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Some Opportunities in Teleoperated Mining

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Abstract

The need for increasing coal production and work productivity while improving the health and safety of the coal miner presents some interesting challenges and opportunities for teleoperation. Systems available for mining coal are described briefly in terms of four subsystems: Fragmentation, materials handling, ground control, and environmental control. The need for automation systems, their requirements, and the state-of-the-art are explored. Technologic deficiencies of longwall mining—the system having the highest potential for full automation—are discussed.

Introduction

Prognosticators of energy requirements agree that if the United States is to achieve some modicum of energy self-sufficiency by the year 2000, the domestic production of coal must at least double—from the current 600 million tons per year to 1.2 billion tons per year by 1985.

The mineral resources of the United States include an estimated 434 billion tons of recoverable coal, which represents 88% of our national energy reserve. Above 137 billion tons of this coal lies under cover of less than 120 ft in beds up to 100 ft thick. It appears then that we have, as a minimum, sufficient coal reserves to support an expanded coal industry for about 400 yr.

How this coal is mined will have significant ramifications on its price, its percentage of recovery, the type of permanence of environmental damage and, most importantly, the health and safety of the workforce.

Mining Methods

At the present time, coal is produced about equally by surface and by underground mining methods.

The choice of mining method depends on a great number of variables. Surface mining is about three times as productive as deep mining (36 tons per manshift vs 12 tons per manshift), and coalbed recovery approaches 100% compared with 55% for deep mining. Surface mining is only about one-fifth as hazardous as deep mining. Nevertheless, the growth of surface mining has tapered off over the last several years. Public opinion and stiffer laws requiring complete land restoration have increased the cost of mining and reduced the availability of surface-mineable coalbeds.

Surface Mining

Where the coal lies under less than about 120 ft of cover, it is often more economical to remove the overburden, extract the exposed coalbed, and restore the excavated ground to essentially its original contour.

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Where the contours are gentle, many parallel cuts may be taken sequentially by dumping the stripped overburden from the current cut into the void created by mining the previous cut. This method, called "area mining," is practiced widely in Ohio and Illinois. A single mining operation may cover many square miles.

In more rugged country, where the cover over the out-cropping coalbed increased rapidly, strip mining follows the coal outcrop contour around the hills. Cut widths range from only about 50–200 ft, depending on the surface gradient. This method, called "contour mining," is practiced widely in West Virginia, Kentucky and Tennessee, often over many miles and occasionally at several elevations on mountainsides.

Equipment used for surface mining ranges from small stripping shovels on contour strips to huge stripping shovels, bucketwheel excavators, and draglines for removing the overburden on area strips, drills for drilling blast holes to loosen the overburden and coal, small shovels for loading broken coal, and trucks up to 200 tons in capacity for hauling the coal to the preparation plant or loading site. The stripped area is reclaimed with bulldozers, graders and carryalls.

Underground mining

Where the coal lies at depths greater than about 250 ft, it usually must be mined from underground. Two different mining systems are recognized: room-and-pillar and longwall.

Room-and-Pillar

This system is based on the concepts of mining about 40% of the coalbed by driving entries in sets of 3–8, leaving coal pillars between the entries to support the roof. If conditions allow, some of these pillars are recovered as the mine is retreated prior to abandonment.

Mining by this system may use "continuous" or "conventional" equipment, depending on physical factors such as the presence of hard bands, sulfur-ball inclusions in the coalbed, and soft bottoms. About 50% of all underground coal is mined by continuous miners, and 45% by conventional mining techniques.

In continuous mining, a continuous-mining machine cuts the coal from the coalbed and loads the broken coal into shuttle cars for hauling to a conveyor belt or into mine cars for transport to the surface. A roof-bolting machine is used to drill vertical holes into the room and install the roof bolts that support the roof.

In conventional mining, the coalbed must be undercut to provide an additional free face for blasting. Holes are drilled into this face, charged with explosives and fired. The broken coal is loaded into shuttle cars by a cat-mounted gathering-arm loader. As in continuous mining, a roof bolter is used to install roof bolts to support the roof.

