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PROGRESS TOWARD A REDUCED EXPOSURE MINING SYSTEM

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Abstract. In 1986 the U.S. Bureau of Mines (USBM) embarked on a major research effort to develop technology that can substantially reduce worker exposure to face hazards simply by relocating the equipment operators to an area of relative safety. This reduced exposure mining system (REMS) research effort enhances the USBM ongoing health and safety research efforts to reduce and control dust and noise and to reduce accidents through training and better mining practices. This paper reports progress of the research that is developing and will demonstrate the technologies required for the computer-assisted tele-remote operation of continuous mining machines, haulage systems, and roof bolting machines.

NEED FOR RESEARCH

Coal is the United States' most abundant fossil energy resource constituting over 82% of all domestic nonrenewable energy reserves. At the present consumption rate, recoverable reserves of coal will last 240 years. Today, about 80% of all coal mined in the United States is used to generate over half (55%) of the electricity consumed by the Nation. 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. Since so much in our lives depends upon electricity, an uninterrupted flow of affordable coal, mined with minimal risk to workers, is essential to maintaining this nation's vitality.

Today, face workers in underground room-and-pillar mines experience disproportionate health and safety hazards compared to their coworkers elsewhere in the mine. Operators of roof bolting and continuous mining equipment comprise one-fifth of the workforce yet accounted for two-fifths of the deaths and lost-time injuries during 1986-1992. Shuttle car haulage is also burdened with hazards.

Facing us is the inevitable—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 U.S. Bureau of Mines (USBM) utilize advanced technology to minimize worker risks and improve mining methods. The nature of the coal industry in this country 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 our nation.

NEW APPROACH

In 1986, the USBM concluded that advances in automation technologies could be used to significantly enhance underground worker safety and health and potentially provide a foundation for new mining methods. It was thought possible that equipment operators could successfully operate their machines without being located in the face area with them, 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 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 transferrable form—that will enable what are now the most hazardous activities of equipment operation to be performed in safety from a nearby control station. We at the Bureau have progressed a long way along the path to reach that goal.

Our 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.

RESEARCH ACTIVITIES

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

Much of our work has been reported at prior SME-AIME annual meetings and 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 six major areas:

(1) 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 which can perform automated drilling and bolting.

(2) Navigation and guidance systems provide the control system with data on the position and orientation of the machine.

(3) Coal-rock interface detection provides the means to keep the mining machine within the desired part of the coal seam.

(4) Data communications is the link between the activities of the machine and a computer located at a convenient control station.

(5) Control software with an architecture such that the program code runs quickly and predictably and is easily understood, modified, and documented.

(6) Visualization and operator interface provide the means for the operator to understand what is going on with the mining machine (visualization) and the facility to control machine actions (the operator interface).

Areas (4), (5), and (6) influence the selection of the computer hardware as well.

Machine

Continuous Mining Machine: We started with a continuous mining machine that was on hand, a Joy 16CM, and then a new machine, a Joy 14CM. We added sensors to report appendage positions, motor currents, and hydraulic pressure, the sensors being most important for machine control. Since the mining machine is working with continuous haulage, we thought it best if the haulage system would carry the supply cables and hoses to the machine. We then devised a method for easily disconnecting the power, water, and communications from the miner. A means for supporting the cables that provides sufficient slack between the haulage system and the continuous mining machine was also devised. Our 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. We purchased a short (18 m) section of a Joy 3FCT that nevertheless represents all the components of a full system. We attached a sensor to indicate the steering angle of the wheels of the hopper car and modified the haulage system to carry the power and communication cables and the water hose for the continuous mining machine. Quick disconnects and two drop loops formed by supporting the cable and hose bundle by a ring, which freely slides on a runner attached to the conveyor boom (tail) of the mining machine, provide the 3.5 m of slack needed to allow 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 automate. 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 has completed a major effort to prepare the bolter chassis to accept computer control. The research team at Spokane has written 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 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 view of the machine, it is best if the machine motion control is done with the help of a computer. To do this, the computer must know where the machine is, the direction it is heading and the boundaries of the coal seam, i.e., coal interface detection, which will be discussed in the next section. One way to determine machine position is to reference its position from the mine geometry; the other is to use an inertial guidance system that can report its position accurately. While we experimented with alternative systems (Anderson, 1989 and 1992; Jobes, 1991 and 1993), an inertial navigation system using three orthogonal laser gyroscopes and accelerometers was being perfected for military applications by Honeywell Military Avionics Division. Several years ago, we obtained a Honeywell system and have 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 our application and test results, the HORTA is presently being aggressively marketed for mining machine guidance systems especially for highwall applications. As of this writing (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. We plan to conduct tests in an open-pit coal mine because we need to be able to compare position and orientation data from the HORTA 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. Our control program restricts the movements of the mining machine to those which the haulage system can follow. We have used 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. 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; the other is the need to leave a layer of coal on the floor or 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, and 1992; Maksimovic and Mowrey, 1993; Pazuchanics and Mowrey, 1991 and 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 are required or geological conditions are not favorable, natural gamma methods will not work. For these instances, we are 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 3-D images of hidden strata.

