NAVIGATION AND CONTROL OF CONTINUOUS MINING SYSTEMS FOR COAL MINING

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Abstract—One of the U.S. Department of Energy,[1] Pittsburgh Research Center (PRC) mine safety and health research programs is developing technology that will allow remote-controlled operation of mechanized equipment normally used in underground room-and-pillar coal mining, thereby permitting workers to be located away from the hazardous coal extraction area (the face). As part of this program, advanced machine navigation and control technologies are being developed for underground room-and-pillar and highwall coal mining that can be applied to commercially available mining equipment. These technologies use off-the-shelf components and a flexible control software architecture to minimize the effort required to adapt them to mining equipment.

An accurate reliable navigation system that can provide the mining machine's heading and location at all times is a critical requirement for a remote-controlled mining system. After much research involving several different types of navigation sensors, the Honeywell Ring Laser Gyro Inertial Navigation System was selected as showing the most promise. It has been installed on a continuous mining machine at PRC's surface test facility. This paper describes the system being employed on a mining machine while final accuracy and performance testing continues.

I. INTRODUCTION

The primary focus of PRC is to make mining safer and more healthful for miners. The PRC research program on remote-controlled coal mining involves the development of technology that will allow remote-controlled operation of all mechanized equipment normally used, while permitting workers to be located away from the hazardous coal extraction area (face). Advanced navigation and control technologies are being developed for room-and-pillar and highwall coal mining that can be applied to commercially available mining equipment. The equipment being employed is off-the-shelf, minimizing the effort required to adapt the new technology to mining situations. Since the technology is modular, only those modules required for a particular application need be applied. While there are differences between underground and highwall mining systems, basic efforts to enhance safety are much the same for both: Move the machine operators a safe distance away from areas where they are exposed

to hazards, such as roof and highwall falls, dust inhalation, and noise, and provide the operators with enough information and technology to effectively operate the machines remotely. PRC believes they have located the appropriate technology. In highwall mining systems, operators are already provided with a protected control center. In room-and-pillar situations, PRC suggests constructing a special control center, provided in the vicinity of the section power center, which in most cases will be less than 150 m from the face area. From this center all activities can be controlled and directed by the machine operators.

Although other machines are used in the mining process, only the continuous miner (CM) will be discussed here. However, PRC has also done work with roof bolters, shuttle cars, and continuous haulage systems. The CM used by PRC for testing is a 50-ton tracked vehicle which consists of a large cob-type coal cutting head and a center-mounted conveyor system. The conveyor system transports the harvested coal from under the cob cutter to the tail of the machine.

II. NAVIGATION

The most important requirement for a remote-controlled mining system is an accurate, reliable navigation system to provide the heading and location of the CM at all times. The navigation system provides information to the machine controller so that the cutting by the CM can be controlled to a predetermined mine plan. For room-and-pillar mining, entries and crosscuts can be cut to required dimensions and location. In highwall mining, a constant rib (web) can be maintained between adjacent holes.

Several different navigation devices have been evaluated[2] in an effort to identify the best one for use on CM's. After investigating the alternatives, PRC decided on the Honeywell Ring Laser Gyro (RLG) Inertial Navigation System (INS).[3] This system, previously known as the Modular Azimuth and Position System (MAPS) but now known as the Honeywell Ore Recovery and Tunneling Aid (HORTA) (fig. 1), is the best navigation device for

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[2]Different types of navigation sensors evaluated include laser ranging, ultrasonic, electronic compass, and linear potentiometers.

