Progress toward a reduced exposure mining system

G.H. SCHNAKENBERG, JR.

G.H. Schnakenberg is research physicist with National Institute for Safety and Health, Pittsburgh Research Center, Pittsburgh, PA. Preprint 96-74, SME Annual Meeting, March 11-14, 1996, Phoenix, AZ. Original manuscript February 1996. Discussion of this peer-reviewed and approved paper is invited and must be submitted, in duplicate, prior to May 31, 1997.

Abstract

In 1986, the US Bureau of Mines (USBM) embarked on a major research effort to develop technology that could substantially reduce worker exposure to face hazards by simply relocating the equipment operators to an area of relative safety. This reduced-exposure mining system (REMS) research effort enhances the USBM's ongoing health and safety efforts aimed at reducing and controlling dust and noise and reducing accidents through training and better mining practices. This paper reports on the progress made on the developing research and demonstrates the technologies required for the computer-assisted teleremote operation of continuous mining machines, haulage systems and roof bolting machines.

Need for research

In the United States, coal is the most abundant fossil energy resource and constitutes over 82% of all domestic nonrenewable energy reserves. At the present consumption rate, recoverable reserves of coal will last another 240 years. Today, about 80% of all coal mined in the United States is used to generate over half (55%) of the electricity consumed. This situation will continue beyond the year 2010, with the demand for electricity expected to increase by 22% by that time. Of that increase, 95% will come from coal. Because we are dependent on electricity, an uninterrupted flow of affordable coal, mined with minimal risk to workers, is essential to the vitality of the United States.

Today, face workers in underground room-and-pillar mines experience disproportionate health and safety hazards, compared to co-workers elsewhere in the mine. During the period from 1986 through 1992, operators of roof-bolting and continuous-mining equipment comprise about 20% of the work force. Yet, this group accounted for about 40% of the deaths and lost-time injuries. Shuttle-car haulage is also burdened with hazards.

Facing the mining industry is the inevitable fact that coal will become more difficult and potentially more hazardous to mine as miners are forced to tap into deeper and thinner seams. Safer and more efficient mining systems will be needed to improve worker safety and control energy costs. It is imperative that the USBM utilize advanced technology to minimize worker risks and to improve mining methods.

The nature of the coal industry in the United States encumbers the USBM with this research responsibility. The Bureau's research on a computer-enhanced mining system under its Equipment Safety Division of the Health and Safety Research program provides an essential component to safely satisfy the coal needs of the United States.

New approach

In 1986, the USBM concluded that advances in automation technologies could be used to significantly enhance underground worker safety and health and to potentially provide a foundation for new mining methods. It was thought possible that equipment operators could successfully operate their machines from a location away from the face area, thus, greatly reducing if not eliminating their exposure to dust, noise, machine and geological hazards. Having recognized this possibility, USBM researchers were obligated to pursue the necessary research. Thus, a new research approach was added to the USBM research arsenal, attacking present and future health and safety hazards affecting coal-mine workers. The computer-assisted mining system research program was thus conceived. It was recently, and perhaps more appropriately, renamed "the reduced exposure mining system" or "REMS" (McClelland et al., 1994).

The USBM research focuses on developing the critical technology — in a practical and transferable form — that will enable what are now the most hazardous activities of equipment operation to be performed in safety from a nearby control station. The USBM has progressed a long way toward reaching this goal.

The research originated with the continuous-mining machine and now includes, in addition to the continuous miner, a continuous-haulage system, a roof bolter and ventilation equipment.

Research activities

Research is being conducted at two USBM research centers — one, the lead center, near Pittsburgh, PA, and one in Spokane, WA. The Spokane Research Center's efforts concentrate entirely on developing the automated drilling and bolting module for the roof bolter. All other research and the technical project coordination are conducted at the Pittsburgh Research Center. The current research schedule plan calls for a convincing demonstration of the technology by September 1997.

Much of the work has been reported at prior SME-AIME Annual Meetings, as well as elsewhere (Schnakenberg and Sammarco, 1991). The essence of the research stems from the need to use sensors and computers for much of the machine control, because the safest position for the machine operator is not within a direct line of sight of the machine. Thus, the research consists of the following six major concepts (research areas):

- The machine, or equipment itself, must be equipped with position sensors on its moving parts, so that the control system gets the feedback it needs for closed-loop control. In the special case of the roof bolter, this research area includes the design of a module that can perform automated drilling and bolting.
- Navigation and guidance systems must provide the control system with data on the position and orientation of the machine.
- Coal-rock interface detection must provide the means for keeping the mining machine within the desired part of the coal seam.
- Data communications must provide the link between the activities of the machine and a computer located at a convenient control station.
- Control software must provide the architecture such that the program code runs quickly and predictably and is easily understood, modified and documented.
- Visualization and operator interface must provide the means for the operator to understand what is going on with the mining machine (visualization) and must provide the facility to control the machines actions (the operator interface).

