required to stay within 10 centimeters of lateral offset of a predetermined path for distances of up to 100 meters or more. Accomplishing this requires control of both the machine's heading and lateral offset (definitions of heading and lateral offset are shown in Figure 3).

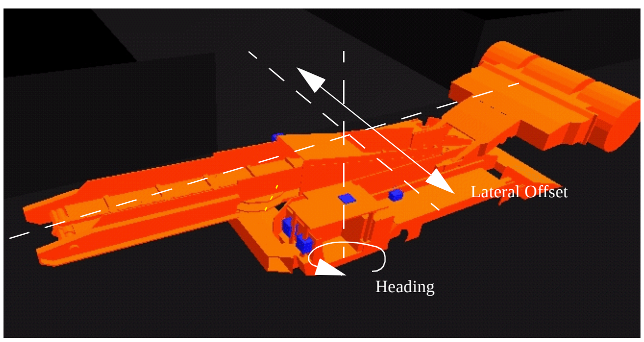

Figure 3: Positioning axes measured by heading control system.

We considered a number of sensor types for monitoring and controlling the machine's heading. We first attempted to design a system capable of maintaining heading without the use of any off-board infrastructure.

A magnetic compass would help keep the machine oriented in the right direction. However, the local variance of the magnetic field is large enough, even on the earth's surface, to add 10 or more degrees of error. Further, this error can be quite systematic, so that it cannot be averaged away over time. Integrating this error over a 100 meter course might potentially result in errors of 10 meters or more. Clearly, a compass alone is insufficient; and the difficulty of modeling its noise characteristics make it difficult to combine with other sensors in a systematic way.

Gyroscopes are capable of measuring angle extremely precisely for short periods of time, though they tend to drift over longer timescales. A degree of noise can be added on timescales ranging from minutes to hours, depending on the quality of the sensor. Since it may be several days between surveys, clearly a gyroscope alone cannot perform the task. They do degrade smoothly, however, with noise that is well modeled by a random walk; and they have a history of use in underground mining automation [5][7].

We also considered use of a one- or two- axis laser range scanner. Such a device could be used to "sight" backwards along the mine entry to ensure that the path has not drifted. These devices have been tested in underground navigation previously[8], they can be built with angular accuracies of a fraction of a degree, and depending on the power of the laser, can return data at distances of a hundred meters or more. Unfortunately, the visibility of this sensor is not guaranteed. At any given time, the view back from the miner may be occluded by equipment, personnel, piles of coal, or changes in the mine roof height. Additionally, at present such devices are neither robust enough nor cost effective to be used underground on continuous miners.

In the end, we decided that a heading control system using purely on-board components was impractical. Instead, we developed a system which makes use of the mine surveyor's laser. These lasers are currently installed by the surveyors in order to guide the operators. Our solution uses these same lasers for guidance. Additionally, we added a gyroscope, allowing the system to function for ten to twenty minutes without receiving any readings from the laser.

A diagram of our system is shown in Figure 4. An off-board laser, using a cylindrical lens to spread the laser beam into a vertical plane, is used as a reference. The laser strikes two parallel steel plates attached to the mining machine at known locations. A camera, attached to the machine at a known location and equipped with a filter to pick up only light with the same wavelength as the laser, images both targets in a single image and transmits the image to a computer equipped with a framegrabber. A schematic of the fan laser, targets, and camera is shown in

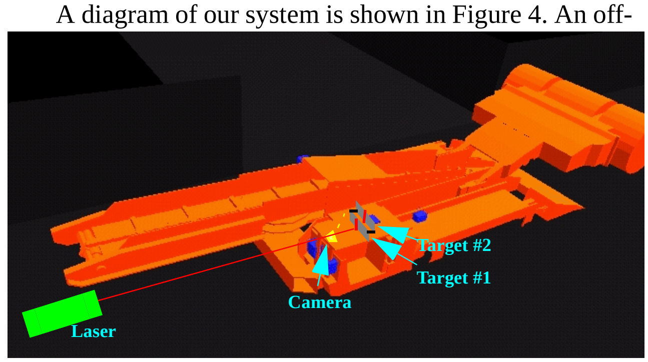

Figure 4: Heading control system components.

Figure 5; in this example, there is a heading misalignment between the fan laser and the camera/target system.