Longwall

With this system, large blocks of coal (450–600 ft wide by 2500–5000 ft long) are developed by driving sets of three entries between sets of main entries. After the block is developed, it is mined out by taking successive slices across the short dimension of the block and loading the broken coal onto a conveyor. A self-advancing system supports the roof over the length of the face throughout cutting and loading; these supports are advanced with the face and the roof is allowed to collapse behind them.

This system is used almost exclusively by all coal-producing countries except the United States and Australia. There are currently only about 50 longwall operations in the United States, and these account for only about 5% of the coal mined underground.

Mining Systems

Regardless of the mining method employed, all underground mining systems must provide for four subsystems: (1) fragmentation, (2) materials handling, (3) ground control and (4) environmental control.

(1) *Fragmentation subsystem*

The function of the fragmentation subsystem is to break the coal from the coalbed at a rate and in a condition consistent with the requirements of the materials handling subsystem.

Where ripper-type continuous miners are used, the coal is milled by a series of cutter picks

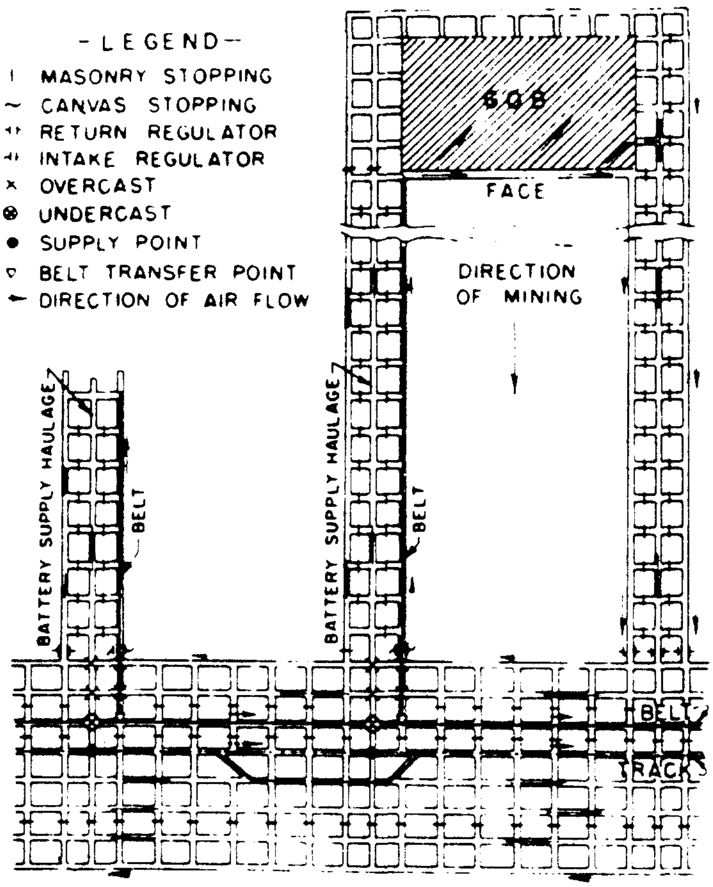

Figure 1. Longwall mining plan.

mounted on a rotating drum (or drums) sumped into the coalbed near the roof to a depth of about 2 ft and then lowered to the floor to extract the full thickness of the coalbed. Most continuous miners mine widths ranging from 8 to 12 ft. After each cut, the machine is advanced a distance equal to the depth of cut and the cycle is repeated.

With conventional equipment, the face is first undercut with a slot about 4 in. high by 10 ft deep by the width of the room to provide room for expansion. Blast holes are drilled at

