Teleoperation for Continuous Miners and Haulage Equipment

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***Abstract*—Hard-wired or radio remote control of continuous mining machines has been available since the early 1970's. This type of remote control situates the machine operator off board but within direct view of the underground coal face. The operator is positioned under permanent roof support but is still exposed to the hazards of roof and rib falls, dust, and methane explosions. Since 1979, the U.S. Bureau of Mines has researched alternative methods to remove the machine operator from these hazards. Working with a private cooperator since 1985, the Bureau has developed an off-board, computer-based remote control system that stations the operator hundreds of feet away from the working face in a highwall mining operation. Details of this new remote control or "teleoperated" highwall mining system (continuous miner plus continuous haulage) at a West Virginia field trial site are described, along with plans to incorporate this technology for thin-seam extraction and haulage equipment in deep, room-and-pillar coal mines.**

Introduction

UNDERGROUND coal mining face equipment is very common; it is used to perform arduous extraction, haulage, and maintenance work once done solely using manual labor. Much of this equipment was developed in the late 1940's and became generally available to the industry in the early 1950's. At first, face equipment designers usually placed the controls on the side of a machine, and the operator manipulated them from a standing or kneeling position. Later, on some machines, controls and operators were placed in rudimentary compartments that allowed operators to be aboard the equipment. Typically, no provisions were provided to protect operators from safety and health hazards. Due to increased concerns about safety and associated legislation passed in 1969, underground face equipment operation from compartments equipped with protective canopies became the norm. Space constraints in thin-seam mining operations (typically below 48 in) make it very difficult to provide adequate, on-board operator compartments with canopies. Off-board equipment operation began with remotely controlled equipment developed in the early 1970's and is accentuated by teleoperated equipment being introduced by the Bureau and others.

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Remote Control and Teleoperation

For mining, remote control usually refers to the actuation of functions of a mining machine from a portable control box linked to the machine through either a wired tether line or by a radio transmitter and receiver. The operator with the control box is within direct line of sight to the mining operations being performed (10 to 50 ft) and receives operational cues directly. A reason that remote control was developed is that for thin-seam applications, there is normally insufficient space to house the operator and controls in a compartment on board the machine. Most commercially available remote control systems for mining are associated with thin-seam applications, especially continuous mining machines. Although remote control is sometimes touted as a safety feature, this is not especially true because operators are not provided the positive protection from roof and rib falls given by operator compartments; in addition they are left exposed to the dust, noise, and congestion associated with the equipment operation. A merit of remote control is that it allows the operation of continuous mining machines for extended cuts that would otherwise place a machine-based operator under an unsupported roof.

For this paper, teleoperation describes the computer-based, remote control of mining machinery from a protected operator compartment located a long way from the mine site so that sensory information about the operation of the equipment cannot be obtained directly. Video, sound, and other relevant information are gathered through sensors and are transmitted electronically to the operator's location. The sensory information may or may not be processed before being displayed to the operator. The teleoperator responds to the information and makes decisions that are initiated by the actuation of control devices (usually switches). These control commands are then electronically transmitted to the machine being controlled, and the appropriate machine function(s) are carried out. In teleoperated systems, partial automation may be introduced by having the operator's actuation of one control initiate a series of machine functions using either open- or closed-loop computer control.

Without question, teleoperation increases the safety of mining machine operators as it removes them from the immediate vicinity of associated hazards to a very safe location. This is especially true for face equipment operators as they are relocated from the zone widely documented as the most hazardous area in all mining—within

