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Computer-Assisted Continuous Coal Mining System—Research Program Overview

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cm	centimeter	MHz	megahertz
ft	foot	m	meter
Hz	hertz		

COMPUTER-ASSISTED CONTINUOUS COAL MINING SYSTEM–RESEARCH PROGRAM OVERVIEW

By George H. Schnakenberg, Jr.[1]

ABSTRACT

Automation of coal mining activities at the face offers improvements in worker safety, health, and productivity. Introduction of integrated computer-sensor systems to current mining machines will enable these machines to perform some of the most hazardous tasks through supervised teleoperation. The U.S. Bureau of Mines is pursuing the development of the enabling technology necessary to achieve this goal. The research program consists of both basic and applied research, each focused on the fundamental issues of computer and sensor technologies. Short-term research is directed to providing computer-assisted, remote supervisory operation of present underground equipment; the long-term goal is the development of progressively more intelligent mining systems.

The research program includes a review of robotic machine and autonomous vehicle technologies and of current mining technology, which provides a base for developing innovative mining methods; research in navigation and guidance technology, emphasizing control of a continuous mining machine; research on coal-rock interface sensing technology for horizon control, and rib thickness control in highwall mining; the development of computer systems and hierarchical architectures for real-time control; and development of expert systems for machine system fault diagnostics and predictive maintenance. This report presents a brief background and the current status for each of these research areas.

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INTRODUCTION

The U.S. Bureau of Mines has initiated significant new thrusts in mining research that focuses on creating significant breakthroughs in mining technology that are required to substantially improve worker health, safety, and efficiency, while also increasing the international competitiveness of the U.S. mining industry. The application of automation and computer technologies to coal mining can make substantial and simultaneous contributions to worker health, safety, and mining productivity, as measured in terms of human, capital, or resource utilization. Because the mining industry and its manufacturers and suppliers are individually unable to perform the extensive high-risk research needed, the task of performing the research falls on the Bureau.

To optimally conduct the program, the research must be planned carefully and must be performed in close relation with private, government, and academic researchers in the space, armed forces, and factory automation and robotics research areas, and with the close cooperation of both labor and management of the mining industry.

The resulting research program to develop intelligent mining systems is a mixture of basic research, applied research, information gathering, and the application and adaptation of existing technologies from a multitude of sources. It was devised through an examination of the basic elements of coal mining while weighing factors such as worker exposure to hazards, greatest potential productivity increases to be gained, the application to existing and future coal mining methods, the depth and extent of universality and applicability of research issues involved, and the degree to which it increased the Bureau's knowledge of the fundamental technologies in computer-assisted machine control systems and mining. The research program contains (1) elements that are of a general nature, (2) elements that are focused on a specific system design and objectives, and (3) ad hoc elements that address a particular mining problem. All of the elements blend together to form a coherent effort to develop the requisite enabling technology for successful intelligent coal mining systems (fig. 1).

The development of intelligent mining systems encompasses a wide range of issues. Rather than take a breadth-first approach and consider all of the issues, the research plan takes a depth-first approach on the three fundamental issues of extractive mining–releasing the coal from the host rock, transporting the extracted material to the surface, and control of the ground. The major, near-term efforts focus on extraction. Other essential elements of mining are maintenance of equipment, provision and transport of supplies and equipment services such as power and water, environmental control, and mine planning and management.

Extraction activities present the most hazards to workers, experience substantial idle and delay times, and provide a wealth of research areas that can be broadly applied to the other essential elements of underground mining. Therefore, the Bureau's research is focused on developing an autonomous extraction machine.

Highly mobile coal mining machines, as exemplified by the continuous mining machine, will have a significant role in the future of coal mining; they will serve as the major method for longwall development, room-and-pillar mining, shortwall mining in a variety of roles, and in highwall mining.

The robotic technology developed for this research machine and the associated mining system can be utilized in other mining equipment and provides the basis for the development of novel mining systems that take specific advantage of the advanced technology. The subsystems developed can be utilized individually in the near term as aids to remote-controlled continuous mining or in extending further the automation of longwall mining systems.

The research is divided into three categories: (1) a fundamental or core program of research that explores and develops the fundamental knowledge and hardware, (2) an applied research program that brings the pieces or integrated systems to a demonstrable, reliable, and fieldworthy stage, and (3) ad hoc solutions to mining industry needs. This report presents a review of this research by giving a brief description of the Bureau's research facilities; a discussion of the fundamental research effort, an introduction to the technology development–the applied research program and the major research effort, and the background and current status for each of the elements within the technology development program.

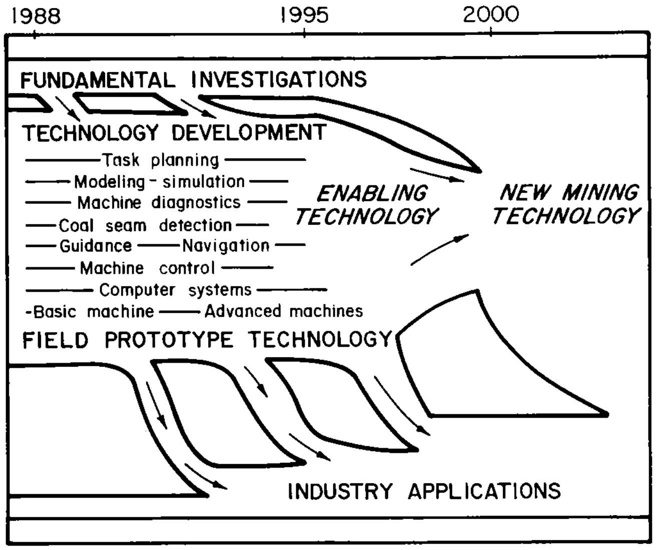

Figure 1.–Technology evolution of intelligent mining systems.

RESEARCH FACILITIES

The research on computer-assisted mining systems is being conducted at the Bureau's Pittsburgh Research Center located at Bruceton, PA, a few miles outside of Pittsburgh. Located at this site is a mining equipment test facility (METF), a complex of large, spacious buildings that house the Bureau's experiments involving full-size mining equipment. Included in this facility is a Joy 16CM[2] continuous mining machine, which serves as the temporary research test bed for the autonomous mining research. Adjacent to it is a 6-ft-high block of coalcrete, an artificial coal used for testing various mining and drilling systems. In the same area will be the Carnegie Mellon University (CMU) Locomotion Emulator, or navigation research platform, a mobile vehicle that is software configurable to emulate the motions of any type of wheeled or tracked vehicle. A trailer with a large viewing window houses the computers and terminals from which either the continuous miner or the LE is operated for research experimentation or visitor demonstrations. An ethernet network (a form of local area network for intercomputer communication) connects the computers in the trailer to the research laboratories and offices located in another building. The computer facilities utilized for this program include five Sun workstations, a Symbolics 3670, and numerous personal computers (PC's) and terminals.