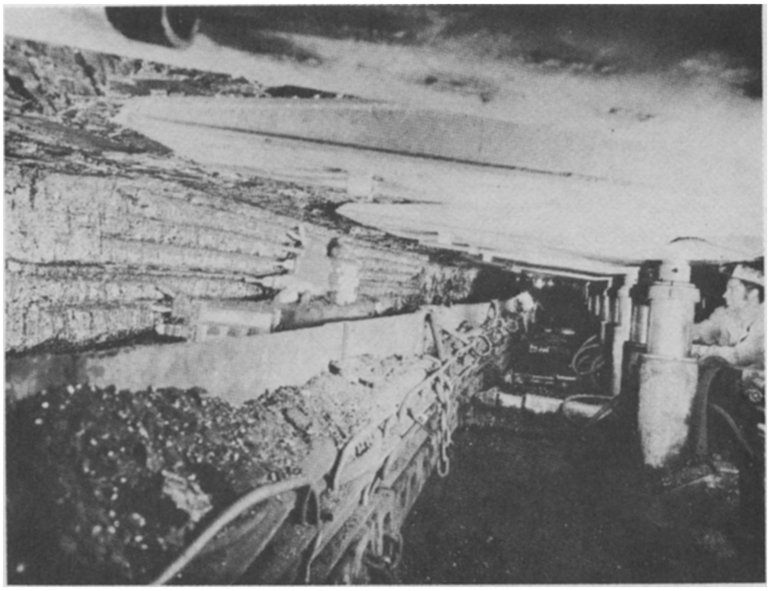

Figure 2. Longwall plow installation (*Courtesy Mining Progress, Inc.*).

intervals across the face essentially to the same depth as the undercut, loaded with permissible explosives, tamped, and fired.

Longwall systems use either a plow or shearer to break the coal from the solid. A plow, as the name suggests, is a cutter approximately the height of the coalbed, equipped on both ends with a series of stationary picks. It is attached to, and runs parallel with, a chain-and-flight conveyor. As the plow is pulled back and forth across the face, it cuts slices of coal 4–8 in. deep from the face. This extraction subsystem is generally used where the coal is soft, breaks freely from the roof and floor, and is somewhat thin.

Where coalbeds are thicker, harder, do not break free from the top and bottom, vary in thickness and undulate, shearers are more often used. These machines employ one or more rotating drugs around the periphery of which are mounted cutter picks. Shearers are available with drums in a range of diameters up to 6 ft and may be single-drum fixed, single-drum ranging and double-drum ranging. Cutting may be unidirectional or bidirectional depending on the machine and/or the space available at the ends of the face. The coal is milled from the full length of the face at depths from 18 to 30 in.

(2) *Materials handling subsystem*

Continuous miners employ a pair of gathering arms and an internal conveying system to pick up the broken coal from the floor and load it into shuttle cars for haulage to a belt conveyor that transports it from the mine. Where conventional mining is employed, a loading machine similar in design to the continuous miner, but without the cutting elements, picks up the broken coal and loads it into shuttle cars.

On longwall faces, the coal is loaded continuously onto a flexible chain conveyor that carriers it to the end of the face, over a state conveyor to a belt conveyor which transports it from the mine.

(3) *Ground control subsystem*

In room-and-pillar mining (and to develop the entries that outline a longwall panel), most roofs are controlled by drilling holes vertically into the roof on about 4 ft centers and installing steel bolts 2.5–6 ft long. A masonry-type expansion bolt is used to anchor the bolt in the hole; a square, steel-plate washer provides a bearing surface against the roof. Where roof conditions are poor, fully grouted resin bolts are used to increase the quality of the anchorage; crossbars may also be needed to prevent spalling of the roof between the bolts. As soon as the broken coal has been loaded, roof bolts must be installed at the working place, since workmen are allowed to work only under permanently supported roof.