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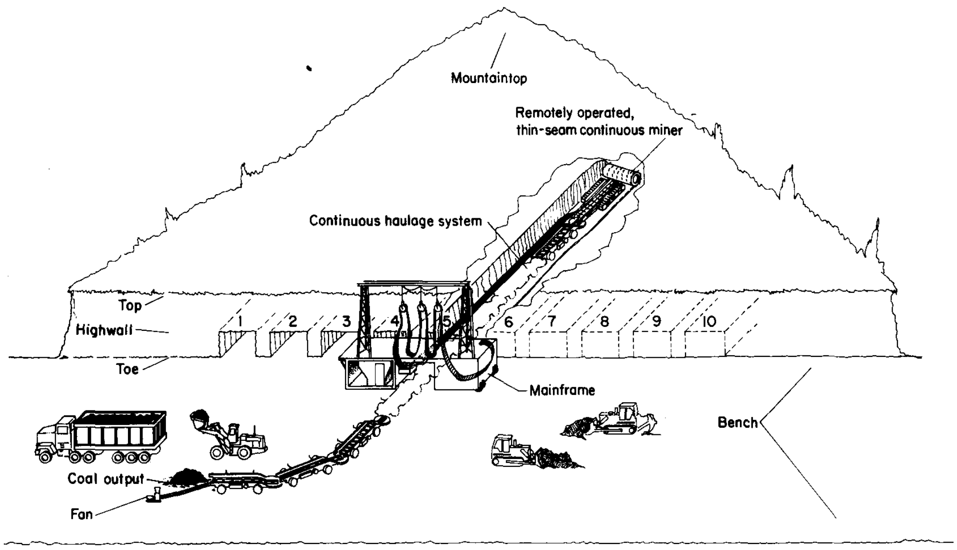

Fig. 1. Artist's concept of teleoperated highwall mining system.

25 feet of the working face. Teleoperation also removes operators from face area health and congestion problems and substantially enhances their comfort.

In addition to safety and health benefits, teleoperation has the potential for the following advantages: 1) improved operator efficiency, 2) high worker productivity, 3) opportunities to extract reserves previously considered not minable, and 4) the present-day employment of technology that bridges the gap between current mining methods and future, highly automated mining systems.

The Bureau's involvement with teleoperation dates back to 1979, when a study began to explore the feasibility of using the methodology for thin-seam continuous mining (TSCM) machines used in deep, room, and pillar coal mining. This feasibility study was positive, and in following years, development of a system commenced to the point of designing and fabricating a computer-based control system. At this point, a suitable TSCM was not available for evaluation of the system. In 1985, an opportunity arose that allowed the teleoperational concept to be evaluated as a subsystem of a cooperator's new highwall mining system. The cooperator agreed to supply a new Jeffrey Model 102HP[1] TSCM that would be extensively modified by the Bureau for teleoperation. Later, it was agreed that the Bureau's multiple unit continuous haulage (MUCH) system would be used as part of this new highwall mining system.

Teleoperated Highwall Mining System

An artist's conceptual drawing (Fig. 1) depicts the teleoperated highwall mining system (THMS). The THMS features a Jeffrey model 102HP TSCM, the MUCH conveying system, the teleoperating system, and support equipment on the highwall bench. A laser, which is located near the mouth of the active entry (with its beam aligned to a target mounted on the TSCM), provides the capability to maintain desired entry orientations. Three workers are required to operate the THMS with none permitted in the mined workings to ensure a very safe operation.

The THMS is teleoperated from a protected, human-engineered operator station located on the highwall bench within a mainframe structure. A computer-based electronics system supervises communications between the operator and the mining equipment. Two microprocessor systems are used: one in the operator station and the other on the TSCM. Operator commands, audio/video signals, and sensory data are transmitted between the station and the mining equipment over small (0.6 in, typically) cables run alongside power and water lines.

Teleoperated Continuous Miner

The system employs a Jeffrey model 102HP TSCM modified for teleoperation. This TSCM was chosen because it offers these advantages over other available machines: 1) the potential for more precise control of the extraction process is offered because the cutting auger is sumped into the face by hydraulic rams, whereas the main body of the miner remains stationary, 2) the flat, upper surface of the machine allows video cameras to be placed in positions with relatively unobstructed fields of view, and 3) more space is available for add-on equipment.

The TSCM was purchased by the cooperator; it was equipped with a tethered remote control module. Considerable effort was expended to adapt and retrofit the machine with the Bureau's teleoperational system. This

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

included the addition of three video systems, explosion-proof housings containing the electronics, and sensors to detect hydraulic pressure, temperature, current, sound, cutting head position, methane, and machine orientation.

Major modifications to the TSCM to allow teleoperation included: 1) Selecting locations for mounting and wiring the electronic sensors, explosion-proof electronic enclosures, camera assemblies, and laser alignment target, 2) adding structural members to the rear of the machine to protect the computer systems and allow the addition of the cooperator's emergency cable retrieval system, 3) extending the width of the cutting auger to provide clearances between the coal ribs and the TSCM, 4) extending the length of the conveyor tail boom to match the receiving hopper on the haulage system, 5) designing and installing a subsystem to remotely reset the computer and the TSCM electric circuit breakers, 6) designing and installing a subsystem for treating pressurized air used to cleanse the camera viewports, and 7) installing equipment for an exhausting-type ventilation system to reduce dust generated at the cutting head and enhance video resolution.