[3]Use of specific products is for identification only and does not imply endorsement by the Pittsburgh Research Center.
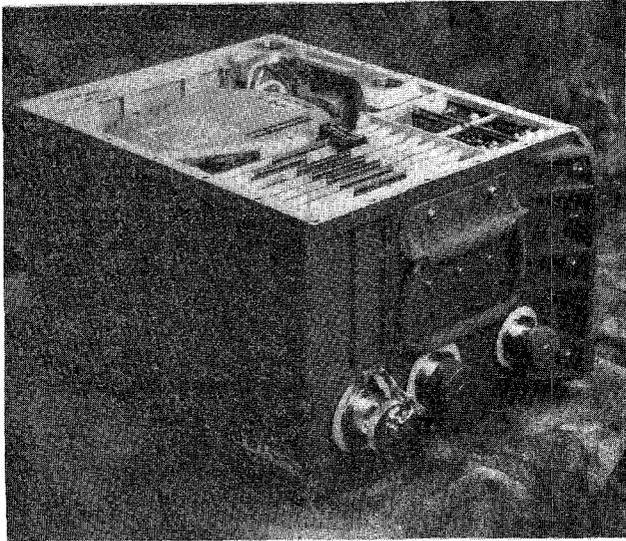

Fig. 1. Inertial navigation system.

this application known at this time. With Honeywell under contract, PRC did many hours of underground testing of the MAPS on a CM while it was cutting coal.[4] Accuracy improvements were made, and at the termination of the underground tests a complete reevaluation of the INS and its implementation into the mining machine control process was done. A list of desired improvements was prepared including increased accuracy, sharing navigation data between multiple computer systems, easier navigation data interpretation, and a simplified user interface for operating the INS. All of these improvements have been implemented in the HORTA. The navigation data provided by the INS includes three-dimensional position, attitude (heading/pitch/roll), angular rates, accelerations, and velocities.

III. INS BASICS FOR THE CM SYSTEM

The main sensing components of the INS are three gyros and three single degree-of-freedom linear accelerometers, all packaged in one box approximately 28 x 38 cm. The three gyro and accelerometer pairs are mounted orthogonally. The triad established by the accelerometers input axes is co-linear with the gyro input axes triad. The gyro (fig. 2) is a unique rate-integrating gyro in that it does not use a spinning mass. Instead it detects and measures angles by measuring the frequency difference between two contra-rotating laser beams.[5] The gyro uses two laser beams traveling simultaneously around the triangular cavity in opposite directions. Mirrors are used to reflect each beam around an enclosed path which produces a "laser-in-ring" configuration. The

resonant frequency of oscillation is a function of optical path length.

Consequently, the two laser beams have identical frequencies when the gyro is at rest. When the gyro is subjected to an angular turning rate about an axis perpendicular to the plane of the two beams, one beam sees a greater path length and the other beam sees a shorter path length.[6] The two resonant frequencies change, and the frequency difference is directly proportional to the angular turning rate.

The frequency difference is measured optically and converted to a digital output. The cumulative pulse count is thus proportional to the angular change.

The process of calculating position and velocity is based solely on the inputs from the accelerometers and the gyros. The accelerometers in the INS provide the acceleration magnitude sensing function and the gyros provide the acceleration direction sensing function (i.e., defines the direction of the accelerometer sensing axes). The basic inertial navigation concept is to integrate the sensed acceleration vector data (corrected for gravity) to determine vehicle velocity, and then integrate the velocity data to determine vehicle position.

As the INS moves (i.e., as the CM moves) it accumulates velocity errors. If they go unchecked, they can become large, rendering the CM position data invalid. To address this potential problem, a velocity error dampening mode called Zero-Velocity Update (ZUPT) is employed. By comparing the sensed velocities to the zero velocity condition, the INS can correct system errors and reset the system velocities to zero. The INS automatically performs a ZUPT when it determines that the CM has stopped, or will request a ZUPT if the ZUPT time interval has elapsed. The mining machine control system software developed by PRC, upon receipt of a ZUPT request from the INS, commands the CM to stop. Once the CM is stopped, a ZUPT will take about 3 or 4 s to complete. Upon completion of the ZUPT, the INS tells the control system software, and it continues with the previous operation.