The last three areas above also influence the selection of the computer hardware.

Machines. The following machines and equipment are being investigated:

Continuous-mining machine: Initial testing was performed on a Joy 16CM continuous-mining machine (which was on hand). Later, a new Joy 14CM machine was tested. Sensors were added to report appendage positions, motor currents and hydraulic pressure, with the sensors being the most important component for machine control. Because the mining machine was working with continuous haulage, it was thought best that the haulage system carry the supply cables and hoses to the machine. A method for easily disconnecting the power, water and communications from the miner was then devised. A means for supporting the cables that would provide sufficient slack between the haulage system and the continuous mining machine was also devised. The work on the continuous-mining machine is essentially complete.

Continuous haulage: The greatest safety gains of REMS will be realized when continuous haulage is employed. The continuous-haulage system must be coordinated with the actions of the mining machine. A short, 18 m (60 ft), section of Joy 3FCT, which, nevertheless, represented all the components of a full system, was purchased. A sensor was attached to indicate the steering angle of the wheels of the hopper car and the haulage system was modified to carry the power and communication cables, as well as water hose, for the continuous mining machine. Quick disconnects and two drop loops, formed by supporting the cable and hose bundle by a ring that freely slides on a runner attached to the conveyor boom (tail) of the mining machine, provided the 3.5 m (12 ft) of slack needed to allow for freedom of movement between the two machines. Two chains also connect the two machines to prevent inadvertent strain on the continuous-miner cables.

Roof bolter: The roof bolter provides the greatest challenge to automation. The drilling, installation and setting of roof bolts are largely a mechanically-assisted human operation. The USBM purchased a Fletcher Model HDDR-13, C-F (WATER) roof-bolting machine to support the research effort. The research team at Pittsburgh completed a major effort to prepare the bolter chassis to accept computer control, and the research team at Spokane wrote the control software and is continuing to design and build an automated roof drilling and bolting module. Although the objective is total hands-off drilling and bolting of a 15- to 20-m mine entry, even the highly injury-saving goal of line-of-sight remote-controlled bolting requires an automated drilling and bolting module.

Ventilation: Ventilation methods and equipment for REMS will not greatly differ from that being developed and used for normal and extended-cut continuous mining. If line curtains are used, the machine activities can be paused while the curtain is advanced. When using continuous haulage, the haulage system can support the fan and tubing for blowing ventilation systems (Taylor et al., 1992). Current research is showing that a properly functioning dust scrubber that is integral with the mining machine is a substantial contributor to good face ventilation for methane control. A sensor that monitors the status of loading the dust-scrubber filter of the continuous miner has been developed and reports to the control system.

Navigation. Because remote manual control over a mining machine is challenging, even when the operator has a clear view of the machine, it is best if the machine's motion control is done with the help of a computer. To do this, the computer must know where the machine is, the direction that it is heading and the boundaries of the coal seam, i.e., coal interface detection (discussed below). One way to determine a machine's position is to reference its position from the mine geometry. The other method is to use an inertial guidance system that can report its position accurately.

While experiments were being performed on alternative systems (Anderson, 1989, 1992; Jobes, 1991, 1993), an inertial navigation system that uses three orthogonal laser gyroscopes and accelerometers was in the process of being perfected for military applications by Honeywell Military Avionics Division. Several years ago, a Honeywell system was obtained, and the USBM worked with the manufacturer to fine tune it for use on a continuous mining machine (Sammarco, 1993). This sensor, renamed the Honeywell ore recovery and tunneling aid (HORTA) for mining applications, is mounted on the mining machine and reports machine orientation and position. As a result of the USBM application and test results, the HORTA is presently being aggressively marketed for mining-machine guidance systems, especially for highwall applications. As of August 1995, the accuracy of the HORTA has not been fully determined. The only true test of the accuracy is to subject it to the mining conditions under which it is to operate (including vibration, machine motions and time), namely, on the miner for highwall and room-and-pillar mining. The USBM plans on conducting tests in an open-pit coal mine, because the position and orientation data from the HORTA must be compared against accurate transit data. At this time, a test site in an open-pit mine appears likely.