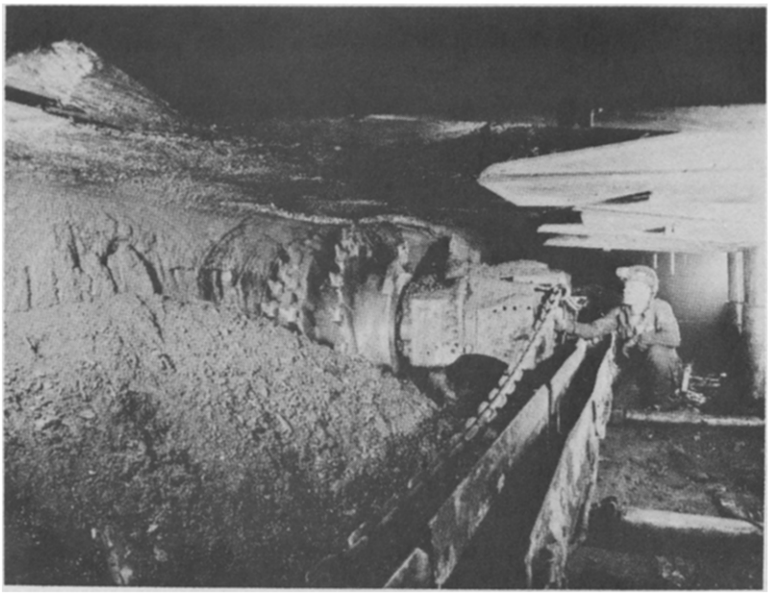

Figure 3. Longwall shearer installation (*Courtesy Mining Progress, Inc.*).

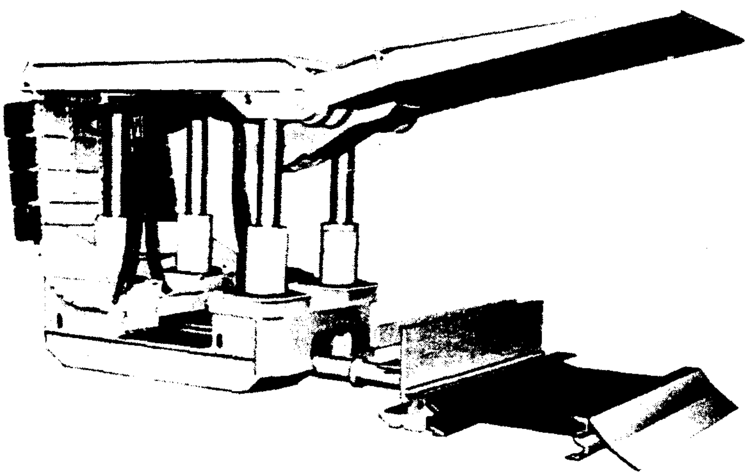

Figure 4. Four-leg chock attached to section on face conveyor (*Courtesy Joy Manufacturing Company*).

Roof control in longwalling is entirely different. Instead of attempting to support the roof permanently as in the development entries, temporary roof support is provided only over the immediate face operations. This is accomplished by hydraulically powered, self-advancing roof supports, known as chocks. Chocks come in a variety of shapes and sizes. Essentially, a chock consists of a heavy cast or structural steel base and two to seven vertical-yielding, single- or double-acting hydraulic cylinders (legs) that carry a structural steel canopy. Chocks are available for use in coalbeds with thicknesses ranging from about 2–12 ft and are capable of supporting up to 750 tons per chock.

The chocks are about 3 ft wide and are usually installed on 4 ft centers. Double-acting hydraulic cylinders (rams) connect the chocks to the armored face conveyor. As the plow or shearer passes each chock as it cuts across the face and loads the cut coal onto the conveyor, the ram pushes the conveyor forward into the void by an amount equal to the depth of the cut. The canopy of the chock is then lowered and the ram is used to pull the chock up to the conveyor. The canopy is then raised to the roof and set in position. This cycle is repeated for each chock across the full length of the face in an essentially continuous operation.

As the face advances, the now-unsupported roof behind the chocks falls harmlessly into the space originally occupied by the coalbed.

(4) *Environmental control subsystem*

Mining can proceed only when the physical environment at the face is safe and healthy. The major problem in maintaining an acceptable environment in underground coal mines that are not accounted for by the ground control sybsystem are methane gas, respirable coal dust and noise.

Methane gas is present in all coalbeds and flows into mine workings through the fracture system of the coal. Emission of methane at the face is aggravated by breakage of the coal from the coalbed and by secondary fragmentation. For control, fresh air is coursed across the face to dilute this explosive gas to a safe concentration and carry it out of the mine. By law, the concentration of methane must be maintained below 1 volume-per cent.

Respirable dust is another serious occupational hazard underground. The law specifies that no person may work in an environment containing more than 2.0 mg of respirable dust per cubic meter of air. In general, this standard is being met by coal operators through adequate ventilation and water sprayed from high-pressure nozzles. In exceptionally difficult cases, it may be necessary to infuse water into the coalbed before mining or to reduce the rate of coal extraction.

