

AUTOMATION AND ROBOTICS TECHNOLOGY FOR
INTELLIGENT MINING SYSTEMS

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ABSTRACT

The U.S. Bureau of Mines is approaching the problems of accidents and efficiency in the mining industry through the application of automation and robotics to mining systems. This technology can increase safety by removing workers from hazardous areas of the mines or from performing hazardous tasks. The efficiency of mining systems can increase through a reduction of machine downtime and through more efficient operation of mining equipment. The short-term goal of the Automation and Robotics program is to develop technology that can be implemented in the form of an autonomous mining machine using current continuous mining machine equipment. This requires technology that would allow a continuous mining machine to perform the same functions in coal extraction as a manually-operated continuous mining machine, only without human intervention. In the longer term, the goal is to conduct research that will lead to new intelligent mining systems that capitalize on the capabilities of robotics.

The Bureau of Mines Automation and Robotics program has been structured to produce the technology required for the short- and long-term goals. The short-term goal of application of automation and robotics to an existing mining machine, resulting in autonomous operation, is expected to be accomplished within five years. Key technology elements required for an autonomous continuous mining machine are well underway and include machine navigation systems, coal-rock interface detectors, machine condition monitoring, and intelligent computer systems.

A navigation scheme consisting of a laser scanning unit, a gyroscope, sonar, and clinometers has been designed, sensors procured, and lab testing initiated. For coal-rock interface detection, Bureau work is focusing on the techniques of machine vibration, in-seam seismic properties, and doppler radar. In-mine testing of these techniques is underway. The Bureau is approaching machine failures through the development of real-time sensor-based diagnostic expert systems. An expert system for the hydraulic and electrical subsystems of a continuous mining machine is being developed. The last key technology element, an intelligent computer system, provides the backbone for intelligent mining systems. The computer system must interface to a variety of sensor systems, and control the mining machine to mine coal according to a mining plan, while being able to react to any abnormal conditions encountered. An onboard computer system has been designed and machine control tests have been initiated.

In this paper, the Bureau of Mines program is described, including status of key technology elements for an autonomous continuous mining machine, the program schedule, and future work. Although the program is directed toward underground mining, much of the technology being developed may have applications for space systems or mining on the moon or other planets.

1. INTRODUCTION

Coal is the most abundant U.S. energy resource. There are enough coal reserves in the U.S. to provide energy for several hundred years. However, a number of factors have contributed to a situation where the U.S. coal industry is losing its competitiveness in the world energy market. Two contributing factors are the costs associated with accidents and system inefficiencies. If coal is to be the solution for U.S. energy needs in the future, something must be done to increase safety, health, and efficiency of mining operations.

Many new technologies have been introduced to mining over the years. Continuous mining machine and longwall coal extraction systems have had a large impact on coal productivity. However, these systems, even though productive, still operate far below their design capacity. Also, the number of accidents occurring annually in underground coal mines has basically leveled off, with no major reduction expected using current mining systems.

The application of high technology including artificial intelligence and robotics is one way for the U.S. coal industry to be competitive, and for coal to be the energy resource of the future. Robotics and automation technology are now commonly used in other industries to increase safety and productivity, and to reduce costs. The automotive industry is one example in which this technology is used with success. A similar success can be achieved in the mining industry. Productivity should be improved by increasing machine availability and efficiency of operation. Health and safety should be improved by removing humans from hazardous areas of the mine.

The Bureau of Mines is committed to a program of research in Robotics and Automation for the mining industry. This paper presents the Bureau's program, discussing key technology areas, current status, and plans for the future.

2. PROGRAM DIRECTION

Room-and-pillar mining using continuous mining machines is a major coal extraction method in the U.S. today and is expected to continue to be a major method. Continuous mining machines are also necessary for panel development for the longwall coal extraction method. Therefore, the Bureau of Mines has initially focused its Robotics and Automation program toward the technology required for an autonomous or robotic continuous mining machine--that is, toward technology that would allow a continuous mining machine to operate without human intervention in a room-and-pillar mining scenario.