IV. THE CONTROL SYSTEM

Continuous miner manufacturers offer radio or umbilical cord control for their mining equipment. This provides line-of-sight operation from close proximity to the machine. Rather than using a radio link, PRC developed a fieldbus-style control network (fig. 3), based on BITBUS[7] standards, that allows nonline-of-sight control of all the mining machine's moving parts.

[4]Sammarco, J. J. Field Evaluation of the Modular Azimuth and Positioning System (MAPS) for a Continuous Mining Machine. Bureau of Mines IC 9354, 1993, 14 pp.

[5]Honeywell, Military Avionics Division, St. Petersburg, FL. H-726 Modular Azimuth Position System--Technical Description 1192-12025, December 1992.

[6]Paul G. Savage, Strapdown Associates, Inc., Plymouth, MN 55441. Introduction to Strapdown Inertial Navigation Systems, Sept. 5, 1991.

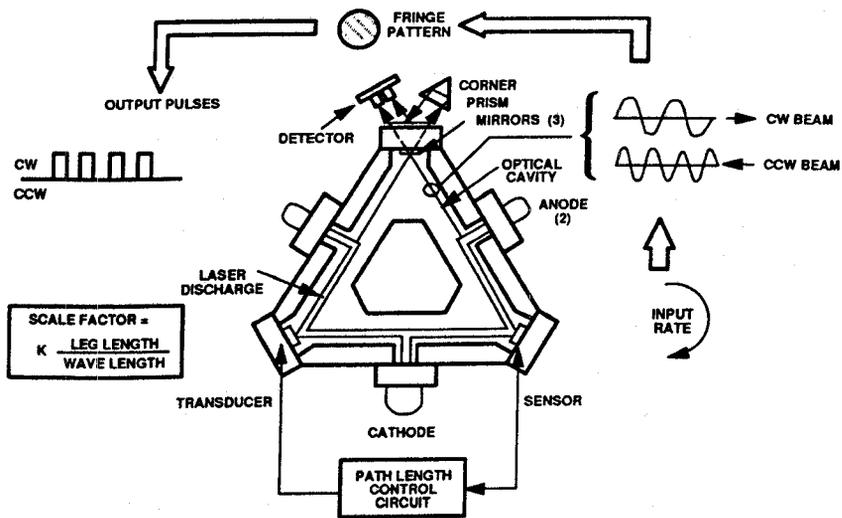[7]BITBUS is a standard developed by INTEL Corp., Beaverton, OR.
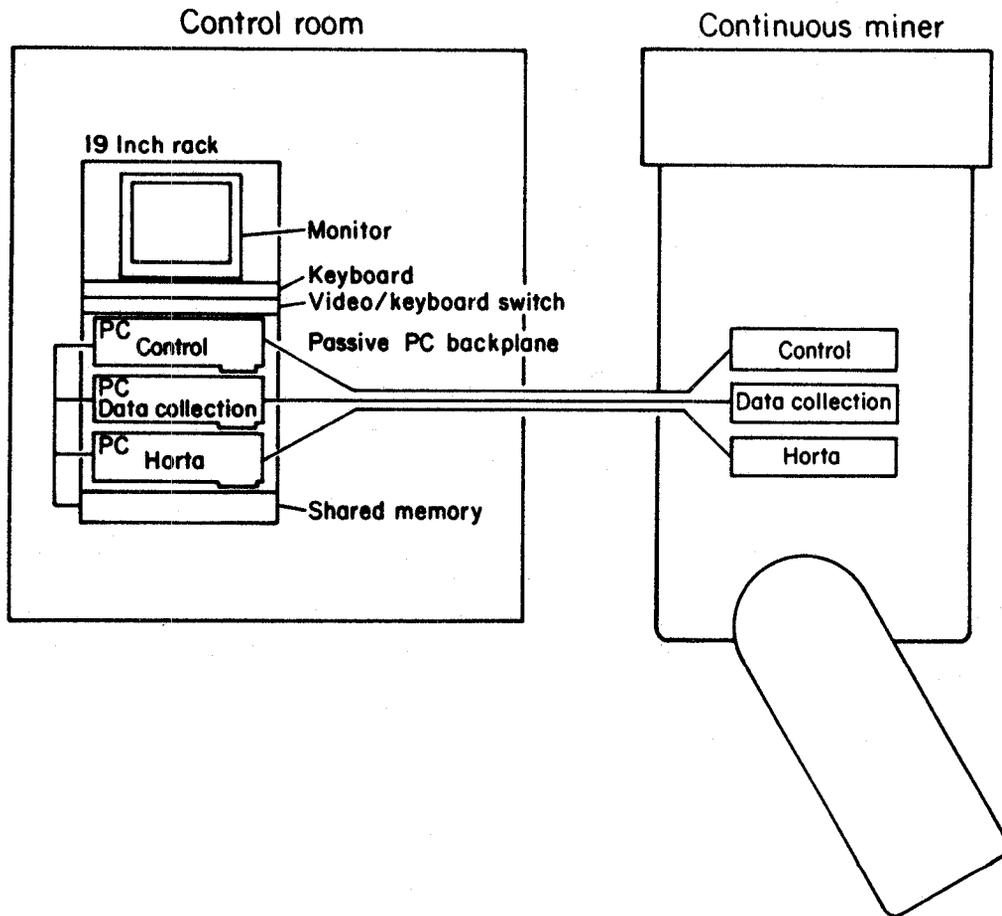
Fig. 2. Ring laser gyroscope.