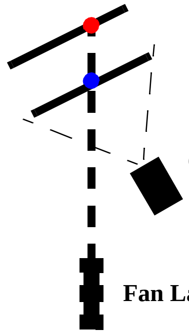

Figure 5: Top view schematic of heading misalignment.

Using a stripe operator and Hough transform, the computer identifies those pixels in the image which are illuminated by the laser (see Figure 6). These points are used to calculate a least-squares estimate of the plane containing the fan laser in the reference frame of the camera. This plane is transformed into the coordinate plane of the miner; finally, heading and offset of the camera are computed from the plane estimate.

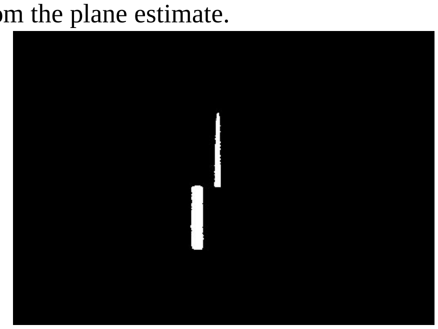

Figure 6: Thresholded camera image, showing the pixels on the two targets illuminated by the laser.

By checking the thresholded image against an internal model, the system is able to detect many failure modes; for example, blockage of the laser, extraneous light sources, bent target plates, etc.

The output of the vision system is then Kalman-filtered with the output of an onboard KVH fiber-optic gyro. Fusing data from these two sensors provides a much better estimate than from either alone, since the sensors have such different properties. The vision system is an absolute sensor, but returns measurements at a fairly coarse resolution (0.5 degrees of rotation and 1 centimeter of offset). The gyro measures only relative rotations, but to very high resolution and very accurately over small time scales. By Kalman filtering the two sensors, the drift of the gyro can be avoided while still providing much better rotational accuracy than is available from the vision system alone. The use of these two sensors also allows the system to reject bad or noisy data from the vision system; the heading control can function for 10-20 minutes without any readings from the vision system at all.

5. Sump depth control

The goal of the sump depth control system is to measure or control the forward motion of the mining machine over short distances. Unfortunately, many of the standard methods we considered for this task have serious drawbacks for this application.

Installing encoders on the tracks was perhaps the most obvious solution. However, this would have required redesign of the actual track assembly. This is an extremely expensive and time-consuming task, and would have to be done separately for each miner design. Further, the tracks on the continuous miner often slip, which would invalidate the encoder readings. For these reasons, we opted not to use encoders.

The output from an accelerometer could be doubly integrated to give a distance measurement. However, the velocities of the miner are small enough (a few centimeters per second while cutting) and irregular enough that the integrated noise would quickly overcome the signal.

We considered using a laser rangefinding system looking backwards at a reference point. As was the case with heading control, this solution was deemed unacceptable because of the uncertainty in the environment behind the machine; due to the constant passage of mine personnel and equipment, it would be difficult to ensure that a stationary reference point remained in view.

We ended up selecting a system which makes use of several stereo camera pairs aimed at the roof and ribs of the mine, as shown in Figure 7.

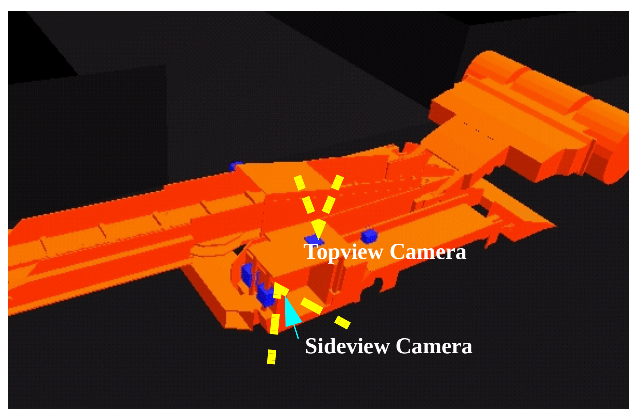

Figure 7: A sample camera module configuration.

As can be seen in Figure 8, the mine surfaces are textured enough that features can be easily tracked; and using these features, the relative motion of the miner to the ribs and roof can be measured. Unlike the view behind the machine, the view to the ribs and roof tends to remain unblocked.