This research involves integrating new technology with existing continuous mining machines to allow them to operate autonomously. The new technology consists of sensor systems and computer intelligence that would allow the mining machine to sense its own status and operation, sense its environment, make decisions, and extract coal according to a mining plan,

while being able to react to changing conditions. While working toward the program goal of a completely autonomous continuous mining machine, much of this technology can also be utilized on existing manually-operated mining machines to have an immediate impact on mining safety and productivity.

3. TECHNOLOGY ELEMENTS

An autonomous continuous mining machine must be capable of performing the same functions in coal extraction as a manually-operated continuous miner, only without human intervention. With a manually-operated continuous mining machine, the operator relies heavily on his human sensory systems to control the machine according to a mining plan (fig. 1). The operator often uses vision to tell when the cutting drum is cutting coal or the overlying or underlying strata. The feel or vibration of the machine and the noise generated by the cutting are also indicators of the material being cut. As the machine goes from cutting coal to a harder or softer strata, vibration and noise change.

To keep the mining machine traveling in the desired heading, as specified in the mining plan, the machine operator must visually align the machine with the survey marks on the roof. Vision is also necessary to guide the machine from one location in the mine to another, to negotiate entries, and to avoid obstacles. Verbal communication with the face foreman is also necessary for machine guidance and to deal with abnormalities.

To detect machine problems or failures, the machine operator uses his senses of vision, hearing, and smell. For example, the operator can visually see a failure such as a ruptured hydraulic hose, hear changes in the sound a motor is making, or smell a hot motor.

All these sensory inputs are then passed to the operator's brain, where decisions are made and control of the machine initiated. The human operator must make decisions not only for normal conditions, but also for abnormal conditions. This sometimes requires the operator to consult the face foreman or other mine experts who are more knowledgeable of how to best deal with the situation.

An autonomous continuous mining machine must be able to sense, make decisions, and carry out machine control (fig. 2) as described above for a manually-operated machine. The key technology elements required for an autonomous continuous mining machine are shown in fig. 3.

Basic Mining Machine

As previously discussed, the drum-type continuous mining coal extraction machine is the first target for the robotics and automation technology. Research is being directed toward machines currently being used in the mining industry so that the technology developed can be easily implemented by mining machine manufacturers.

Computer Systems

The computer system provides the backbone for intelligent mining systems. In an intelligent system, the computer must interface to a variety

of internal (machine world) and external (surrounding environment) sensors, gather data from the sensors, be able to make decisions based on the real-time sensor data, and initiate and carry out machine control. Essentially, the computer system has to play the role of a human to sense the environment, make decisions, and control the machine based on those decisions. The computer must know what to do not only under routine conditions, but also during abnormal conditions.

Machine Control

Establishing accurate, computer-based control of a continuous mining machine is the first step in the development of autonomous, robotic equipment. Machine control refers to the steps necessary to establish and maintain accurate control of the mining machine appendages (cutting boom, gathering head, conveyor elevation and swing, and stabilizer jack) and locomotion tracks.

Guidance Systems

An autonomous mining machine must be able to guide itself not only in the face area, but also throughout the entire mine. This requires sensors to provide information on machine position and heading, and the distance to walls and other obstacles. An intelligent computer system must take this real-time information, add it to already known information such as the mining plan, and decide where to cut coal or where to next navigate.

Coal-Rock Interface Detection

Not only must an intelligent mining machine be able to navigate horizontally throughout a mine, but it must also be able to keep its cutting within the coal seam or to some other specified vertical cutting pattern. Known as coal-rock interface detection, this ability is critical to any autonomous mining system. The machine must be able to tell when it is cutting coal, and when it crosses the coal-rock boundary to cutting overlying or underlying rock strata. Sensors to detect where the cutting head is vertically in the coal seam are necessary.