The guidance of the continuous-haulage system is another task that is nearing completion. The objective is to keep the position of the conveyor discharge (tail) of the mining machine over the center of the hopper of the continuous-haulage system while coal is being discharged from the miner. At other times, the hopper car must be positioned to receive coal or to avoid stressing the cables of the mining machine. The control program developed restricts the movements of the mining machine to only those that the haulage system can follow. Three string potentiometers mounted on the front of the hopper car with the free ends of the strings attached to the rear of the continuous mining machine have been used. Triangulation calculations applied to these data provide the haulage-control computer with the orientation and position of the hopper relative to the mining machine. The controller (detailed below) interprets this information and uses it to steer the guide wheels of the hopper and to move the haulage system forward and backward as necessary.

Coal-rock interface determination. One of the most difficult problems that the USBM faces in developing computer-assisted mining is keeping the cutting head of a mining machine within the desired boundaries of a coal seam, whatever the type of geology encountered. Two in-seam guidance situations are usually encountered: One is the desire to extract all the coal to the seam boundary, and the other is the need to leave a layer of coal on the floor, roof or both for reasons of ground stability or coal quality. Furthermore, properties of overlying or supporting strata vary from seam to seam. Techniques useful in one seam may not be useful in others. The USBM has put extensive research effort into these problems (Mowrey, 1991a, 1991b, 1992; Pazuchanics and Mowrey, 1991, 1993; Maksimovic and Mowrey, 1993).

When some thickness of coal is to be left on the roof and/or the floor, a commercially available coal-thickness sensor that uses the ability of the coal to attenuate the naturally occurring gamma radiation emanating from the host strata can be used (Mowrey, 1991a, 1991b; Maksimovic and Mowrey, 1993). When coal thicknesses greater than 0.6 m (2 ft) are required or geological conditions are not favorable, natural gamma methods will not work. For these instances, the USBM is evaluating using commercial ground-penetrating radar to measure coal thickness. The USBM has also developed a highly unique spatial-domain radar system that can, among other uses, determine the distances from the air-coal interface to the roughly planar boundaries of the layers of strata for depths of a few meters (Chufo and Johnson, 1991). Within the next couple of years, this radar system will be able to produce three-dimensional images of hidden strata.

For those situations in which no coal is to be left on the roof, a sensing system that detects when the bits of the continuous miner touch the overlying strata has been developed. This system uses an infrared- (surface-temperature sensitive) imaging video (TV) camera that detects the immediate heating of the bits, the rock surface and the dust, which is caused by friction with the harder overburden. A simple video alarm system, which is normally used to detect intruders by sensing movements in a stationary video scene, is used to detect the increased thermal activity the instant it occurs. As the control computer raises the boom toward the roof, it monitors the signal from the video alarm and stops raising the boom when the alarm signal is detected (Mowrey and Ganoe, 1995).

Communication and computers. Sensor data and commands must quickly and confidently flow between the mining equipment and the machine-control computer outby. In an effort to keep the systems on board the machine as simple as possible, Intel' s Bitbus, a network of microcontrollers, was chosen. One microcontroller card gathers all the sensor data (except that from the HORTA) and repeatedly and continuously transmits it over a twisted-pair data link to the control station. On a separate twisted pair, machine commands that turn the motors or hydraulic valves on or off are sent to a second microcontroller card on board the machine (Schiffbauer, 1994). The USBM empirically determined appendage motion response characteristics and devised the appropriate servo control algorithms. Control delays are essentially those of the machine hydraulics.

The HORTA is connected to its own controlling off-board computer by two twisted-pair wires. All four twisted pairs are bundled and enclosed in hydraulic hose conduit that is bound to the machine's power cable.

In the case of the continuous-haulage system, it was desirable that the manufacturer's control system be utilized as much as possible. With the aid of the manufacturer, the steering-wheel-angle sensors and string potentiometers for guidance were connected directly into the manufacturers system. The manufacturers current-loop communication network for passing the status and sensor data into and pass commands from the control computer was used.

The outby control station for REMS, intended to be located near the power center in room-and-pillar operations, contains three or four single-board PCs, an associated shared monitor and a keyboard. Microcontroller cards reside in one PC to communicate with the mining machine and haulage system. Another PC exclusively operates the HORTA. A third PC runs the control software — software that interprets the data from the machines and issues commands to turn on motors and control hydraulic valves for performing mining and haulage tasks. A Silicon Graphics workstation and monitor displays the work face with the machines in action and, also, serves as the operator interface, so that the machine operator can observe what is happening and can intervene if necessary. All of the above-mentioned computers are interconnected, so that they can immediately share sensor and control data. The hardware described fits into a single compact frame inside a control hut that advances with the section.