For those situations when no coal is to be left on the roof, we have developed a sensing system that detects when the bits of the continuous miner touch the overlying strata. This system uses an infrared (surface temperature sensitive) imaging video (TV) camera that detects the immediate heating of the bits, rock surface, and dust, caused by friction with the harder overburden. A simple video alarm system, 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 onboard the machine as simple as possible, we chose Intel's Bitbus, a network of microcontrollers. 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 onboard 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 offboard computer by two twisted-pair wires. All four twisted pairs are bundled and enclosed in hydraulic hose conduit and bound to the machine power cable.

In the case of the continuous haulage system, we wanted to utilize the manufacturer's control system as much as possible. We worked with the manufacturer to enable us to connect our steering-wheel angle sensors and string potentiometers for guidance directly into their system. We used their current-loop communication network to pass the status and sensor data into and pass commands from our control computer.

The outby control station for REMS, intended to be located near the power center in room-and-pillar operations, contains 3-4 single-board PC's, 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 our control software—software that interprets the data from the machines and issues commands that turn motors and control hydraulic valve on or off to perform mining and haulage tasks. A Silicon Graphics workstation and monitor displays the workface with the machines in action, and serves also as the operator interface where the machine operator observes what is happening and can intervene if necessary. All of the 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 we developed is modeled after that 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 the advantages of ease of understanding, readability, modification, and a deterministic and well-understood behavior. We have found these claims to be true and useful. The programming language used is C and 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 line of sight of the machine they are controlling, and because TV cameras (which will probably always be present) cannot always provide the best perspective, we have developed an alternative. The basic research objective is to develop meaningful (information conveying) pictures (3-D portrayals) of the machine in its working area and animate or update these pictures in concert with machine actions or environmental changes. We have developed two prototype visualization concepts. In one case we show our indoor research area consisting of a block of artificial coal, the mining machine, the continuous haulage machine and our research control hut. 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, we provide simultaneous top, side, and end views as "flat" drawings (orthographic projections). In the side view, we show the mining machine in profile, the coal that is extracted, and the coal thickness left on roof and floor 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 a view of the pillar (web) width, and views 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 could enhance development and use of automated longwall mining.

We are 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 permit facile manual control of machine tasks or actuators whenever it becomes necessary. The design is a particularly difficult task since the USBM does not have continual access to a mine in which we can operate REMS so that we can experience real mining scenarios and develop the appropriate informative interface from those experiences. However, we are developing the basic structure and components that should allow easy reconfiguration and prototyping. A preliminary interface is under development.

FUTURE RESEARCH

At the present time (August 1995), the USBM is 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. 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 such as two-pass advances and turning crosscuts; the radar system for maintaining web thickness in highwall; evaluation of the visualization system; and will provide an opportunity to get the operating time that is 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 and thereby provide the incentive for equipment manufacturers to use 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 can now allow 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 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.

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