Diagnostics

Machine downtime is a significant cause of lost productivity from underground mining equipment. Being able to predict a machine failure in advance of its occurrence or to rapidly determine the cause of a failure would provide a significant increase in machine productivity. A machine diagnostic-predictive system is even more crucial when a human is not onboard the machine to see the failure occur.

Planning and Supervision

In a robotic application where a stationary robot is doing a routine, repetitive action, planning for the robot is greatly simplified. However, in a situation where the environment can change significantly, and where the robot is mobile, planning for the robot is complex. The robot must be able to update or change plans as conditions change. With an autonomous vehicle, a machine planner is required to make sure that a particular machine goal is

achieved. For an autonomous continuous mining machine, the planner must be able to instruct the mining machine to mine coal according to a mining plan, while making adjustments as conditions warrant. This planner must deal with normal and abnormal conditions. The Bureau's Automation and Robotic program is addressing each of the key technology elements required for an autonomous continuous mining machine.

4. PROGRAM STATUS

A Bureau-owned Joy 16CM¹ is currently used as a testbed for evaluation and prototyping of systems for the Robotics and Automation program. The machine was available from previous mining research and met the needs at the time. However, because it was originally designed as a miner-bolter, it has certain peculiarities that make it unsuitable for use in future plans to take the machine underground. Therefore, a new machine will be acquired for evaluation of technology underground.

The Joy 16CM is currently under computer control [1]. An onboard computer has been designed, assembled, and programmed for collecting data from machine sensors and for controlling the machine. The computer is a real-time, multitasking, multiuser system consisting of off-the-shelf hardware. It is based on the Intel 80286 processor. Near-term expansion of the computer system will involve upgrading to a distributed processing network, Bitbus. This will allow each separate machine subsystem, such as a coal-rock interface detector, to have its own processor for carrying out its function. The Bitbus network will also permit other computers such as a PC, SUN workstation, or Symbolics computer to be interfaced to the onboard computer, through the network, for offboard tasks such as planning. It will significantly enhance system capabilities.

Accurate, closed-loop computer control of the Joy 16CM has been established. That is, through computer commands, each of the movable parts of the Joy 16CM can be controlled by sensor feedback with good accuracy. This has involved a series of open-loop and closed-loop tests of the Joy 16CM operating in free space at the Bureau's test facility. Sensors installed on the machine to provide the angular position of the movable parts provide the necessary feedback information for closed-loop control. Once accurate control of the mining machine was established, the ability to maintain that accuracy and stability under stress conditions was determined by cutting simulated coal known as coalcrete. Accurate computer control was maintained.

During the last year, a navigation scheme for an autonomous continuous mining machine operating in a room-and-pillar, two-pass mining scenario was defined [2]. It makes use of a suite of sensors that work in concert to enable the mining machine to navigate not only locally in the face area, but also throughout the mine. Sensors being evaluated for the sensor suite include sonar, a laser scanning system, a gyroscope, a fluxgate compass, and clinometers. The navigation scheme uses a reference frame, a mobile control structure, on which the laser-scanning units are mounted. The laser-scanning

¹Use of manufacturer's names is for identification only and does not imply endorsement by the Bureau of Mines.

units send out a horizontal laser beam at a 90° field of view toward the mining machine on which retroreflector targets are mounted. The beam is reflected off the targets and returned to the scanning unit and detected by a photo detector. The other sensing systems are installed on the mining machine in the navigation scheme. These sensor systems are currently being evaluated on the mining machine testbed and on a locomotion emulator, a rubber-tired vehicle that can emulate the motion paths and control commands of various types of mining equipment.

Research on coal interface detector (CID) sensors involves several techniques. First, an investigation [3] of the fundamental physical properties of the coal-rock interface of the U.S. coal seams where the majority of the coal is produced and/or is expected to be produced in the future, is being conducted. Coal and rock samples from the major seams are being analyzed in the lab to determine if natural gamma radiation, which has been successfully used in Europe, or a new technique using optical, electrical, or mechanical properties of the coal-rock interface may be useful as a coal-rock interface detector.