Machine controller software. The USBM chose to use a hierarchical, real-time control system to integrate and manage computer-assisted machine control. The system developed is modeled after one that was developed by the National Institute of Standards and Technology (NIST) (Quintero and Barbera, 1992) and is the practical implementation of NIST's NASREM architecture developed and adopted for the NASA space program (Albus et al., 1989). This form of control programming was selected because it claimed to have the advantages of ease of understanding, readability and modification and because it has a deterministic and well-understood behavior. It was found that these claims were true and useful. The programming language used is C, and the program runs in MS-DOS on one PC. The structure of the software is a hierarchy of tasks with the higher level tasks being composed of a parallel and serial combination of more simple tasks. With this structure, tasks can be easily added or modified. Our controller provides a "researchers" interface featuring pull-down menus that allow selected issuing of task commands at any level or direct control over each machine actuator. Although this interface is handy for the researchers, it is inappropriate as an operator interface.

Visualization and operator interface. Because the machine operators will not be within the line-of-sight of the machine that they are controlling and because TV cameras (which will probably always be present) cannot always provide the best perspective, an alternative was developed. The basic research objective was, and is, to develop meaningful (information-conveying) pictures (three-dimensional portrayals) of the machine in its working area and then to animate or update these pictures in concert with machine actions or environmental changes. Two prototype visualization concepts were developed. In one case, the USBM's indoor research area, consisting of a block of artificial coal, the mining machine, the continuous-haulage machine and research control hut, is shown. As the machine or its appendages move, the picture of the machine on the monitor also moves. Moreover, the operator can zoom in on the machine or view it from any angle, including from underneath the ground. In another instance, which was developed for highwall mining, simultaneous top, side and end views, presented as "flat" drawings (orthographic projections), are provided. In the side view, the mining machine in profile, the coal that is extracted and the coal thickness left on roof and floor is shown using readings obtained from the coal-thickness sensors. This information for the current cut is overlaid on a similar picture of the previous cut. These X-ray-like views provide machine operators with a better "view" than if they were there with the machine. Using these views, they can optimize the extraction by using knowledge of the previous cut to adjust roof or floor height to take or leave more coal. A top view allows one to see the pillar (web) width and shows a projected path of the miner to see whether the pillar is narrowing or getting wider. Steering corrections can be made manually if needed. The visualization system does not have to be used with a computer-controlled mining system, but it does need to be able to get navigational and appendage data from the mining machine.

The visualization system described above could also depict a longwall shearer, the seam boundaries and the shield supports and their movements, and, thereby, the system could enhance development and use of automated longwall mining.

The USBM is currently developing an operator interface for the continuous-mining machine and continuous-haulage element of REMS. The objective of an operator interface is to quickly inform the operator of the status of the machine operation at all times and to permit facile manual control of machine tasks or actuators, whenever it becomes necessary. The design is a particularly difficult task, because the USBM does not have continual access to a mine in which REMS can be operated. Such a mine would allow the researchers to experience real mining scenarios, so that they could develop the appropriate informative interface from those experiences. However, the basic structure and components that should allow easy reconfiguration and prototyping are being developed. A preliminary interface is under development.

Future research

As of August 1995, the USBM was planning to conduct challenging tests of the continuous-mining machine using open-pit and highwall mines. The accuracy of the HORTA will be determined by performing full-scale highwall mining scenarios in an open-pit mine. The absence of overburden provides researchers access to measure machine position using surveying equipment. The open-pit site will offer opportunities to test and refine automatic mining scenarios, including two-pass advances and turning crosscuts, the use of a radar system for maintaining web thickness in highwall and the evaluation of the visualization system. In addition, the system will provide an opportunity to obtain the operating time needed to improve the designs of an operator interface. A highwall mine will provide a test site for the coal-interface detection systems as they are integrated into the control system.

The combination of successful open-pit and highwall mining tests should spark the interest of the highwall- and underground-mining industry, which would provide the incentive for equipment manufacturers to use the USBM technology.

The roof bolter, when ready in a year or so, will be tested in an underground mine in an area of previously bolted roof

Summary

The USBM is engaged in a research program that utilizes advances in machine-control technology to improve worker safety and health in underground coal mines. Sensors and computer technology now allow for remote operation of the continuous-mining machine, continuous-haulage system and roof bolter from a nearby, safe location during the most hazardous tasks of cutting and hauling coal and bolting the roof. Substantial progress has been made, and components of the REMS, such as coal-interface detection and visualization, can be utilized individually in today's mining systems to increase safety. Provided that the resources are available, the performance of the system can be tested and demonstrated using test sites of open-pit and highwall mines. The demonstration should convince industry and equipment manufacturers that REMS can improve the bottom line substantially by reducing injuries and fatalities and their associated costs. ■

Editor's Note. Through successive actions of the US Congress in 1995 and 1996, the USBM was dissolved. As a result, the health and safety research functions of the USBM at Denver, CO and Minneapolis, MN were closed and those at Spokane, WA and Pittsburgh, PA were transferred to the National Institute for Occupational Health and Safety (NIOSH) as NIOSH-SRC and NIOSH-PRC, respectively.