As shown in Fig. 2, the heavily modified Jeffrey 102HP TSCM is capable of operating in seam heights ranging from 42 to 48 in. However, it can be modified to operate from 30 to 54 in. This compares with a standard machine that is capable of operating in seam heights from 34 to 48 in.

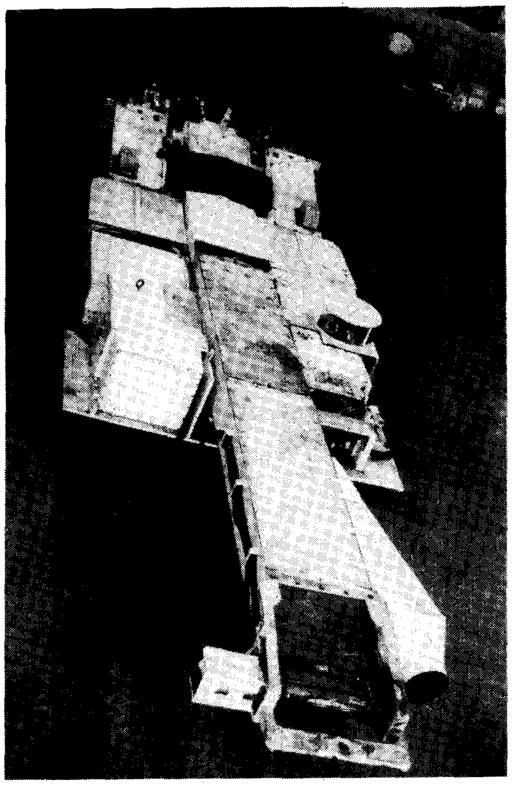

Fig. 2. TSCM modified for teleoperation.

Haulage System and Modifications

Although the design of the THMS will allow a variety of continuous haulage systems, this first prototype version employs a modified version of the Bureau's MUCH system [1]. The technology for this unique haulage system was realized by the Jeffrey Mining Machinery Division of Dresser Industries, Inc. under a former Bureau contract. The MUCH system was originally intended to improve productivity and safety in room-and-pillar deep mining by providing a continuous, self-tracking, rubber-tired, face haulage system to reduce the inefficiencies of conventional shuttle car haulage systems. Each MUCH vehicle has an integral chain conveyor and features four-wheel steering and two-wheel drive. A unique, patented (U.S. Patent No. 4 382 607) mechanical linkage couples adjacent vehicles into a train with automatic mechanical tracking and retracking at 80 ft/min. Coal is transported along the conveyor/vehicle train at a maximum rate of 12 T/min. The system is capable of making 90° turns.

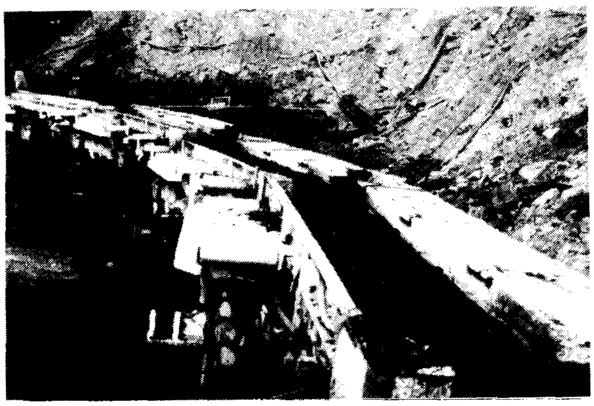

Fig. 3. MUCH system modified for teleoperation.

The current MUCH system, as shown in Fig. 3, consists of 12 vehicles: one lead vehicle, ten intermediate vehicles, and one discharge vehicle with a bridge conveyor. Intermediate vehicles can be added or removed from the train to suit individual mining site requirements. The length of the present system to include the bridge conveyor is 250 ft. The receiving hopper of the lead vehicle is extended by 90 in, compared with an intermediate vehicle, to reduce the frequency at which the train must be jogged to follow the TSCM discharge tail-boom during the mining cycle. A semi-flexible ventilation system is carried along the length of the MUCH system [2].