Second, several specific techniques are being investigated for a coal-rock interface detector, including machine vibration and in-seam seismic [4,5]. In both techniques, sensors, in this case accelerometers, are attached to the mining machine for machine vibration, or to the coal, roof, and floor for in-seam seismic, to sense signals generated as the mining machine is extracting coal. Different signals are generated when the machine is cutting coal versus when it is cutting rock. Powerful, intelligent signal processing computer programs, referred to as "Adaptive Signal Discrimination Networks," are used to discriminate this difference. Once the system has been trained on known conditions, it can distinguish the difference on unknown conditions. The key to this technique is the intelligent signal processing program. In-mine data are being collected for lab analysis and training in the lab.

Lastly, another technique for CID being investigated [6] is a doppler radar system. Research into this unconventional radar technique is being pursued instead of the conventional brute force approaches of pulse, impulse, and FM/CW radar, which have reached their maximum limits of feasibility. The doppler radar concept is not dependent on the parameters that have limited the performance of previous coal interface detectors. The present concept is to move the sensor antenna through a small spatial cycle by electronically switching signals among four small stationary dipole antennas. The doppler history caused by the apparent antenna motion is stored in computer memory and is then correlated with a prestored template of all coal dielectric and depth combinations. A matrix array of dielectric and thickness probabilities is then obtained. A new parameter matrix is then picked, and a new doppler history array is generated. The process is repeated until one dielectric and one thickness correlate. An advantage of this technique is that the dielectric need not be known nor a dielectric value assumed, as in previous radar techniques, before the thickness can be determined. Only enough measurements need be made to obtain the desired statistical confidence level of correlation.

The Bureau is addressing the problem of machine failures and downtime through the application of expert system technology to the problem. An expert system is being developed to diagnose and/or predict continuous mining machine

failures. It is a real-time, sensor-based system, using input from onboard sensors. The goal is to make it a predictive maintenance system which would be capable of monitoring sensor data over time, looking for degradation of machine components that would indicate a failure may occur in the future.

There are three main subsystems for the continuous mining machine maintenance expert system: electrical, hydraulic, and mechanical. Two parallel efforts are currently underway to develop the maintenance diagnostic expert system, one for the electrical subsystem [7], and one for the hydraulic subsystem [8]. In both cases, sensors have been defined and installed on the mining machine to accurately detect system failures, and to provide information to the expert system of them. The knowledge for each respective knowledge base is being developed in conjunction with experts in the field.

Research for machine planning is underway in several respects. Under contract [9] with West Virginia University, the Bureau is developing an expert system to assist a face foreman in decision-making. The same rules and thought process used in the expert system will be part of autonomous machine planning. Under another cooperative contract, Carnegie Mellon University is working on planning strategic level actions. They have produced a Small-talk-80 implementation for strategic planning, modeling a network of actions describing a continuous miner in entry and crosscut operations. Effort currently underway is to develop the merging of machine task planning with a geometric model of the domain. An object representation for face, ribs, floor, and roof will be developed for the local environment, as well as an object representation for the extended environment, typified as a mine map.

5. SPINOFF TECHNOLOGY

Although the Bureau's program is investigating technology for a completely autonomous mining machine, much of this technology can be applied to mining problems in current mining scenarios to provide an immediate benefit. Two mining scenarios in which this technology may be immediately beneficial are in deep cut mining and highwall mining. In deep cut mining, continuous mining machines, operated by radio or tethered remote control, are used to make cuts of 40 ft, going beyond the point of supported roof. Since the operator is not on the machine, this deeper cut is permitted. However, with this deeper cut, the operator may not always be able to see the face or, in certain cases, the mining machine. Both vertical coal-rock interface detectors and lateral guidance systems would be beneficial in these cases.