FUNDAMENTAL RESEARCH

BACKGROUND

The major role of the Bureau's fundamental research program is to provide a resource of computerized machine control systems and mining technologies by assembling information. The resource information covers robot-specific components and systems in areas such as sensing and vision, manipulation, control, and locomotion. Mining technology and methods are also being investigated and documented. The resource information will be kept current and used as reference and familiarization material. The enabling technology developments from Bureau research will be included as well. This effort will also be used as a means to conceptualize novel mining methods by using a systems approach to coal mining given the combined capabilities of robotic and advanced mining technologies.

This program is also investigating hardware and software for the intelligent control of mining machines. Bureau-sponsored work at the National Institute of Standards and Technology (NIST) [formerly known as the National Bureau of Standards (NBS)], Robot Systems Division, will capitalize on NIST's experience in control systems developed for the NIST Automated Manufacturing Research Facility (*1*)[3] and adapted for the National Aeronautical and Space Administration (NASA) as NASA/NBS Standard Reference Model (NASREM) Architecture for the Space Station Telerobot System (*2*). Over the next 3 years, NIST will develop a Mining Automation Standard Reference Model (MASREM) starting with the development of a concept document, a design model using a new, advanced modeling tool, and a mining simulator requirements specification that will be an adaptation of NIST's simulator used for the multiple autonomous underwater vehicle developed for the Department of Defense.

Also included in the fundamental research is Bureau-sponsored work at CMU under contract HO358021, "Robotic Sensing and Control for Underground Mining." After having examined several options, researchers at CMU have decided to pursue the implementation of strategic planning in Smalltalk-80, an object-oriented programming language. Strategic-level planning uses reasoning to make the major decisions involved in the mining of an entry. It uses the knowledge of the mine plan, the relationship of the machine to the surrounding geometrical and geological environment, and similar levels of knowledge, to formulate subgoals for the mining machine. For example, the strategic-level planner is concerned with determining where the machine is to move or mine next but not with how it is to perform the moves or the cutting; these planning tasks are left to lower levels in the control hierarchy. CMU is also developing a means to generate a representation of mine ribs and corners (the point or line representing the intersection of ribs or a rib and the face) using occupancy grid models in conjunction with ultrasonic range data.

The essence of the NIST and CMU activities is to investigate the fundamental issues involved in the hierarchical control of mining equipment activities and to provide the Bureau with a structured approach and structured software systems in which to implement the control of the Bureau's research test bed, the continuous mining machine. Duration of these programs is 3 or more years, starting from 1988.

ACTIVITIES AND STATUS

Resource information on robotic systems technology has been assembled for electrical actuators and mechanical mechanisms for manipulators, sensors used in robotics, diesel power for locomotion, and ventilation and dust control systems. CMU has explored rudimentary planning

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[2] Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

[3] Italic numbers in parentheses refer to items in the list of references at the end of this report.

of continuous miner moves using the "knowledge" of miner location, face and rib locations, and mining objective. The work is being done in Smalltalk-80 on the Bureau's Sun 3 workstation. The miner and mine entries are graphically represented in order to visually show results of the program's operation. A means to communicate machine commands that move the Smalltalk-80 screen picture of the miner to the real machine via a standard RS232 communications link has been developed in preparation for eventual machine control. Work is continuing on expansion of the program beyond the prototype stage, including occupancy modeling using ultrasonic range data.

TECHNOLOGY DEVELOPMENT

OBJECTIVE AND APPROACH

The objective of the technology research is to develop and evaluate the enabling technology for autonomous mining systems. The Bureau's approach is to select a target system that attacks the major mining safety and productivity improvement goals that provide opportunity for incremental advances and thus supports the slow, evolutionary introduction of technology into mining, and whose results are not limited to only the target system itself. Such a focused approach provides the researchers with tangible objectives and can show demonstrable results throughout the evolution of the technology.

TARGET SYSTEM

The target machine for this research is the rather universally used continuous mining machine. Its control and operational characteristics are representative of the class of high-mobility extraction machines used in coal mining for longwall entry development, room-and-pillar mining in advance and retreat, shortwall mining, and the like. Using this machine as the target machine exposes a large number of research issues and allows incremental introduction of intermediate developments.

INTELLIGENT CONTROL

The Bureau is careful to make the distinction between automation and autonomous or between programmed and intelligent control. In the first case, a machine is controlled by a fixed script or command list that is executed in a fixed order. The target values for the machine and its appendage positions are placed in a list and executed in order without alteration. Intelligent control alters or rewrites the script based upon the analysis of the current circumstances derived from sensor data and a programmed knowledge base. It is the use of current circumstances, including human operator input, to alter the next and subsequent machine actions that makes the machine intelligent and thus able to operate autonomously. It is appropriate to note that the analysis and alteration process can take place at differing levels of complexity, from a relatively simple situation in which the mining forces are too great so that the cutting rate slowed down (force cognitive feedback) to a rather complex situation in which a roof fall or geological anomaly results in the changing of the mining position and cutting sequences. Also the reaction times vary with the differing levels of control, generally with a quicker response needed for the simpler, lower level control. The natural result is a hierarchical control structure.

INTELLIGENT TASKS OF EXTRACTION

An examination of the actual functions that a machine operator must perform in order to extract coal discloses the key research and development topics critical to the development of an intelligent mining machine. The operator must *guide* a cutting *machine* tool *within* a *coal* seam following a *plan* that can be *altered* by local conditions and events. These key words, machine, guide, within coal, plan, and altered, form the guiding structure to the Bureau's development of enabling technology. Tying all of these functions together is a backbone of data gathering and information processing residing in a complex computer system. It is the computer system and software that embodies the human operator's capabilities. The result is a list of critical path technology categories shown in table 1. This list is the guide for the discussions in the remainder of this report.

Table 1.–Intelligent mining machines-critical systems and technologies

System	*Dominant components and issues*
Basic machine	Mechanical, electrical, hydraulic.
Computer system	Processor boards, operating system; communication networks for real-time multiple-processor operations.
Machine control	Position, electrical, hydraulic sensors; computer data acquisition, closed-loop control algorithms, command language.
Guidance systems	Position and heading sensors and systems; obstacle and mine rib detection and registration to map data; computer software for data fusion and filtering.
Coal interface detection.	Coal and strata properties and differences; multidisciplinary systems for real-time sensing of cutting positions; artificial intelligence data interpretation.
Machine diagnostics	Sensors of machine condition; expert system interpretation and analysis; human interfacing.
Planning	Data interpretation, knowledge representation, artificial intelligence, human interfacing.

BASIC MACHINE

BACKGROUND

A typical mining machine is an assembly of mechanical, electrical, and hydraulic systems working together to form a machine with certain functions and operating characteristics. In general, machines in mining are not automated nor configured for computer-controlled operation, and thus each one must be modified for closed-loop control. That is, all parts normally controlled by the operator to perform work–the appendages and means of propulsion–must be retrofitted with actuators that respond to the electrical signals from the controlling computer. The appendages must be retrofitted with sensors that report to the computer the position of the appendage with respect to the machine. The basic machine system is strictly concerned with the hardware and its selection, design, and operating characteristics.