As originally designed for deep mining applications, the train of vehicles was to be steered by an operator in the lead vehicle and an operator at the outby end. For the THMS, steering of the lead vehicle was modified by the cooperator to automatically track the path of the TSCM during mining. Limited steering capability was provided on the discharge vehicle; it is utilized when the mining system is being retracted from the highwall entry. The teleoperator actuates controls to move the MUCH system inby or outby and start or stop the chain conveyors.

Highwall-Based Support Equipment

The cooperator designed and fabricated a massive mainframe structure that is situated in front on the highwall entry being mined. The structure is transported from one active entry to another as mining progresses along the highwall bench. The primary functions of the mainframe structure are as follows: 1) Enclose and protect the remote operator station, 2) house a cooling system for electric auger motors on the TSCM, and 3) house a system that allows the mining equipment to be extracted from the entry in an "emergency event," such as when a large ground fall occurs.

The THMS requires that control signals be sent from the operator station to the TSCM and that face area video and sensory information be sent in the opposite direction. Electrical circuits for emergency lighting (when trailing cable power to the TSCM is lost) and an emergency stop function were also provided. Because power cables and a water hose must extend to the TSCM and haulage system from the highwall bench, wireless communications offered no overall advantage. Therefore, the decision was made to run small diameter cables (0.6 in) carrying the electronic signals alongside the other lines.

The design of the THMS requires that additional lines be run from the bench to the mining equipment. These lines include an air hose to cleanse the camera viewports, two hoses to circulate auxiliary coolant to the frequently operated TSCM motors, and two hydraulic lines to power leveling jacks and guides used during system retrieval.

A proprietary system allows all the electric cables and hoses to be bundled and paid out or retrieved according to the movement of the mining system. This system is depicted in Fig. 1 and does not employ cable reels or electrical slip-ring contracts.

The success of the THMS mining plan is dependent on the ability to maintain straight extraction entries with coal barriers of predetermined thickness (for ground control) between the entries. Because the THMS penetrates the highwall face by a maximum distance of 300 ft in the current prototype system, a laser-based alignment system was determined to be adequate for the application.

The alignment laser is located near the mouth of the active entry with its beam aligned to a target mounted on the TSCM. The laser spot on the target is viewed through one of the video systems mounted on the TSCM and transmitted to a video monitor in the control station. Because the laser target is located on the forward section of the TSCM, the operator can simultaneously view it and the face area. By observing directional changes of the laser spot from the original position on the target, the operator corrects the heading of the TSCM and maintains a straight course.

The THMS mining plan requires that the area along the highwall be surveyed before mining to establish reference points for positioning the mainframe structure and alignment laser.

Teleoperation System

A teleoperating system was developed specifically for the THMS to control the TSCM, the MUCH system, and some bench-based support equipment. Control of all coal and haulage equipment penetrating the highwall is accomplished by a single teleoperator, which is situated at an ergonomically designed workstation within a protective enclosure on a highwall bench. This workstation consists of a special task chair, two control modules, two color video monitors, an array of displays, and a control computer.

Communication Computers: The core of the teleoperating system features two microcomputer systems—the MAIN (located in the operator station) and the REMOTE (located on the TSCM) [3]. Advantages gained from the use of these two computers include the following: 1) Machine function control and sensory data are transmitted over one twisted-wire pair; 2) a wide range of sensory information is collected at the face area and displayed to the operator on user-friendly output devices; 3) operational and hardware changes are easily achieved; 4) there is future automation potential. Design goals for the teleoperating system included reliability, economy, and operational flexibility.

The MAIN and REMOTE computers employ the Intel BITBUS series of remote controller and input-output boards. The data transmission between the computers occurs at an effective rate of 375 Kb/s. The communications protocol is managed by the hardware and firmware.

The REMOTE computer is essentially a computer-controlled input-output port. When a valid command is received from the MAIN, the REMOTE outputs an appropriate command sequence that activates relays onboard the TSCM; it also samples data on its input ports and encodes and transmits the information to the MAIN. The REMOTE computer is shown in Fig. 4; electronic components are housed in a compact, shock-mounted, custom-fabricated, explosion-proof housing mounted on the TSCM.

The primary function of the MAIN computer is to command the REMOTE, based on input received from the operator. Information transmitted from the MAIN causes the REMOTE to operate the mining machinery and video systems. When the MAIN receives sensory data from the REMOTE, they are processed and presented to the operator on digital bargraph displays. The MAIN computer is located in a cabinet that houses the video monitors and several power supplies.