Fig. 3. Control system.

The control network consists of a microcontroller board on the CM, and a single microcontroller board that resides in the 19-in rack and attaches to a PC. The two ends of the control network are connected together with a twisted-pair cable.

PRC added a second fieldbus network to provide data collection (data network) of the positions of all the controllable moving parts of the machine, as well as the status of the machine's critical parameters, such as motor currents, hydraulic pressures, and temperatures, as well as other relevant parameters. This network consists of sensors, signal conditioning modules, and a microcontroller board on the CM, and a PC-AT card which plugs into a passive backplane in the 19-in rack. The two ends of the network are connected with a twisted-pair cable. The separation of the control network from the data collection network was the best way to integrate this system to obtain the greatest performance.

The third connection between the CM and the 19-in rack is two twisted-pair cables that connect the machine-mounted INS to a PC-AT card that is plugged into a rack-mounted passive backplane. The control network, the data collection network, and the HORTA are each hosted on their own 486 class single-board PC that is mounted in a passive backplane in the 19-in rack. All three single-board PC's share a common monitor and keyboard using a video/keyboard switcher. One of the key elements of this application is the introduction of a shared-memory box and hardware that allows the single-board PC's to intercommunicate with each other through extended memory read and write.

The controller computer (PC CONTROL) is the key element for providing advanced coal mining operations. By using the data collected from all the CM sensors and the INS, and by executing commands on the CM, the controller is able to perform various coal-cutting scenarios. Scenarios now include pre-mine tests, room-and-pillar mining, and highwall mining. The pre-mine tests perform a complete evaluation of all machine functions to ensure the CM is capable of performing its mining activities. Room-and-pillar mining consists of cutting 40-ft lifts in two passes, with 90° crosscuts and using shuttle cars to load-out the coal, or cutting 60° angle crosscuts and using continuous haulage to load-out the coal. Also, a highwall scenario has been created. Testing of these scenarios to date have mostly been performed at the PRC surface test facility while cutting coalcrete (a simulated block of coal composed of cement, flyash, and coal). As this paper is being written, arrangements are being finalized with a cooperator to test all of the system being described here at the cooperator's open-pit mine. Some details are provided later in this paper.

V. AN EXPANDED CONTROL SYSTEM

Many applications can and have been added to the design of the basic control system. Each module adds another level of functionality to the system. Thus, PRC is capable of adapting their technology to the most primitive or most sophisticated application, simply by adding the modules required to suit the application. Fig. 4 shows the PRC control system's full capabilities at present.