The computer-driven actuator-machine-sensor system must be fully studied in order to characterize its behavior in detail in preparation for the development of algorithms for closed-loop control. The machine systems possess operating capabilities and limitations in terms of mobility and functional performance; these must be fully characterized to be used as data for path planning and task planning software.

In the final prototyping stages in preparation for in-mine testing, attention must be given to electrical permissibility (for use in gassy mines) and safety. Sensors for diagnostic machine condition monitoring must be selected, installed, and tested, and data must be gathered on normal and abnormal conditions.

ACTIVITIES AND STATUS

The Bureau-owned Joy 16CM continuous mining machine is being used as the test bed for the initial testing and evaluating of sensing and control systems. Sensors for appendage movement, the electrical system (voltage and current), and the hydraulic system (pressure, temperature, flow, debris, and fluid level) have been selected, installed, and interfaced to the computer. The computer has been interfaced to the electrically actuated hydraulic control valves for appendage movement and to the control relays for the crawler tracks.

Appendage motion and control characteristics have been obtained (*3*). Locomotion response characteristics as measured by onboard sensors were obtained only recently.

COMPUTER SYSTEM

BACKGROUND

The computer system forms the backbone of the machine control system for any autonomous, intelligent, or robotic machine. At the lowest level it handles the closed-loop control of the various appendages. In this role it takes data from the appendage position sensor, compares these values with the target value desired, and initiates, maintains, or stops appendage movement as necessary. At the highest level it will perform complex planning of machine goals: the sensor data that were abstracted are compared with the goals represented in suitable form, and an ordered list of subgoals is generated. A model of the computer functions is presented in figure 2.

As a practical matter, the computer system must grow with the project. Although the complexity of the final system is somewhat predictable, the rate at which computer capabilities are changing effectively limits the investment in a system to that which is not much more complex than is needed to support approximately 2 years of research. The computer system should support multiple processors and/or computers, provide access to machine control primitives (e.g., shear up 10 cm) from any level of processor or computer, provide access to system variables from any level, support real-time control, provide an environment for experimentation and development using heterogeneous computers, provide flexibility and extendibility, and use off-the-shelf hardware.

ACTIVITIES AND STATUS

The computer system consists of a central control and data acquisition computer mounted on board the mining machine (*4*). It is an Intel 80286 processor-based system running Intel's iRMX86 real-time, multitasking operating system. The software is written in PL/M-86 and provides a menued interface at a terminal for keyboard control of the mining machine functions. Individual machine functions and motion can be selected, and target values or operational durations can be set and executed. A script writing, editing, and execution mode is also provided to aid research, evaluation, and demonstration. Closed-loop control of the appendages is performed solely by this computer. This computer provides the foundation and the low-level control functions of the machine control hierarchy. It is also the primary means for data acquisition from the sensors on the hydraulic and electrical systems for condition monitoring and diagnostics. A magnetic bubble memory cartridge substitutes for floppy or hard disk mass storage media and provides the operating software for the system.

The computational requirements for an intelligent machine far exceed those of a single, multitasking computer. Several processors and/or computers will be required and must be able to share data and have access to the machine control commands and sensor data. A real-time control network of heterogeneous computers is required. The Bureau has chosen to use the Intel BITBUS distributed control environment, which is a polled, high-speed, secure communications network operating over twisted pair wires. Each computer or processor connects to the network through a node interface card, itself a small dedicated computer. The separation between nodes can exceed several hundred feet.

Although this system uses off-the-shelf components and software, the actual implementation and customization of the operating system and BITBUS network is not trivial. At this point, the BITBUS network is configured and fully operational; it is capable of supporting the Bureau's development for the next 2 years or more.

At the present time, a 10-MHz, single-board computer programmed in BASIC for gyroscope heading control, a Sun 3/60 workstation programmed in C for the laser-based guidance system, a Sun 4/110 color workstation also running C programs under UNIX for a system view port, a Sun 3/160 functioning as a planner, and a Symbolics 3670 color computer, running LISP and displaying hydraulics system status graphically, are attached to the BITBUS network. The system is shown in figure 3.

Within the next year the network will expand to include an elementary form of wall and face recognition, location, and mapping using ultrasonic ranging sensors; elementary path planning and cutting sequencing; and condition monitoring and diagnostics. Each will be running on its own workstation. This system is complex as it is being used for research and development. A final delivery system will utilize several compact but high-powered single-board computers.

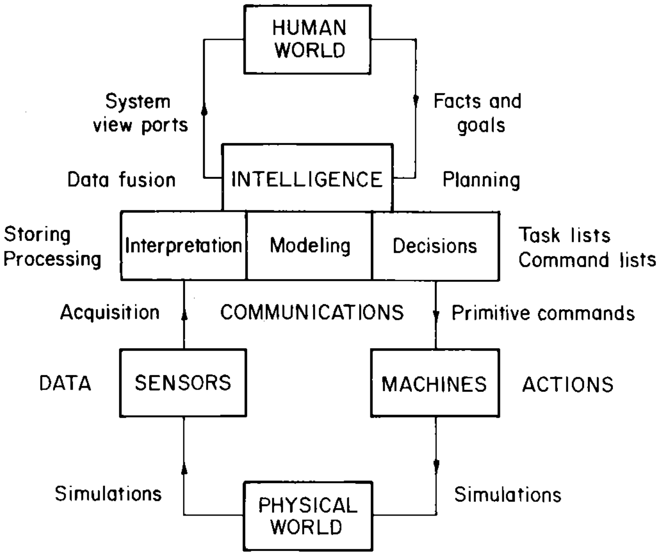

Figure 2.–Computer functions for intelligent machines.