Because the THMS is currently powered by portable electrical generating units, electrical transients and power fluctuations occur. Because electrical aberrations cannot be tolerated by computer systems, uninterruptible power supplies (UPS) power the computers. The UPS inputs are connected to industrial-grade, powerline transient-suppression devices.

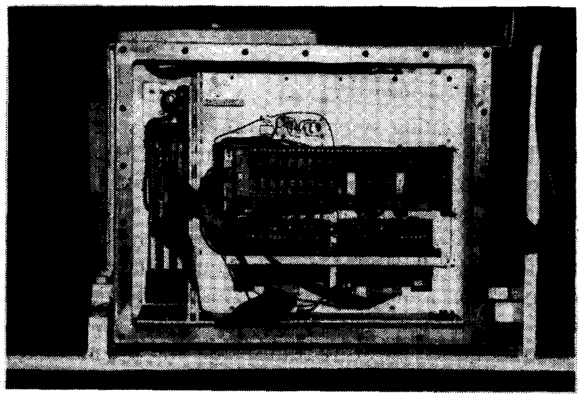
Fig. 4. REMOTE computer system.

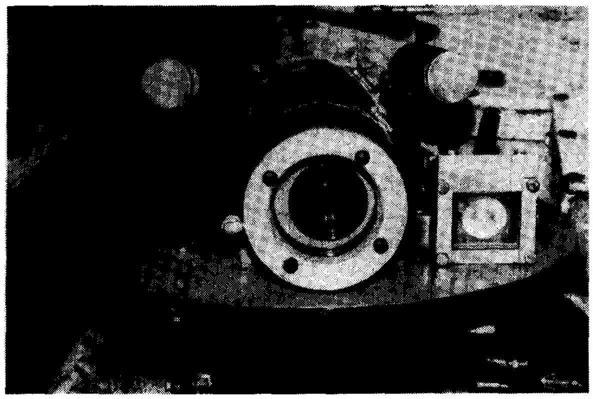
Fig. 5. Pan-tilt video system with microphones.

Video Systems: The primary means for the teleoperator to monitor the THMS is via its three independent closed-circuit video systems. These systems provide the teleoperator with visual feedback of the conditions at the working face, the cutting head position relative to the coal-roof interface, the orientation of the THMS with respect to the laser alignment beam, and the flow of cut coal along the conveyors. One color video camera is positioned above and forward of the REMOTE computer enclosure, providing a fixed general view of the cutting auger and face area. A second color video camera is located on the miner's right fender and mounted on a hydraulic pan-tilt pedestal. This arrangement allows the teleoperator to position the camera to view an area of interest such as the miner's laser target or haulage system. Fig. 5 shows the pan-tilt video camera assembly used on the THMS. In the event of a failure of the main fixed color camera, the movable unit can also serve as a backup. The two color cameras are compact solid-state units attached to a motorized zoom lens with adjustable iris, focus, and zoom. A third black and white (B & W) video camera is located to the left and alongside of the REMOTE computer enclosure. It provides the teleoperator with a view aft of the continuous miner. The B & W camera is smaller than the color units and offers enhanced low-light sensitivity and resolution.

All of the video cameras and associated lenses are housed in individual custom-designed explosion-proof enclosures with an antireflection-coated optical viewing port. The enclosures are designed to be waterproof and dust-proof. The video cameras are custom-mounted within the enclosures to isolate them from machine-generated shocks and vibrations. Each enclosure is equipped with an air-wipe system that directs a curtain of pressurized air across its optical window. This prevents the accumulation of dust from deteriorating the video system resolution. Sturdy shrouds are attached to the machine mainframe to protect the color video camera assemblies from roof or rib falls.

Illumination for the THMS video systems is provided by five compact tungsten-halogen headlamps. Two lamps are mounted on either side of the cutting head boom to illuminate the face. The remaining three lamps are mounted adjacent to and aimed parallel with the axis of the video camera assemblies. In the case of the pan-tilt unit, the headlamp moves with the camera.