The visualization system (VISUALIZATION) uses both collected and ongoing machine data to provide accurate 3D graphic representation of the mining machine, its past and present movements, and associated hardware relative to the mine surroundings. The visualization system user's interface permits the operator to zoom around the scene to view any part of the process he/she may be interested in. Additionally, top down and side views of the CM for present and previous cuts can be dynamically displayed.

Software called MINENAV will be developed in the future to provide navigation information to execute a complete mining plan from start to finish, using accurate navigation and sensory data.

The simulator application (SIMULATOR) developed generates a steady stream of data that corresponds to data that would normally be provided by the mining machine sensors, including the INS. This allows development and testing of the controller without engaging the massive hardware, such as the CM or haulage system.

The haulage application (HAULAGE) provides control and monitoring of the haulage system that is used in the system.

The coal interface detection application (CID) provides information about the thickness of the coal on the roof and on the floor, and can also provide information about the thickness of a rib of coal (web coal) for highwall applications.

VI. INS SYSTEM TESTS

Tests on the INS have been performed with the PRC mining system have centered on determining the accuracy of the INS and the feasibility of the control system. Some of the underground tests done in 1992 have been referenced previously in this paper. Additional tests were and are being performed at the PRC surface test facility. Each testing situation had/has performed with some limiting factor that restrained PRC's ability to fully validate the INS and the control system.

In the underground tests some of the limiting factors were:

1) The underground mine where the tests were performed was sold and closed before system improvement could be made and tested.

2) The control system and software algorithms were not mature enough to perform all of the tasks that were mentioned in the "Control System" section of this paper.
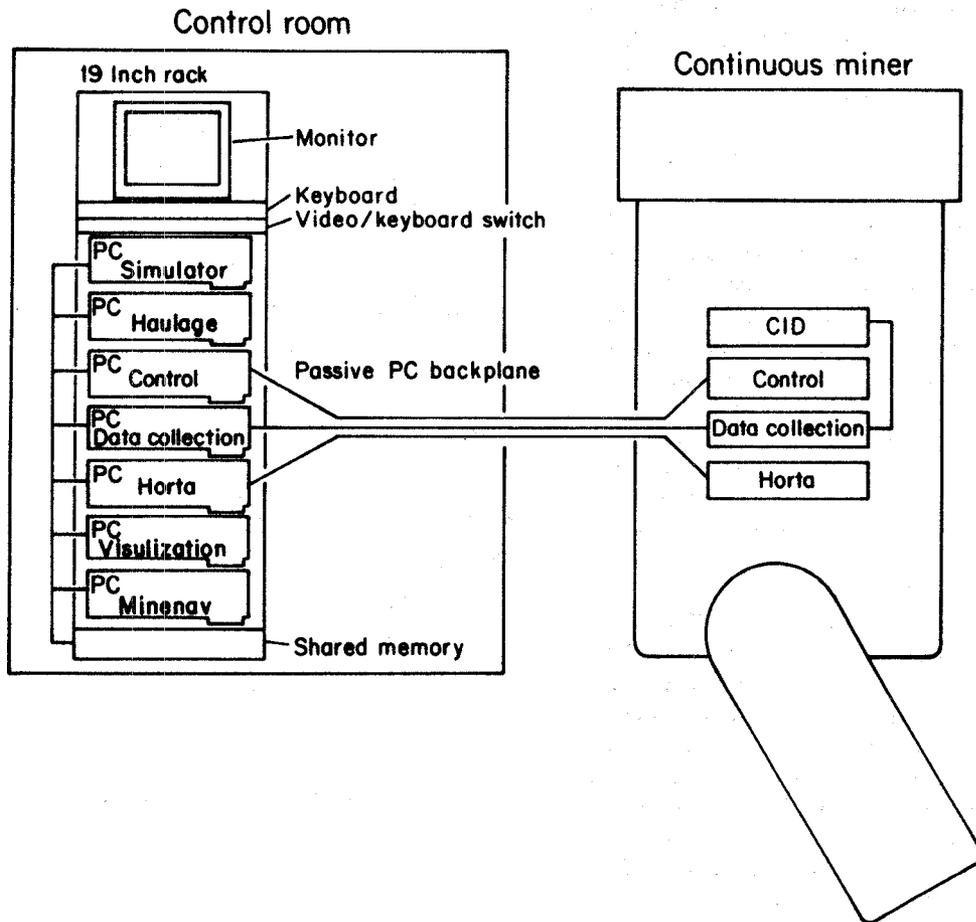
Fig. 4. Expanded control system.