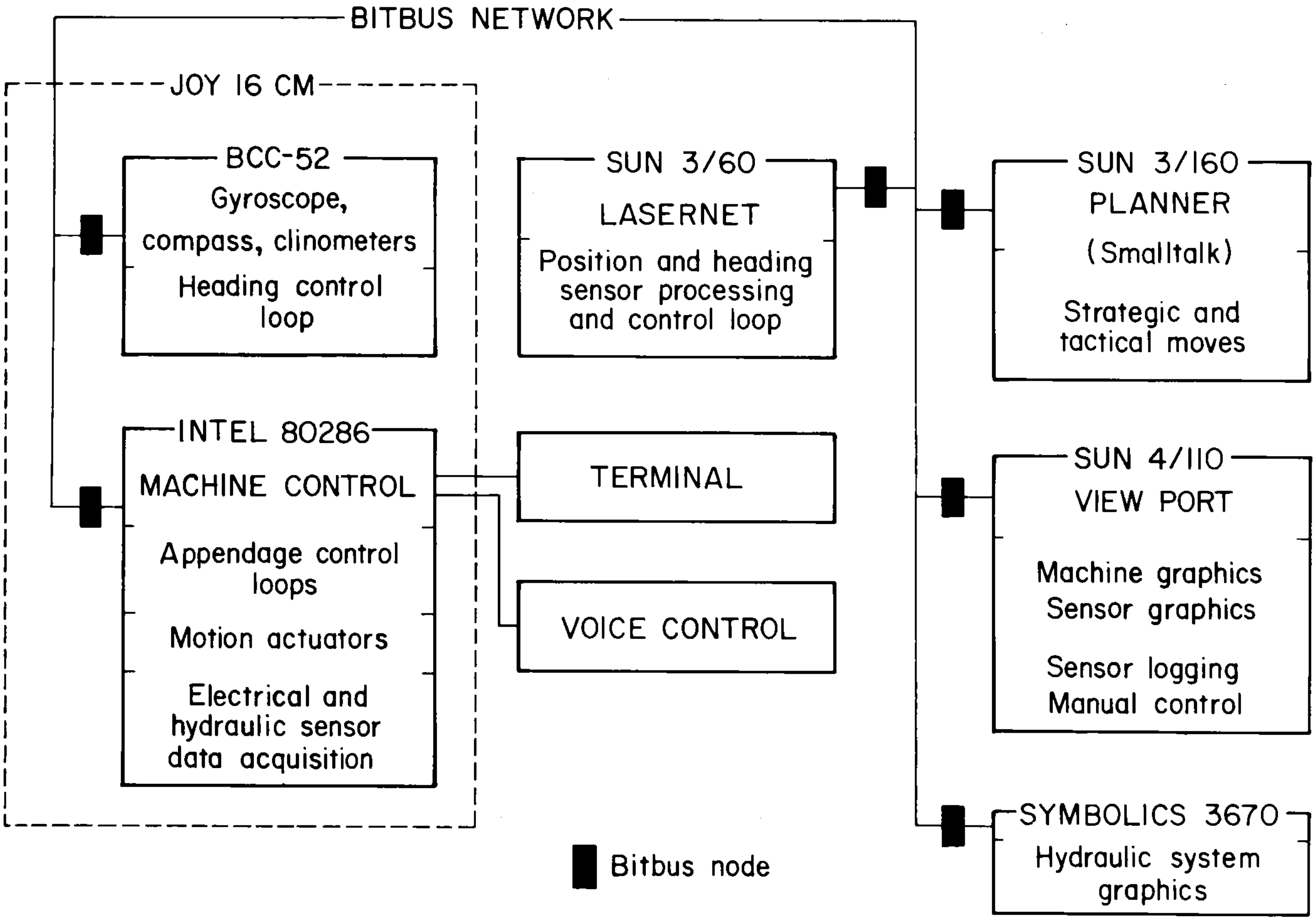

Figure 3.–Computer network and components, 1988.

MACHINE CONTROL

BACKGROUND

Machine control represents an integration of the machine hardware, position sensors, and control computer systems. It is this element in the development that results in a machine that accurately executes commands containing target values; i.e., a machine that is operating under closed-loop control. In closed-loop control, a function is named and a target value specified. These target values are either a destination position, a specified change in position, or a duration for a particular function. The control computer creates a task to issue a signal to the machine actuator (solenoid on a hydraulic valve) and another task to continuously read the output from the sensor reporting the position of the appendage being actuated. The sensor output is compared with the target value using an algorithm developed to optimize function performance. When the specified target value and sensor output agree according to the comparison algorithm, the computer shuts off the signal to the machine actuator. The computer is also able to accept a halt command to stop any actuation before it is completed. This system is described in detail in reference 3.

Safety issues must also be considered. A computer malfunction or crash could cause a machine shutdown; systems must be developed to avoid this problem.

At a higher level of control, the forces on the machine components, sensed in the form of increased motor current or hydraulic pressures, can be used as part of the control loop, primarily to prevent damage to the machine. These forces could also be used to indicate changes in geology and used to alter a cutting sequence, for example.

The generalized tasks involved in sensor-based machine control are as follows: Select a sensor for the controlled appendage function; develop the computer-sensor and machine-sensor interface; test the machine and sensor system; analyze the data; formulate control algorithms; test control in free space; test in simulated mining conditions (artificial coal); analyze data; repeat development, testing, and analysis as necessary.

ACTIVITIES AND STATUS

All the development, test, and analysis tasks have been completed for the position sensors for all movable appendages and the crawler tracks on the Bureau's test bed mining machine. Thus the shear elevation, gathering head elevation, conveyor swing, conveyor elevation, and stabilizer jack elevation have been placed under closed-loop computer control. The crawler tracks are not under closed-loop control using crawler movement sensors, nor will they be, since crawler slippage with the ground renders measurement of crawler travel useless as data for precise control of machine position.

Over 2,700 graphs of machine appendage response data were generated and cataloged in the computer-machine-sensor response testing phases. Analysis of this information enabled the formulation of control algorithms, verification of sensor operation, and determination of parameters for control fault detection. Tests for shearing arm elevation control were performed in coalcrete, an artificial coal consisting of a mixture of fly ash, coal, and cement. The shear drum height can be controlled to within 1 cm.

At this point the machine is computer controlled and its appendages are controllable to any specified position in the operating range. The locomotion is not yet under closed-loop control. The research for closing the loop on the locomotion is being performed under the navigation and guidance element, presented in the "Guidance Systems" section.

The development of machine control is not finished even though the work to date has been successful. To move the control from the test bed to a real machine in a real mine, additional work is anticipated including improvements of the control accuracy; i.e., the development of adaptive control in which changes in machine and sensor characteristics are compensated for dynamically. Additionally, a special effort must be made in error and fault detection to provide a check on vital machine functions and conditions prior to machine operation, provide autocalibration of position control sensors, and devise software to detect and prevent runaway motions. The hardware complexity and cost must be reduced to minimize production costs.

Under this research element, 20 diagnostic sensors have been mounted and interfaced to the computer on board the continuous mining machine. The data from these sensors are available to the condition monitoring and maintenance diagnostic systems being developed.

GUIDANCE SYSTEMS

BACKGROUND

Navigation and guidance is one of the most critical elements in the development of safer and more productive mining equipment that can operate without human presence in hazardous areas. Without an adequate means of self-guidance, too much human interaction and presence will be needed for machine control.

Extraction machine guidance falls naturally into two divisions–lateral and vertical. The first refers to positioning the machine laterally within the open spaces of an entry, and the latter refers to keeping the machine within the coal seam and maintaining the extraction to given tolerances and dimensions relative to the overlying and underlying strata. Vertical guidance is so fundamentally different from lateral guidance it is treated as a separate research issue. This section discusses only lateral guidance research.