Sound System: A sound system is employed to extend the teleoperator's sensory perceptions during operation of the THMS. Initially, two dynamic cardioid pattern microphones were utilized to provide aural information to the teleoperator. These microphones were mounted in specially designed holders to protect them from shock and vibration from the continuous miner mainframe. The microphones were mounted on the movable video camera assembly to provide the teleoperator with a spatial sensation via stereo speakers or headphones. This arrangement is shown in Fig. 5. Initial testing of the microphone sound system demonstrated poor sound quality due to the obliteration of desired ambient sounds by interference from locally generated machine noises such as pump motors and conveyors. Superior results have been obtained by utilizing a pair of accelerators coupled with the continuous miner auger head bearing cap. One accelerometer is mounted parallel to the machine's vertical axis, whereas the other is along its longitudinal axis. With this sensor arrangement, coal cutting operations are efficiently transferred to the accelerometers, minimizing other undesired noises. During initial field testing, the teleoperator reported that the accelerometer-based sound was an important input for determining coal/rock interfaces.

Other Sensors: A variety of other sensors are mounted on the THMS to augment the information presented to the teleoperator [4]. These sensors monitor operating parameters of the continuous miner, haulage equipment, and mine methane level. Fig. 6 shows the sensor arrangement on the teleoporated TSCM; Table 1 summarizes the sensor specifications. Selection of the sensory information presented to the teleoperator involved design tradeoffs. The primary objective of the sensor selection process was to furnish the operator with adequate information to control the mining system equipment at all times and discern the health of its major subsystems.

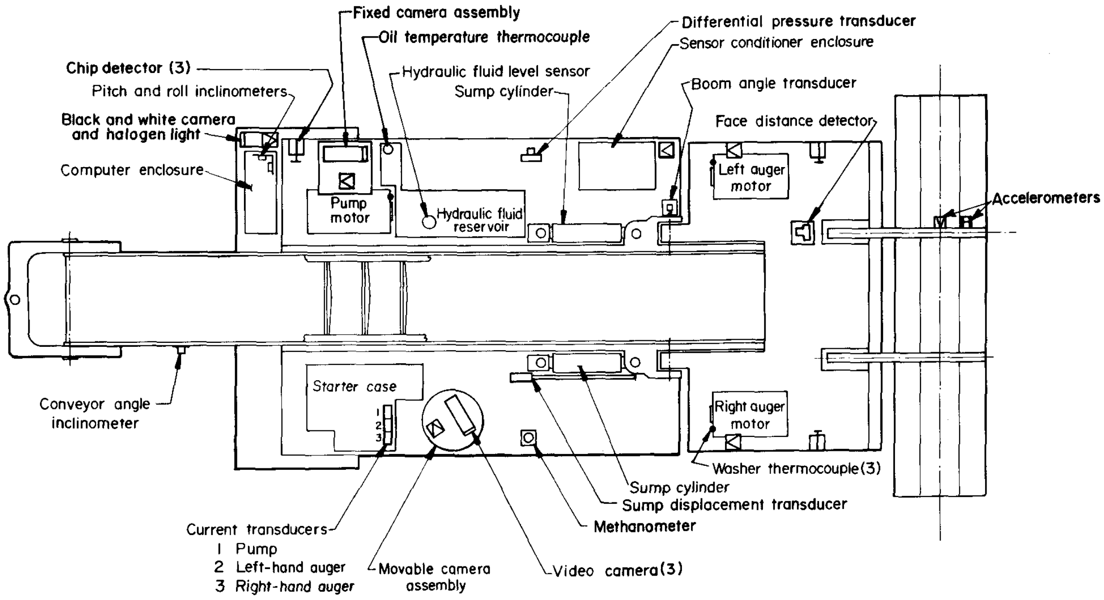

Fig. 6. Sensors arrangement on the teleoperated TSCM.

TABLE I
THIN-SEAM CONTINUOUS MINER SENSOR SPECIFICATIONS

Parameter	Sensor	Type
Hydraulic fluid temperature	Thermocouple	Type-J shielded probe
Motor temperatures	Thermocouple	Type-J 13 mm washer
Motor currents	Current transducer	Electronic rectifying
Machine pitch and roll	Inclinometer	Electrolytic
Conveyor boom angle	Inclinometer	Electrolytic
Pilot filter restriction	Differential pressure transducer	Strain gage
Hydraulic fluid level	Liquid level sensor	RF capacitance
Sump distance	Linear displacement transducer	Magnetostrictive
Auger boom angle	Angle transducer	Rotary voltage differential transducer
Methane concentration	Methanometer	Catalytic
Face sounds	a) microphone	Dynamic cardioid
	b) accelerometer	Quartz
Color video	Video camera	Charge coupled device
Black and White video	Video camera	Tube type