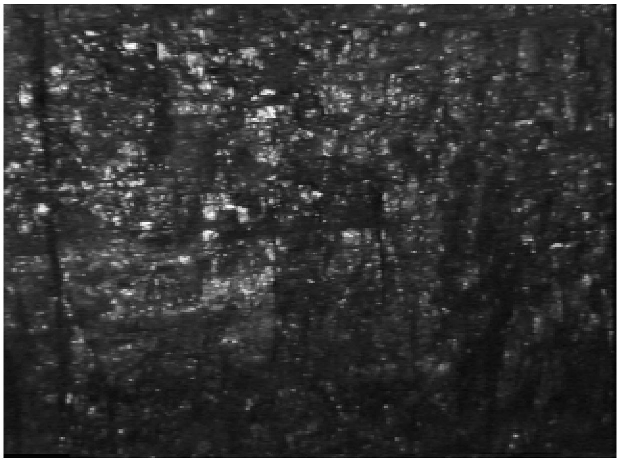

Figure 8: Coal face image as seen from rib-view cameras.

Each stereo module consists of two cameras equipped with band-pass filters and a diffuse light source, as shown in Figure 9. We opted to use a collection of infrared-emitting LEDs as the light source, mounted in a ring around each camera. As these light sources emit outside of the visible spectrum, they don't interfere with the human operator's vision. The band-pass filter was selected to precisely match the wavelengths of the diffuse light source, thereby strongly reducing the effect of other incidental light sources.

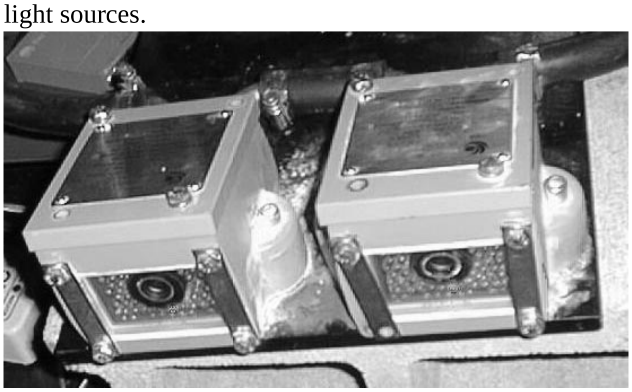

Figure 9: Stereo module including cameras, filters, and lighting.

Incoming video from the two cameras is digitized simultaneously. Each stereo system then performs the following processing steps:

1) Four feature windows are selected from a coal face image. These features are selected using an interest operator which selects four windows which have strong texture in all directions.

2) Using stereo vision, the 3D position of the center of each feature window is calculated [4]. In order to accomplish this, we make use of camera calibration software provided by the Jet Propulsion Laboratory [2].

3) Using binarized normalized correlation, the features are tracked to an image from the same camera during the next time step. Again, the new 3D position of each window center is calculated.

4) The camera motion between the two frames is computed by using a least-squares algorithm to fit the correspondence between the first set of 3D point positions and the second set. We have experimented with obtaining all six degrees of freedom of this motion, but our current system only solves for four: three degrees of translation and one rotation.

5) If the features have drifted near the edge of the image, select new features as in step 1; otherwise, continue with the original feature set.

6) Loop to step 3.

Each of the stereo systems sends its results to a central module. The central module gathers the position estimates from one or more of the camera modules, and Kalman filters them in order to obtain a single, best estimate of the motion of the mining machine. Each of the camera modules is mounted to view a different part of either the coal rib or the coal roof. In this way, even if one or more of the camera modules fails, machine motion can be estimated from the remaining camera modules.

6. Results

Testing of this system has been performed primarily in two locations. Most of the testing has been performed in our simulated mine, complete with a Joy 12CM-12 miner, on site at the Robotics Institute. Additional testing was performed in a nearby non-production underground coal mine (the "Tour-Ed" mine.)

Our simulated mine consists of an entry roughly 40 meters long and 7 meters wide. The entire area is enclosed in black plastic, to block out extraneous light. Simulated mine ribs were created from cast polyurethane molds taken from multiple actual mines. These molds were then cast in plaster and painted black, so that they appear to the sump depth cameras as similar as possible to actual coal ribs in both color and texture. The mine roof is made from a mosaic of digital photographs of actual mine roof, blown up to the proper scale.