The Bureau has divided the lateral navigational problem into three domains: the face area, the section, and the whole mine. It was decided that the face area was most important for research at this time, and that when that problem was solved, navigation and guidance within the section and throughout the mine would be relatively easy. The Bureau is also working on the guidance of deep-penetrating highwall mining machines, which in addition to staying within the coal seam must be laterally guided to maintain the rib thickness to within certain tolerances dictated by maximizing recovery and maintaining sufficient ground control.

Face navigation and guidance research are concerned with determining how a machine moves from place to place, or how it positions itself for doing a function and not with why the moves or positioning occurs, the latter being a higher level planning task. The research determines the sensing systems, the interpretation and representation of sensor information for obstacle avoidance and motion planning, the extent of knowledge of machine locomotion characteristics, and the intelligent software that integrates all these things to produce an ordered list of elemental machine move commands.

The inputs to the navigation and guidance system are the coordinates and heading to be reached that are within the sensing system's range of knowledge (visual horizon); the output is one or more elemental machine moves that will place the machine at this position and heading without having any part of the machine collide with the ribs or known obstacles. For a continuous mining machine using crawler tracks as the means of locomotion, these elemental commands are forward fast or slow, backward fast or slow, turn left or right with opposite track forward, turn left or right with opposite track reverse, pivot turn left or right. While the machine moves, the sensor visual horizon moves with the machine, the knowledge is updated, and the move list generation process continues.

Guidance at the face requires sensing systems to provide machine location coordinates (x,y), the machine yaw (heading), the location of obstacles such as ribs and face, and the corners formed by the intersection of two ribs or ribs and face. For accurate closed-loop control of the elemental moves, machine location and heading must be acquired sufficiently fast. The machine pitch and roll and the location of the roof may be required. All of the guidance sensor information must be in a form from which machine moves can be planned, machine positioning at the face for cutting can occur, and maps can be constructed or updated based on knowledge of machine location in the mine coordinate frame as the coal is removed.

ACTIVITIES AND STATUS

Accurate knowledge of the mining machine's position and orientation in the mine coordinate system is needed in order to mine according to a set mine plan. The absence of features in the mine ribs at the face precludes the use of feature recognition techniques. Because crawler track slip on the floor precludes the use of dead reckoning odometry methods, an external reference structure that can be accurately located in the mine and from which the machine location can be determined was deemed necessary. The existence of the mobile roof support–the open rectangular structure shown in figure 4–suggested its use as a suitable reference frame for initial research. A mobile roof support adds "features" to the mine ribs that may be detected by ultrasonic ranging, and can support other active or passive devices for determining the range and heading of the mining equipment operating in its vicinity. The structure could also have additional functions such as supporting the roof, handling electrical cables and water hoses, supporting ventilation tubing and dust scrubbing devices, making environmental measurements for methane and air flow, and providing a vibration-free location for control computers, to name just a few.

The Bureau's first iteration in guidance system development uses commercially available, off-the-shelf sensors. The present configuration for research and development of machine guidance uses multiple laser-based scanners for determining the position (x,y) and heading angle with respect to the control structure on which the scanners are mounted. A gyroscope for short-term control of machine heading relative to a previous heading, a fluxgate compass for heading relative to magnetic north, and clinometers for pitch-and-roll angles relative to gravity are mounted on the mining machine. Ultrasonic ranging is being investigated for indicating the position of ribs and concave and convex corners.

The laser scanner method for determining position and heading as described in reference 5 works as follows: The Lasernet, a commercially available device, scans a horizontal plane at 20 Hz for retroreflective targets within its 30-ft range and 90° field of view. Upon request, it reports the angular position of the detected targets. When multiple targets (at least three for a single laser scanner, at least two for two laser scanners) are arranged in a known, fixed geometry, the location and position of the target arrangement can be determined by triangulation solely from their angles as reported by the laser. When the targets are mounted on a piece of mining equipment, the location and heading of the equipment are determined. The range of the laser scanner can be increased by using a more powerful laser and more sensitive detectors.

At the present time, the laser system, gyroscope, and fluxgate compass are being individually evaluated for performance and accuracy. The control and analysis software is being written. Initial indications are that the