Operator-Machine Interface: The successful operation of the THMS depends significantly on the operator-machine interface. The teleoperator is required to control the mining system for extended periods. As a result, major emphasis was placed on the design of optimum human engineering features for the operator's workstation [5]. Operator comfort if an important element of the design. The operator needs to change seating and body positions while still having full access to control and monitoring equipment. Fig. 7 shows the ergonomically designed remote operator's control room. The operator controls the continuous miner, major functions of the haulage equipment, and some functions of highwall-based support equipment, performing the tasks of five or more traditional mining system workers. Seated in a semi-reclined position on a special, adjustable task chair, the operator has convenient access to clustered control, readout instrument panels, and multiple video monitors. Sensory information from the continuous miner and haulage equipment is presented in color-coded bargraph displays mounted in an adjustable, swingaway console located in front of the operator. Main continuous miner controls are grouped on a small hand-held module, whereas secondary controls are located on an adjustable floor-mounted panel next to the operator's task chair. Two 19-in color video monitors are housed in a custom cabinet at the optimum viewing distance from the operator's eyes. The left monitor is dedicated to the fixed color camera displaying the cutting auger and surrounding coal face. The right monitor displays the video information from the movable color

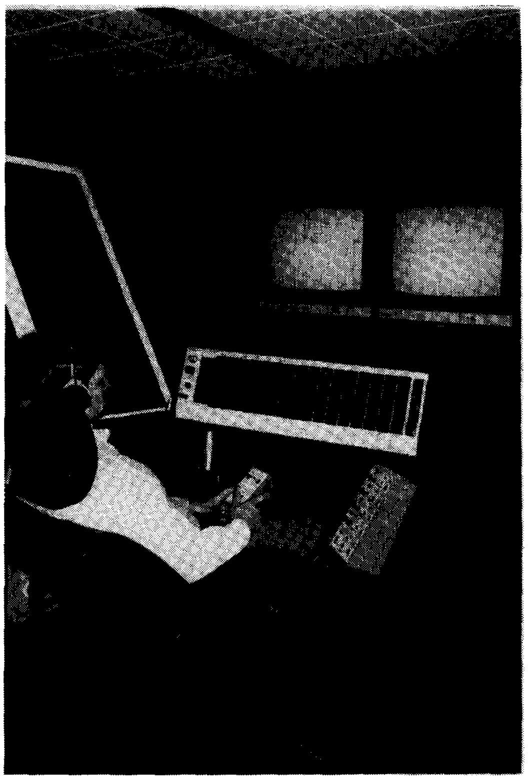

Fig. 7. Ergonomically designed workstation for teleoperator.

camera as positioned by the teleoperator's pan and tilt controls. Additionally, the right monitor is equipped with a video special-effects generator for simultaneous presentation of the image from the B & W video camera as a smaller inset picture. The images from the movable color camera and fixed B & W camera can also be interchanged as the main and inset pictures with the teleoperator's hand-held remote control unit. Aural information from the continuous miner is presented to the operator either from stereo headphones or dual external speakers.

Teleoperated Highwall System Results

Surface Evaluation

Surface testing and evaluation of the THMS was conducted during 1988 at the Bureau's Mine Equipment Test Facility located near Pittsburgh, PA. This testing included a series of cutting operations using a block of coal-like material (coalcrete) consisting of coal, flyash, and cement. The surface evaluation was performed using a total of 12 different operators. The overall testing results were positive, demonstrating that the remote operators were provided adequate sensory information on which to base decisions and control the equipment. Specific results included the following: 1) Establishing control of machine and video system functions over a 450-ft cable; 2) transmitting, processing, and presenting sensory information from three video systems, 16 analog sensors, and two audio sources; 3) the expected fact that operators found the video information the most useful input; 4) the fact that sound extracted from the output of accelerometers mounted on the cutting auger frame provided valuable information; 5) the fact that the motor current displays were useful for determining if the cutting auger was in air, coal, or other material; 6) the fact that the unique, ergonomically designed workstation formed an excellent interface between the operator and the equipment.