With highwall mining, operators are interested in penetrating into the highwall 500 to 1,000 ft. Since the miner is out of visual view, again CID is necessary. In highwall mining, a constant rib thickness is maintained for the length of the penetration. If too little rib is left, the roof may fall. If wider than necessary rib is left, coal is wasted. Therefore, an accurate lateral guidance system is needed. The radar system being researched for CID is also expected to be useful here.

CID technology would also be beneficial for vertical guidance of longwall shearers. Longwalls typically produce far less than their design capacity, and the operator is often exposed to respirable dust. Vertical guidance technology will both increase productivity and remove miners from unhealthful conditions.

6. PROGRAM SCHEDULE

Work under the Robotics and Automation program will develop technology, as described in this paper, for a completely autonomous mining system. A timeline showing major milestones (large circles) and the research (small circles) required to attain these milestones, is shown in fig. 4.² Machine control [1] was established in 1988. Machine presence, the next milestone, will be completed in 1990. For this milestone, position-heading navigation technology [2] and coal-rock seam detection [3,4,5,6] must be completed. In 1992, the machine guidance milestone will be completed, incorporating machine planning, which includes contingency reactions and machine action lists. Between 1992 and 1995, machine diagnostics [7,8] will be available, MSHA approvals will be addressed, in-mine evaluations will be conducted, and the equipment will be ruggedized. This all leads to technology for an autonomous mining machine being available in 1995.

Again, as technology pieces for an autonomous mining machine become available, they will be implemented, as appropriate, to current mining machine operations.

7. FUTURE RESEARCH

While the thrust of the Automation and Robotics program is directed toward the short-term objective of technology for an autonomous continuous mining machine, longer term objectives are taking a broader approach, looking at robotics technology and how it can lend itself to improving the coal extraction process. This may lead to new machine designs or new mining processes.

8. SUMMARY

The Bureau of Mines Robotics and Automation research is addressing the problems of mining inefficiency and accidents in underground coal mines through the development of technology for autonomous mining systems. Work on the key technology elements required for an autonomous continuous mining machine, including intelligent computer systems, machine control, guidance systems, coal-rock interface detectors, diagnostics systems, and planning systems is underway.

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²The timeline only relates to the major milestones; most of the research for these major milestones is already underway.

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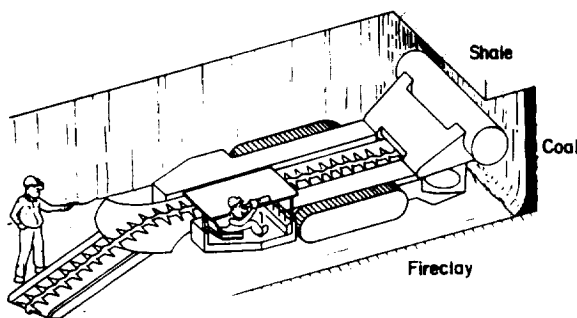


Fig. 1. - The operator of a continuous mining machine relies on his sensory systems to control the machine.

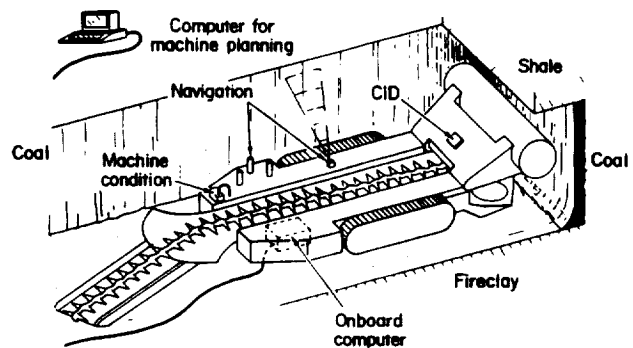


Fig. 2. - Key components for an autonomous continuous mining machine.