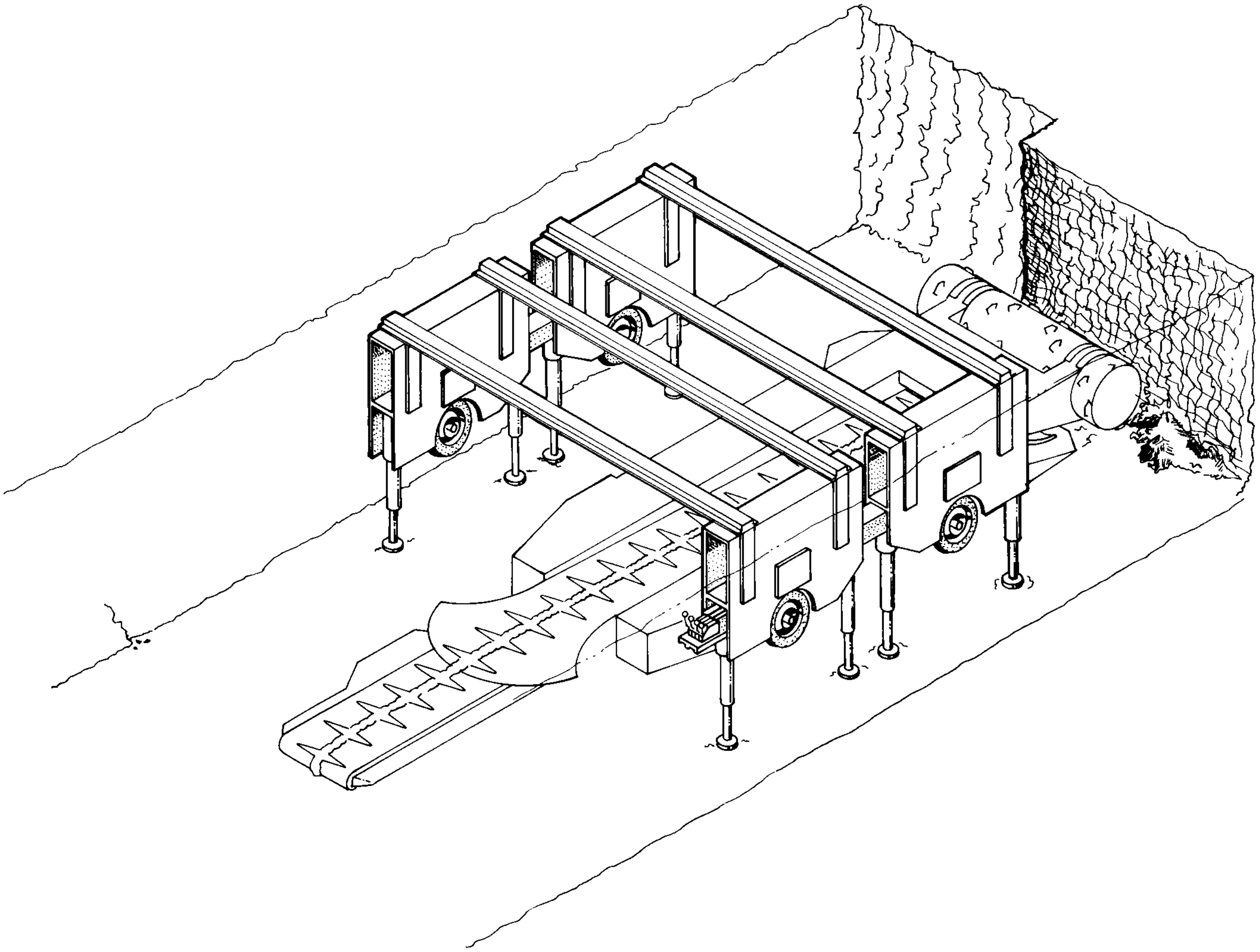

Figure 4.–Mobile roof support.

laser scanners have adequate angular resolution but limited range. The software for target recognition and position and heading calculations has been written in high-speed (10 MHz) BASIC on a commercially available single-board computer. This BASIC language has proven to be too slow and the software is being rewritten in C on a Sun workstation. The work with the gyroscopes and fluxgate compass is discussed in reference 4.

The ultrasonic ranging devices are Polaroid transducers that have been thoroughly investigated only recently for their response to real mine surfaces. CMU is currently investigating the use of the limited resolution sonar data for the generation of mine geometrical features using occupancy modeling. There is some question whether Polaroid transducers produce data with sufficient resolution to make feature determination possible.

Because of the individual limitations of each of the selected sensing systems, the present concept for sensor-based machine guidance at the face involves the integration or fusion of the data from each of the systems, and the utilization of the most accurate readings to update references for the other systems. For example, the gyroscope and not the scanning laser system will probably be used for closed-loop control of the heading changes of the mining machine, but the laser heading data will be used to update the gyroscope's reference periodically to compensate for drift. Because the gyroscope and laser system are being developed on different computers and the data must be processed at the same time, the need for a computer network is obvious. Closed-loop position and heading control of the test bed mining machine was achieved in November 1988 over a limited range of angle and distance using a single scanning laser and three targets. In October, the gyroscope demonstrated heading control of the machine over a full 360° range. The integrated navigational and guidance system concepts are shown in figure 5.

Because the sheer physical size and expense of mining equipment makes continuous testing using this equipment unattractive and uneconomical, and because the navigation

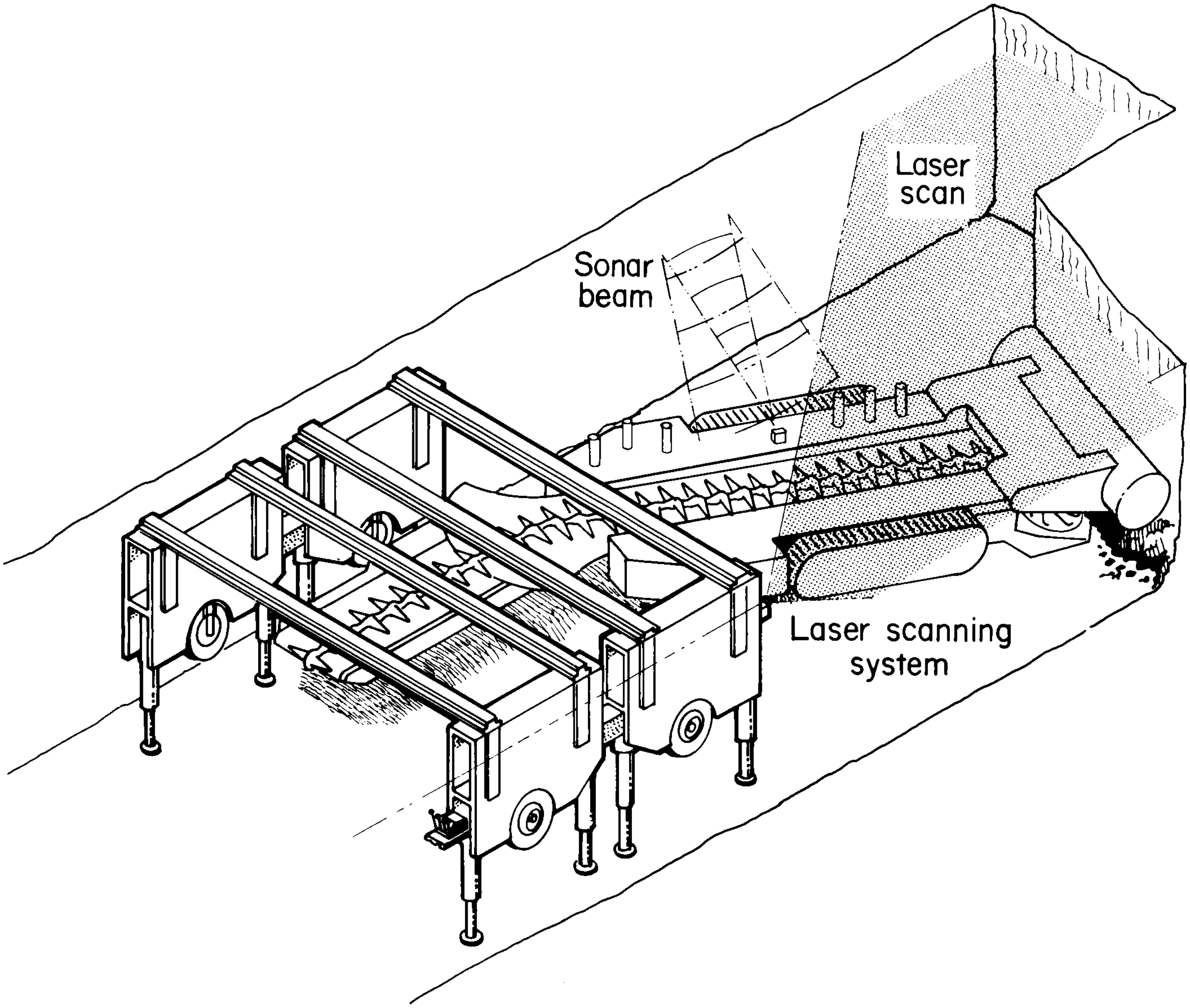

Figure 5.–Integrated navigational and guidance system concepts.

and guidance research will not be limited to a single vehicle, the Bureau conceptualized an all-purpose vehicle, a locomotion emulator (LE), that could carry sensing systems for testing. It would use the same command set as the target vehicle for which the systems and control software were being developed.