A sump depth control system (using only a single stereo pair) was tested inside this mock-up in two ways. First, it was tested as an operator aid, in which position measurements from the system are conveyed back to the miner operator via a simple graphical display. In this capacity, repeated sumping motions of 1-2 meters were performed with the rib varying between 50 and 200 cm from the side-view cameras. Comparison of ground truth to the calculated distances revealed agreement to within 2% over 95% of the time. With the support of Joy Mining engineers, we connected this sensor to the on-board machine controller, and used it to perform a fully autonomous sump motion. The accuracy of this automated motion was also measured to be within 2%.

The heading control system was also tested as both a miner aid and in a closed-loop system together with the controller. As a miner aid, the system consistently measured heading to within 0.3 degrees and offset to within 2 centimeters. As a closed-loop system, the miner was programmed to follow the course indicated by the laser. The steering control of our machine is somewhat unpredictable, largely due to the lack of damping typically provided by the coal face. Nonetheless, the system was able to follow this course with an error of under 5 centimeters.

Both systems were also tested (in their miner aid instantiation) at the Tour-Ed mine. The sump depth system was tested for 10 sump motions, of which nine resulted in errors of under 2%. While we were unable to measure ground truth for the heading control system, the measured variance in heading and offset appeared similar to the results from our simulated mine, at distances of up to 80 meters from the laser.

Testing of both systems were performed in conditions of heavy water and dust. The heading control system is largely unaffected by these problems, due to its ability to function purely off of the gyro for long periods of time. While extremely heavy dust can pose a problem for the sump depth control system, dust levels commensurate with those of a miner in actual operation proved to be unproblematic. Additional testing in several active mines, including multiple sump depth camera systems, is planned for both systems in the coming months.

Finally, a professional continuous miner operator was brought in and asked to evaluate the usefulness of both systems as operator aids. After operating the machine in our mine mock-up for a half day, he expressed the view is that both systems would help increase production even at their present level of development.

7. Conclusions

Underground mining remains a prime candidate area for automation, due to the repetitive nature of the tasks and increasing pressure to produce more for less cost. Our strategy for enabling this automation has been to first automate small portions of the mining task and introduce them into the industry as miner aids, and to gradually increase the level of automation as the technology develops and industry acceptance widens. To this end, we have developed two mining aids: a system to measure and control the sump depth of a continuous miner, and a system to measure and control the machine's heading.

Both systems make use of only natural infrastructure and equipment already found in mines to accomplish their tasks. They have been tested successfully both in a simulated mine environment and in an actual underground mine under conditions of high dust and water spray. In light of these successes, the focus of the project has now shifted to testing in active coal mines and commercialization of the technology within the next 18 months.

Acknowledgments

The authors would like to thank Bryan Campbell, Dave Herdle, and Frank Higgins for their collaboration on this project. Support was provided by NASA under grant number NCC5-223 and Joy Technologies, Inc.

References

[1] Baiden, G. "Multiple LHD Teleoperation and Guidance at Inco Limited", Proceedings of the International Mining Conference, 1993.

[2] Gennery, Donald."Least-Squares Camera Calibration Including Lens Distortion and Automatic Editing of Calibration Points". To appear in Calibration and Orientation of Cameras in Computer Vision, A. Grun and T. Huang, Springer-Verlag.

[3] Herteau, R. et. al. "Optical Guidance System for Underground Mine Vehicles", Proceedings of 1992 ICRA.

[4] Horn, Berthold. Robot Vision. McGraw Hill, 1986, pp. 299-333.

[5] Makela, H. et al. "Navigation System for LHD machines". Intelligent Autonomous Vehicles, 1995.

[6] Mowry, G.L. "Promising Coal Interface Detection Methods". Mining Engineering, January, 1991, pp. 134-138.

[7] Scheding, S. et al. "Experiments in Autonomous Underground Guidance", Proceedings of 1997 IEEE Conference on Robotics and Automation, April, 1997, pp. 1898-1903.

[8] Shaffer, Gary, and Stentz, Anthony. "A Robotic System for Underground Coal Mining". Proceedings of 1992 IEEE Coneference on Robotics and Automation, May, 1992, pp. 633-638.