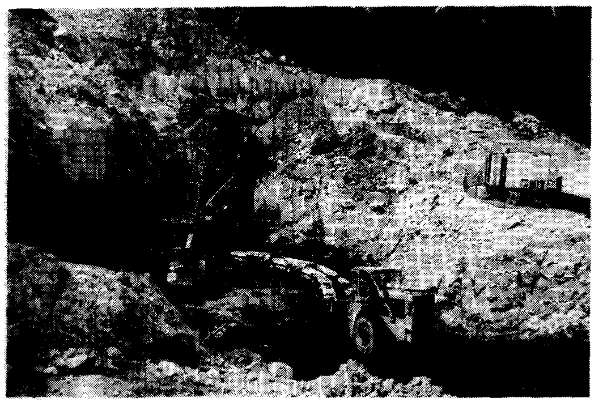

Fig. 8. Teleoperated highwall mining system at production site.

Production Testing

During August and September 1989, the THMS underwent a brief, successful shakedown trial at a highwall site located in Marion County, near Sugar Grove, WV. Fig. 8 shows the THMS deployed at the site, which had known poor conditions, including excessive water, a poor roof, and an undulating coal seam. The site was selected primarily on the basis of being available and was "permitted" to allow auger mining, which is a condition required for operating the THMS. A short bench with exposed highwall (approximately 80 ft in width) was left for the THMS by the strip mine operator.

Actual mining occurred for two entries that were extracted to an average depth of 120 ft. Additional mining was not attempted at the site due to numerous roof falls, extremely wet conditions, and the laser alignment system operating outside of its design range due to unusual pitching of the coal seam. Although the full production potential of the THMS was limited due to conditions, this complex, totally new mining system performed at or above expectations. The following was accomplished:

1) The THMS was capable of mining coal on the initial attempt, even though the teleoperator had no prior experience in controlling a mining system.
2) The coal seam pitched down, leveled off, then pitched up. Given this geological situation, the THMS penetrated the highwall to depths that could not be achieved by other commercial highwall mining systems [6].
3) Virtually all the new technologies met or exceeded

expectations. This included the prototype MUCH haulage system, the computers and software, the three TSCM-mounted video subsystems, other machine-mounted sensors, and the ventilation subsystem. The performances of the ergonomically designed workstation and the accelerometer-based sound subsystem were noteworthy.

4) The THMS demonstrated very impressive productivity rates ranging between 15.9 and 22.3 T/man-hr. As a comparison, productivity for auger mining machines is considered very good at rates up to 6 T/man-hr; recent productivity for U.S. underground deep coal mines has been calculated at 3.0 T/man-hr [7].

A highwall site with better (normal) conditions is being sought for continued production evaluation of the THMS.

Teleoperated Deep Mining System

The original project objective is being pursued toward the goal of a teleoperated TSCM for deep room-and-pillar mining. Fabrication of this system has commenced with these overall goals in mind: 1) Placement of the main teleoperator in a protected station located near the electrical power center for the section; 2) employing a continuous face haulage system; 3) enhancing safety through the use of powered cable reels to replace manual cable handling; 4) operation in seams ranging from approximately 29 to 48 in. A used Jeffrey Model 101 (which is similar to the TSCM used in the THMS) has been secured for use in this project.

Conclusions

The teleoperation of mining equipment represents a present-day application of advanced electronic technologies to foster safety. The methodology has been successfully tried in a new highwall mining system and appears promising for a deep mining application under development. If the Bureau is successful in this quest, this technology development will mark a significant milestone in achieving safe, efficient mining operations. Teleoperational systems should bridge the gap between current, worker-intensive methods of controlling mining equipment to highly automated systems that are likely to evolve in the next 10 to 20 yr.

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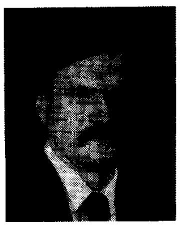

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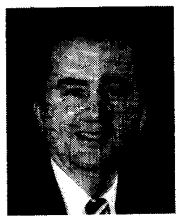

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He currently holds a position with the U.S. Bureau of Mines, Pittsburgh Research Center, as a Supervisory Physical Scientist. As a Group Supervisor, he supervises a multidisciplinary group of engineers and technicians that conduct mining research and development in areas including coal extraction techniques for deep and surface mines, coal haulage and transport methods, handling of material supplies, and hoisting system developments. Prior to joining the Bureau, he served as a Special Projects Engineer, Director of Engineering and Maintenance, and acting Vice President of Operations for the Fry Coal and Stone Company.

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