Reference

Albus, J.S., McCain, H.G., and Lumia, R., 1989, NASA/NBS Standard Reference Model for Telerobot Control System Architecture (NASREM), NIST (formerly NBS) Technical Note 1235.

Anderson, D.L., 1989, Position and Heading Determination of a Continuous Mining Machine Using an Angular Position-Sensing System, USBM, IC 9222,* 8 pp.

Anderson, D.L., 1992, Underground Test Results of a Laser-Based Continuous Miner Tram Control System, USBM RI (in publication, available from author, Bureau of Mines, PO Box 18070, Pittsburgh, PA, 15236, USA).

Chufo, R.L., and Johnson, W.J., 1991, "A radar coal thickness sensor," *Conference Record of the 1991 EEE Industry Applications Society Annual Meeting,* Dearborn, MI, pp. 1182-1191.

Jobes, C.C., 1991, Utilizing Mechanical Linear Transducers for the Determination of a Mining Machine's Position and Heading, USBM, RI 9364,* 19 pp.

Jobes, C.C., 1993, "Mechanical sensor guidance of a mining machine," *EEE Transactions of Industry Applications*, Vol. 29, No. 4, pp. 755-761.

Maksimovic, S., and Mowrey, G.L., 1993, Basic Geological and Analytical Properties of Selected Coal Seams for Coal Interface Detection, USBM, IC 9296,* 58 pp.

McClelland, J.J., Randolf, R.F., Schnakenberg, G.H., Jr., and Fowkes, R.S., 1994, Safety Breakthrough Reduced Exposure Mining System (REMS), USBM, SP-26-94,* 38 pp.

Mowrey, G.L., 1991a, "Promising coal interface detection methods," *Mining Engineering*, Vol. 43, No. 1, pp. 134-138.

Mowrey, G.L., 1991b, "Horizon control holds key to automation (Part 1)," *Coal Magazine*, pp. 44-48.

Mowrey, G.L., 1992, "Horizon control holds key to automation (Part 2)," *Coal Magazine*, pp. 47-51.

Mowrey, G.L., and Ganoe, C.W., 1995, "An infrared-based coal interface detection system;" *Proceedings, Third International Symposium on Mine Mechanization and Automation*, Golden, CO, June 12-14, 1995, L. Ozdemir and K. Hanna, eds., pp. 3-21 to 3-31.

Pazuchanics, M.J., and Mowrey, G.L., 1991, Use of Adaptive Signal Processing Techniques to Discriminate Between Coal Cutting and Rock Cutting, USBM, IC 9269, * 13 pp.

Pazuchanics, M.J., and Mowrey, G.L., 1993, Recent Progress in Discriminating Between Coal Cutting and Rock Cutting with Adaptive Signal Processing Techniques, USBM, RI 9475,* 15 pp.

Quintero, R., and Barbera, A.J., 1992, A Real-Time Control System Methodology for Developing Intelligent Control Systems, NISTIR 4936, US Department of Commerce, National Institute of Standards and Technology, Robot Systems Division, Gaithersburg, MD 20899, 84 pp.

Sammarco, J.J., 1993, Field Evaluation of the Modular Azimuth and Positioning System (MAPS) for a Continuous Mining Machine, USBM, IC 9354,* 14 pp.

Schiffbauer, W.H., 1994, "A distributed communications and real-time control network for robotic mining," *Proceedings of the ACE Specialty Conference on Robotics for Challenging Environments*, Albuquerque, NM.

Schnakenberg, G.H., Jr., and Sammarco, J.J., 1991, "Overview of the Bureau of Mines computer-assisted mining research program," *Proceedings of the International Symposium on Mine Mechanization and Automation*, Golden, CO, pp. 9-9 to 9-29.

Taylor, C.D., Goodman, G.V.R., and Vincze, T., 1992, "Extended cut face ventilation for remotely controlled and automated mining systems, *Proceedings of SME 1992 Annual Meeting*, 11 pp.

*All US Bureau of Mines publications are available from the National Technical Information Service, Springfield, VA 22161, USA; phone: (703) 487-4650; fax (703) 321-8547.