INTELLIGENT MINING EQUIPMENT

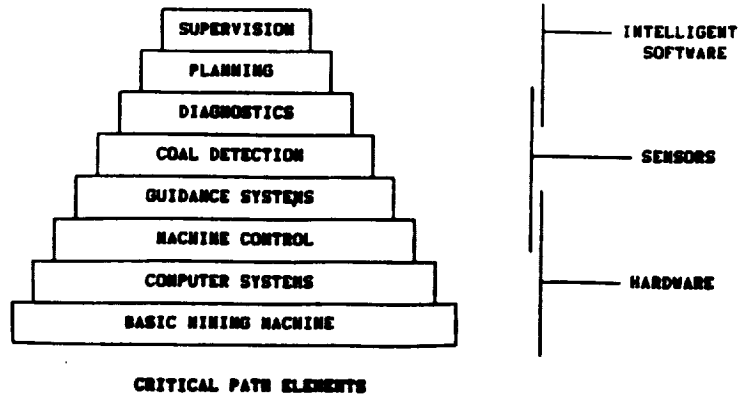


Fig. 3. - Key technology elements for an autonomous mining machine.

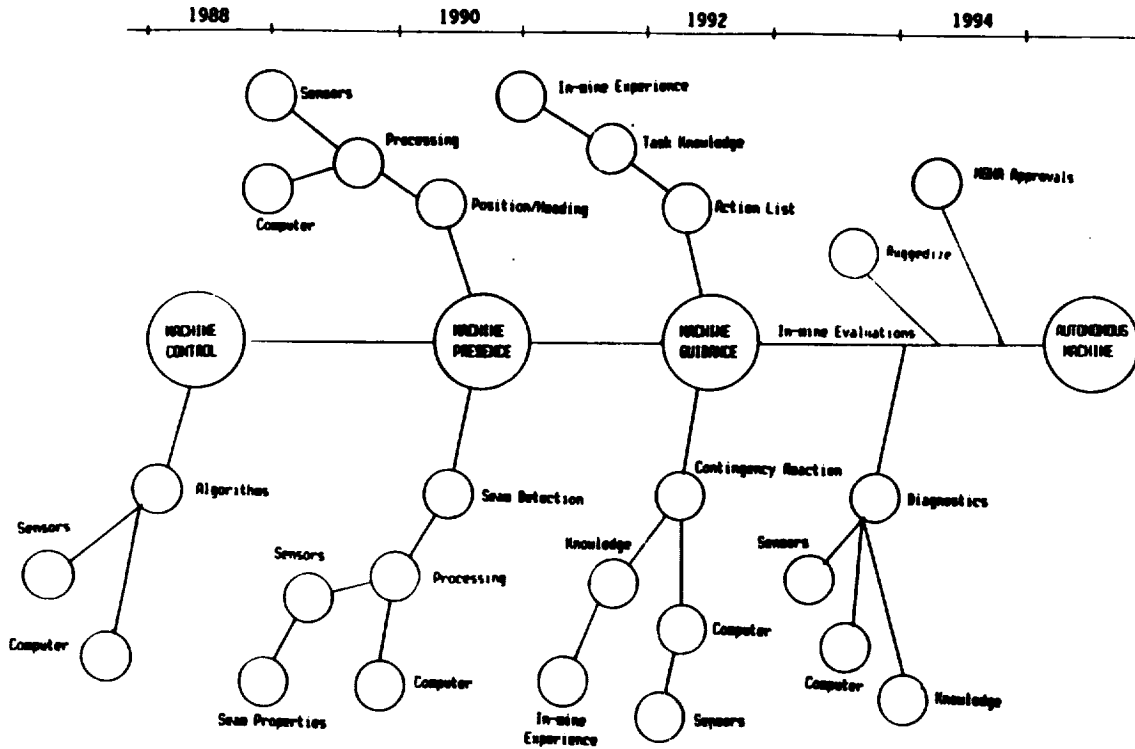


Fig. 4 - Technology timeline for an autonomous mining machine

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ROBOT SENSING AND PLANNING