Noise underground comes primarily from mining machinery components such as the gathering arms on loaders and continuous miners, and chain-and-flight conveyors. These are inherently noisy and the confines of the mine environment prevent noise from dissipating. Good maintenance, quieter construction materials and improved engineering design can bring noise levels experienced by a face worker into compliance with the law.

Continuity of operations

Coal extraction by a continuous miner is cyclic, shuttle-car haulage is intermittent, and the mining machine can advance only about 20 ft before its operator approaches unsupported roof and must back out of the working place while roof bolts are being installed. Conventional mining is even more cyclic because the coal at each face must be undercut, drilled, broken by explosives that must be tamped and shot and, finally, loaded into shuttle cars.

Only in the longwall system do the subsystems approach continuous coal production: cutting is linear and continuous across the full width of the face; loading of coal onto the face conveyor, through the stage loader, and onto the belt conveyor is continuous; roof control advances with the face and is continuous; and the control of methane and dust by ventilating air coursing the face and by water sprays near the cutting elements is continuous.

Teleoperated Systems

The systems described thus far represent degrees of automation ranging from the one-at-a-time-in-series tasks of conventional mining to the potentially continuous production of coal by longwalling. What then is the outlook for teleoperations in mining?

Probably the single major impediment to applying the principles of teleoperations to mining coal underground is the fact that we must deal with a tabular material that occurs in a dark, hazardous, and severely confined environment. Coal is a metamorphosed sedimentary rock that varies widely in chemical, physical and mechanical properties. It may contain copious quantities of methane, other gases and water. Coalbeds may thicken or thin within short distances, undulate and, in places, be faulted, eroded, or wanting. Essentially, coalbeds lack the attributes desirable to the design of a sophisticated mining system. Although the average thickness, stratigraphy, and chemical composition of a coalbed like the Pittsburg coalbed may be remarkably consistent over hundreds of square miles, local variations in the drawslate thickness, the occurrence of sulfur balls, and diverse stratigraphy frustrate any guidance and control concepts based on predictive mathematical modeling or assumptions of uniform planes.

What then are the requirements of a truly continuous mining system? Clearly, any system designed to mine a tabular deposit (coalbed) from a stratigraphic geologic section at depth must be able to control the extraction of the coal by sensing the interface between the coal and enclosing rocks. The extractor must be capable of mining coalbeds that vary in physical properties, thickness and that undulate. The conveying system must follow closely the cutting operation and remove the coal from the face area cleanly and continuously. The roof must be supported adequately and continuously as the face advances.

The double-ranging-drum longwall shearer meets all these requirements. By adjusting the cutting horizons of the leading and trailing drums, a coalbed that varies in thickness and/or undulates can be accommodated. Because the cutting drums can move independently of the shearer frame (and hence independently of the conveyor), the machine can follow reasonable coalbed perturbations.

Standard armored face conveyors upon which the shearer travels provide guidance in the horizontal plane and can haul coal from the face area continuously at high capacity. As the face conveyor is pushed forward by the double-acting rams on the chocks immediately following cutting and loading, it provides the added function of advancing the shearer incrementally (and essentially continuously).

As already noted, all types of underground mining incorporate the same subsystems. All have the same generic problem, that of following the coal seam; therefore, only the longwall system will be discussed in detail. Longwalling has the advantage of a securely anchored reference system from which to work, that is, the chock-conveyor. Longwalling with a shearer incorporates several degrees-of-freedom of motion, thanks to an efficient yaw (horizontal trajectory) control, roll control and variable-thickness vertical (pitch) control of the drums along the face.

Automation of the longwall roof control subsystem is a reality. To advance each chock, the chockman must push the conveyor forward, lower the canopy slightly, advance the chock to the conveyor and then raise the canopy to the roof. About five cuts across the face are required on a face producing 1000 tons per shift on a 500 ft wide face in a 4 ft thick coalbed with a shearer taking a 2.5 ft deep cut. With 125 chocks on the face, about 2500 separate chock operations are performed during a single shift of operation.