Such an all-purpose vehicle has been built by the Field Robotics Center of the Robotics Institute of CMU. As figure 6 shows, the LE consists of a three-wheel-set vehicle with all wheel sets being driven and steerable, a rotating table for the mounting of sensors and/or mockups of machine structures, and two computers. The computers handle motor control, communications, and the algorithm processing that enable the LE to emulate any of the following configurations: skid steered, articulated, and Ackerman-steered (automobile). Additionally, it can be set up to go to any position and heading from an arbitrary start (unicycle configuration) and can be joystick-controlled through keyboard or joystick for easy positioning. All relevant vehicle variables are parameterized and selectable, including the introduction of random inaccuracies to imitate slippage. The LE at the METF will function as the Bureau's primary physical test vehicle in simulated mine geometries for the testing of sensors and control software for machine guidance and navigation prior to their installation on real machinery.

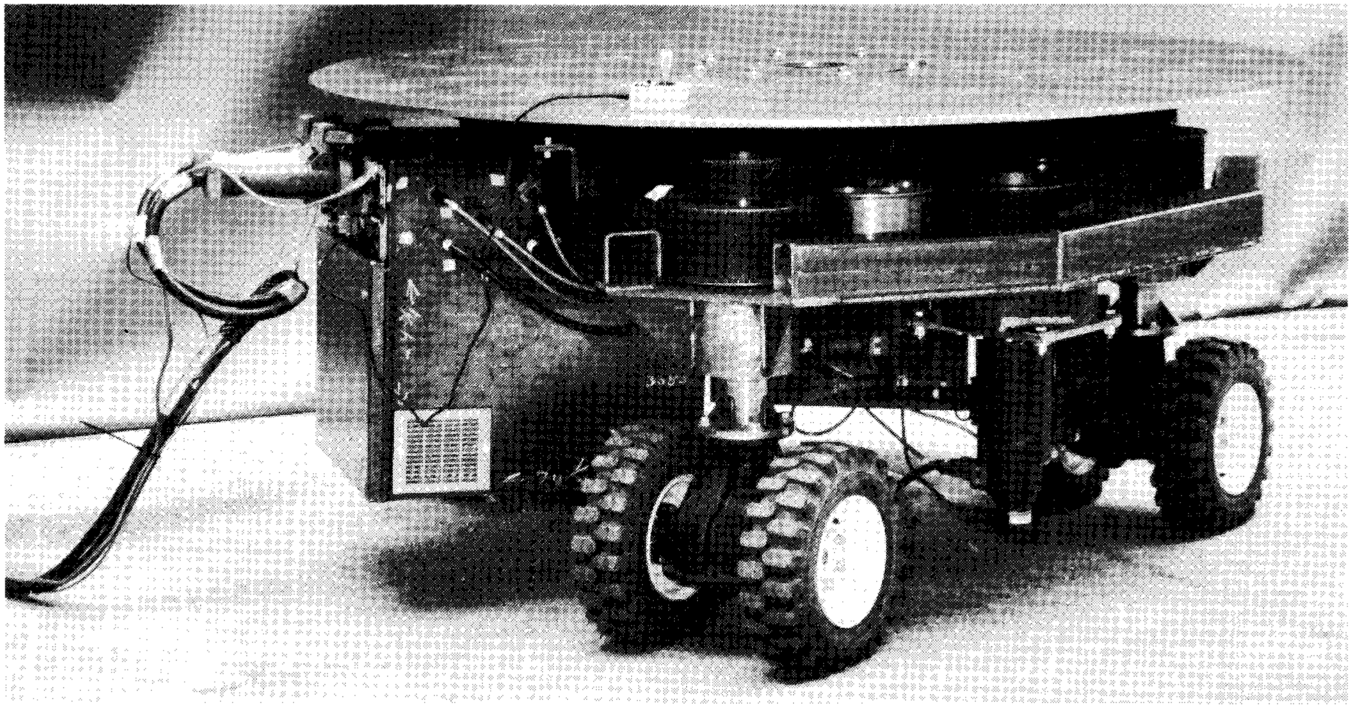

Figure 6.–Locomotion emulator.

COAL INTERFACE DETECTION

BACKGROUND

Of equal importance to lateral guidance, and of more immediate application, is the task of developing technology that automatically maintains the coal cutting geometry to that desired. Simply stated, the objective is to keep the cutting head in coal no matter what geology is encountered. Coal seams vary in pitch and thickness, and may have varying characteristics because of the surrounding strata. No single coal interface detection scheme will suffice; it will take the intelligent interpretation of data from a suite of sensors, each operating on different principles for each of the differing strata characteristics, to keep the cutting head in coal.

Many techniques have been proposed and tried without success. The only technique that is commercially available is the natural gamma developed by British Coal. This system works well in the appropriate geologies, but unfortunately not in all. The Bureau believes that all earlier efforts failed because the fundamental properties of the strata were not thoroughly investigated. Additionally, advances in technology have provided several methods that were not available to earlier researchers. The research effort is described in more detail in reference 6.

ACTIVITIES AND STATUS

Studies are being conducted on the fundamental properties of the strata adjoining the roof and floor in several different coal seams. The fundamental properties are those measurable aspects of coal and strata that are useful for distinguishing between the two by using instrumentation. The goal is to understand those properties and use them for the general solution of the coal-interface detection problem.

There have been advances in the technology for discriminating among differing electrical signals. The electrical signals could be generated by accelerometers that measure mining machine vibration and seismic vibrations in coal or adjoining strata. The Bureau is investigating whether the differences in these vibrational signals produced by cutting coal or cutting into the adjoining strata are significant and consistent enough to allow classification using the advanced discrimination and classification techniques (*7*). If this is feasible, the classification can then form a means to detect when the mining machine starts to cut into the adjoining strata and thus provide a controlling signal to adjust the cutting height. The few experiments that have been tried so far show that there is promise for this technique. For any given mining situation, the classification system would be "taught" the difference between the signals by purposeful cutting of coal and the adjoining floor and roof.

Another area of active investigation is the use of an infrared imaging video camera that responds to fractional differences in temperatures by using different colors. Experiments have recently shown that there is a detectable difference in cutting bit and dust temperature depending on whether artificial coal or a concrete cap rock is being cut. These differences remain even in the presence of water sprays. A system for constant monitoring of the video images could effectively be used to control the cutting.

New developments in radar technology are being investigated with the hope that coal strata and coal-air interfaces can be detected and measured. Not only would this technique help in vertical guidance, it would provide a means to measure rib thickness in highwall mining. Rib thickness is the primary measurement needed for the lateral guidance of highwall mining machines.

Another method being tried is the use of strata probing drills for indicating the difference between coal and strata, or coal and air in the case of rib thickness. Precise measurement of torque versus penetration distance may provide the necessary data for cutting control. In the long run, multiple sensor systems will be needed. The data will be fed into a powerful computer that filters the data and indicates the best estimate of the location of the coal interface or coal thickness.