A system has been developed recently that cycles a chock by the push of a button. This system has been extended to a bank of 10 chocks triggered in sequence. It is well within the state-of-the-art to improve the system still further by having the passage of the shearer trigger each support to automatically sequence to conveyor pushover and then advance the chocks.

Existing environmental control and materials handling subsystems are adequate for incorporating into an automated and/or teleoperated longwall system, although in many cases a substantial improvement in reliability and maintenance will be needed.

Penetrations into the area of automation and teleoperation in mining operations have been reported by all major coal-producing countries.

In the 1960s, the British National Coal Board demonstrated that chocks could be operated remotely from a console at the end of a longwall face, but the main factors delaying remotely operated faces were the lack of a suitable pitch control system and the high cost of remotely operated equipment.

The single greatest impediment to automated and/or teleoperated longwalling is the lack of automatic means of controlling the pitch of the cutting drums on a double-ranging-drum shearer. At the present time, operation of a shearer involves two operators: one to range the leading drum at the coal and roof interface, the other to range the following drum at the coal and floor interface. The machine operators must function both as error detectors and controlers; for example, they must observe the elevations of the cutting drums and operate controls to raise or lower the drums to cut at the desired elevations. Because coal is opaque, the operators must rely on the noise, vibration, color of cuttings and on the relationship of the current cut to the previous cut. The efficacy of this feedback system thus depends largly on man's ability to detect errors and to take corrective action.

Patently, what is needed is a system of sensors that can detect the elevation of the cutting drums relative to the desired cutting horizons and use this information to provide automatic vertical ranging of the drums as they travel across the face.

As noted, the drum operator perceives noise, vibration, color of cuttings and the results of previous cuts. This visual information must be obtained in a poorly light area, impeded by coal dust and water mist, and by the often subtle color differences between coal and noncoal. Tactile information is derived from encounters between the cutting drum and rock and must be filtered from other sources of tactile stimuli. Audio information must be sorted out of many competing sources. There is no vantage point from which a "bird's-eye" view can be obtained.

Even if the drum operator is stationed some distance remote from the cutting operations, he remains in the control loop and must function as goal selector and decision-maker.

The longwall system is a relatively expensive system requiring constant surveillance to protect men and equipment. Failure of the roof to fall as the chocks are advanced is a typical case where human intelligence is far more effective than even the most sophisticated instrumentation. Failure to detect such an anomaly could create a cantilever that could result in the development of inordinate forces on the chocks and jeopardize the operation.

In perspective then, the pitch control could best be accomplished automatically by a sensor. Tied into this immediate system, and conversant with it, must be a human system to select goals, provide planning, monitor production, detect failures and determine maintenance needs as an indispensable adjunct to the system operation. This human system could be located remotely and be provided with visual (via video), auditory (microphones), and tactile (accelerometer pickups) aids, as well as information from automatic checkout and monitoring instruments.

Approaches to interface detection and horizon control

The coal and noncoal interface is a space surface. In some instances, it is sharply defined; in others, differences are subtle. Further, the interface surface is rarely regular. It can vary in composition and texture and undulate irregularly with periods of a few feet. Pitch control of the cutting drugs must be based on some combination of three data sources: (1) the location of the interface prior to cutting, (2) its location during cutting, and (3) its location after cutting. The first source appears to offer the best solution, but it also constitutes the most difficult approach because it requires prior knowledge based on measurements of the coal yet to be cut. No progress has been made in "looking ahead" into the coal.

The second approach utilizes "sensitized pick" techniques to measure the forces on one or more cutting elements. This system was used to sense the cutting of hard roof rock on Joy's Pushbutton Miner† in the 1950s. In view of the significant advances in electronic control technology, this concept might be advanced to provide a useful signal for indicating roof (hard rock) or floor (soft rock) as distinguished from coal.

The third approach makes use of the British National Coal Board's nucleonic probe. With this sensor, several inches of coal must be left on the roof to generate a useful signal. It cannot range off the floor, uses a radioactive isotope, must maintain intimate contact with the roof, follows the cutting drum by about 3 ft, and is unidirectional. It is unlikely that this probe can be adapted for the control of a double-drum ranging, bidirectional shearer. Sensing based on the magnetic, mechanical, acoustical and electro–magnetic properties of coal is also being investigated, but at best these studies are still in the laboratory stage. A sensor based on differences in machine vibration is being developed by the General Electric Company under a Bureau of Mines contract.

Assuming that a suitable sensor operating in one of the above modes will be perfected, what then? In the first approach—"perfect" knowledge—the control of the drum is relatively straightford. The second and third modes require a control scheme for the drum. For example, with the second type of sensor, if the drum encounters rock, it is driected to lower. But how much and for how long? If it continues to lower or remains in the lowered position, appreciable amounts of uncut coal would be left because no further instructions would follow. However, it is conceivable that a programmed elevation command could be given periodically to seek the rock roof.

With the third type of sensing, where the interface to be encountered is predicted from that specific cut, control algorithms are needed. If the sensor following the cutting drum detects leftover coal, it instructs the drum to rise; if rock is encountered, the drum is commanded to move down.

Additional study of the shearer pitch control problem may allow inclusion of data obtained from hypsometry, thus achieving a hybrid system that utilizes geometry-in-the-small and geometry-in-the-large.

The final pitch control systems will probably require the use of more than one type of sensor and at more than one location. For example, a sensor system could consist of a sensitized pick and a nucleonic probe, and thus provide a system capable of keeping the drum within 2 in. of the roof and floor.

The remaining degrees-of-freedom that require control in addition to pitch control are roll about the shearer longitudinal axis and yaw about the vertical axes. The heading of the shearer and the subsequent trajectory it executes in the horizontal plane is determined by the flexible conveyor, whose "trajectory" in turn is determined by the line of chocks. Deviations in the desired shearer heading are not corrected instantaneously, but subsequently, by alignment of the individual chocks. Control is desirable since excessive roll of the shearer can cause saw-toothed cuts in the floor and roof, and thus create serious problems for chock advancement.

Conceptually, available technology can achieve both yaw and roll control. Possible solutions include external references, such as alignment to a laser beam, and basically self-contained onboard equipment ranging in complexity from a simple inclinometer to such inertial equipment as laser-ring gyroscopes and stable platforms. Since oversophistication can be costly and impractical, the solution probably lies in the development of rugged, inexpensive inertial instruments that can be realigned periodically and automatically from an external (presurveyed) reference.

†Reference to specific companies is made for information only and does not imply endorsement by the Bureau of Mines.

Acceptance requirements

If the technical requirements for teleoperated mining systems can be met, how would the system be received by coal mine operators? All other things being equal, and if technological feasibility is established, there remains the major economic hurdle.

Whether the installation of a teleoperated mining system is profitable will depend on many factors. Most items to be considered include converting an existing system to teleoperation, acquiring new system, maintaining additional equipment, personnel training, etc. To justify the adoption of a teleoperation system, its production rate must more than offset these items and its uptime ratio must be higher than those of the present systems. Among other things, this will require greater reliability and maximum maintenance.

The development of automation and teleoperation is proceedings. We do not hold it likely that the development of a "perfect" coal-interferface detector will be the pancea for automation; it will probably provide more information than can be presently utilized profitably. We do, however, believe than the solution lies in a well-balanced mixture of men and machines—with men removed from the hazardous areas of the face, but exercising real-time supervisory control over the system. Components and subsystems will be sufficient for the task, but should not be designed to a level where the system performance suffers and suboptimization takes place. All production-distribution systems produce some scrap, some orders are late, stock shortages occur and some labor occassionally will be underemployed. If none of these "wastes" occur, we are overcontrolling.

Conclusions

At the present time, we at the Bureau of Mines and at NASA's Marshall Space Flight Center are cooperating on the development of a suite of sensors and a control system that will provide intelligence to automate a double-ranging-drum shearer. We are confident that once these sensors are developed, guidance and control systems can be designed to ultimately provide a fully atuomated longwall mining system that will reduce the hazard and improve the efficiency of underground miners, recover a higher percentage of a coalbed, reduce the amount of impurities in the mined product, reduce machine maintenance and increase coal production.