MACHINE DIAGNOSTICS

BACKGROUND

The downtime of a mining machine during production is costly today and it will become even more costly with computer-assisted machines since a more productive and expensive machine is involved. Much downtime is due to breakdowns that could have been prevented by early detection and immediate attention. Without humans in the near vicinity of the computerized mining machines, the detection of malfunctions or deteriorating components must use sensors. The data from these sensors must be processed by a computer in real time and involve little or no human interaction in acquisition, analysis, and interpretation. The final result will be a recommendation by the computer to a human for maintenance, or if there is a fault, the location of the faulty part and a procedure for its replacement. The nature of the problem suggests the utilization of expert systems that use sensor data as input.

The major problems encountered in dealing with expert systems are selecting of an appropriate expert system method, finding an expert system development tool that can utilize sensor data and do so in real time, acquiring the knowledge from human experts, and coding this knowledge into the expert system knowledge base. Much of the data used by humans for diagnosis are obtained by hearing and feeling, the two senses and processing techniques that are not readily available in electromechanical sensors and computers. When taken much beyond the elementary level, the expert system must use sensor data that are machine system specific; such data are not available from experts and may have to be empirically obtained.

Three machine subsystems are involved: hydraulic, electrical, and mechanical. The initial approach has been to utilize a sensor-based expert system for hydraulic system component fault detection, and to develop an electrical system fault diagnostic system based solely on human input of data in response to questions.

ACTIVITIES AND STATUS

A prototype hydraulic diagnostic expert system (*8*) is being built using Goldworks, an expert system development environment. The advantage of Goldworks is that it not only allows rules for knowledge representation, but it is a frame-based system that allows a frame network to be set up that can model a hierarchy of objects and the relationships among these objects. In this case, a frame network has been set up to model the hydraulic system circuits, components, and sensor information, and their relationships. The hydraulic frame network stores information descriptive of the hydraulic system and can accept new and variable information from sensors or the human operator. The diagnostic rules will in turn digest this information and produce a diagnosis if a system malfunction exists. Goldworks is also an attractive package because it runs on higher level PC's (286- or 386-based systems). Although it is written in LISP, it can interface with higher level languages such as C and can also interface with widely used data base and spreadsheet data files. At present, the hydraulic frame network and the diagnostic rules for the main, pilot, and five functional hydraulic circuits have been completed. This knowledge will undergo review by the domain expert and mine maintenance experts for validation. There are presently 18 sensors installed on the test bed miner that either characterize the hydraulic system (pressure, flow, temperature, level) or reveal the state of action of the miner. The next step is to complete the group of sensors for hydraulic system characterization and design an interface linking the sensor data to the diagnostic expert system through an onboard data acquisition and control system. Finally, the expert system will be validated and evaluated by inducing faults into the system and allowing the diagnostic knowledge base and sensor data to produce system diagnoses.

A different approach was taken for an expert system to help troubleshoot the electrical system of a mining machine (*9*). The objective was to produce an interactive troubleshooting aid to help or train maintenance personnel in the identification of control malfunctions in the pump, tram, conveyor, and cutting electrical circuits. It uses Level 5 as the expert system development tool. Graphical displays have been utilized to help the user identify points of electrical measurement and location of parts. The prototype system has been used by untrained personnel to locate six induced faults in the electrical system of the Joy 16CM. Serious limitations with the Level 5 tool have been encountered: the specifics of the machine are buried within rules that make adaptation to other machines difficult, and the ordering of the rules drastically affects the apparent intelligence and efficiency in locating faulty components. An effort is underway to find a more suitable expert system tool and to encapsulate the whole system into a mineworthy form for on machine installation.

PLANNING

BACKGROUND

Planning is the major element that is responsible for machine intelligence–the ability of the machine to make decisions autonomously, as do humans, based on an analysis of current circumstances in the context of the job to be performed. It represents the most complex of research issues. Planning takes place at many levels in the hierarchical control system. At the lowest level, the planning may determine the elemental moves to change the location of a machine without crashing into the ribs or pillars. At a higher level, planning may determine the sequence of positions that the machine must reach to mine 40 ft down an entry or to move to a different entry. At even higher levels, it may involve the planning of entries to avoid a clay vein that is known to exist from survey data. At all levels, planning involves input data, whether from sensors or a data base; it involves a representation of that data and a context for its interpretation; and it involves the decomposition and sequencing of tasks whether they are defining goals, subgoals, or machine commands. Figure 2 indicates the extent of this issue.

The task of planning research includes defining the appropriate levels and the means to represent and contain the knowledge. The decomposition of the tasks for computer control of a machine is highly machine dependent and requires indepth knowledge of mining and machine operating techniques. The computer environment and human interface must be designed to be able to accept new knowledge as it is accumulated by the observation of the machines and to allow human intervention when they get into circumstances beyond their intellectual capabilities.

ACTIVITIES AND STATUS

At this point in the development of computer-assisted mining machines, there is little more than a recognition that this research must be done. As mentioned in the "Fundamental Research" section, both CMU and NIST are actively pursuing research in this area for the Bureau. During the next year, once the mining machine motion can be controlled through guidance system sensors, the development of path planning software will begin at the Bureau.

SUMMARY

The U.S. Bureau of Mines is committed to research leading to fundamental technologies that will allow the evolutionary development of computer-assisted mining systems for underground coal mines. The resulting relocation of the equipment operators to a secure, remote location underground will substantially reduce worker exposure to face hazards–falls of roof, equipment accidents, dust and noise, and explosions–with a resultant drastic lowering of the incident rates of injuries, deaths, and health problems.

This report has described the major elements of this research and how these elements were selected. The status of the research in each of the major areas has been presented, showing the direction being taken and the level of advancement. Some vital issues were not discussed such as the need for substantial industry cooperation in providing a site for underground testing of prototype machinery, and for providing detailed knowledge of mining techniques, and the cooperation of the machine manufacturers in providing a suitable machine for modification and testing. The issue of permissibility and modifications to the health and safety regulations was not discussed and the discussion of intelligent machine action planning, although touched upon, was incomplete out of necessity.

The Bureau's approach is to obtain a complete representation of the research issues from the top down and conduct its development of prototype systems from the bottom up.

At this point, the appendages of a continuous mining machine have been brought under computer control. A computer system network has been defined and links to heterogeneous computers established; a multiple sensor-based navigation and guidance system has been conceptualized, hardware has been purchased, and software is being developed and evaluated. A system view port and manual control console have been developed on a Sun 4/110 that serve to log sensor data and facilitate the testing of guidance sensor locations and machine moves in software. An all-purpose vehicle emulator is built and ready for physical testing of guidance systems. Prototype expert systems for hydraulic and electrical system diagnostics have been developed. The basic principles of coal-interface detection are being investigated, and some are showing promising results. Object-oriented language is being investigated as a tool for rapid prototyping of intelligent planning.

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