3) ZUPT's were not handled by the software in the control system; therefore, inaccuracies due to velocity errors were present.

4) Geological restrictions (the basic nature of room-and-pillar mining) limited the tests that could be performed.

5) The navigation reference device (transit) being used by baseline accuracy measurements was manually operated and required a number of seconds to perform a position calculation. Since the accuracy of the INS is time-dependent, the time for transient measurements added to the inaccuracy of the INS navigation data.

In the surface test facility some of the limiting factors are:

1) A valid test should be performed while cutting coal, because the vibration of the machine while cutting coal can have a large effect on the accuracy of the data provided by the INS. The coalcrete used for testing in the surface test facility is not a very good simulation for coal. It is much harder than coal and very abrasive, which causes excessive wear to the CM. A good substitute to simulate real coal has yet to be found.

2) The test area in the surface test facility is relatively small and the amount of coalcrete available to do tests is limited.

3) A manually operated transit was used to provide the reference for INS accuracy measurements. As mentioned before, it added to the inaccuracies of the INS derived navigation data.

We realized that an open-pit mine and advanced surveying technologies could eliminate the limitations noted above. First, the open-pit site would remove the geological restrictions and expose the CM to an almost normal production situation. Second, automation of the process of verifying the position of the mining machine as it was moving would optimize the performance of the INS.

VII. THE OPEN-PIT TEST

An open-pit mine operator and PRC signed a Cooperative Research and Development Agreement in January 1996. Since then, PRC has been preparing for open-pit testing that should occur in the late summer of 1996. The second major part of the plan, to find a method of automating the process of determining

the position of the CM, was pursued. PRC found two solutions to this problem: (1) the Global Positioning System and (2) an Automated Tracking Transit. Each of these systems and how they may be used are briefly described below.

VIII. GLOBAL POSITIONING SYSTEM (GPS)

GPS is a satellite-based navigation system that was developed by the U.S. Department of Defense more than a decade ago. The full constellation of 24 satellites, including 3 spares, was finally attained in 1994, and is now fully operational. Navigation data derived from the satellites are obtained by using special receivers. GPS was introduced to surface mining (open-pit) as a navigation aid just a couple of years ago, and is now used on a daily basis at many open-pit mines.[8] The accuracy requirements of moving vehicles in an open-pit mine make it necessary to use a differential type of GPS. Differential GPS (DGPS) provides accurate position determination of moving vehicles in near real time.

The reference system on which to evaluate the INS requires accuracies of 2 to 3 cm. Also data are needed in real time, and the CM should never stop if the GPS receivers need to reinitialize themselves. To meet the requirements necessary for the INS test, a relatively new derivation of DGPS that is called Real-Time Kinematic (RTK) GPS is required. Fig. 5 shows how the system will be configured for these tests. One RTK GPS receiver (the base station) will be placed at a previously surveyed point, near the open-pit site. Another receiver will be mounted on the CM. A computer in a control hut will collect the navigation data from all points in the system using radio links. The data brought into the control hut will be used to drive real-time graphic displays and also used as a baseline reference for accuracy determination of the INS, and will be archived for future study. A list of a dozen or more vendors capable of supplying the equipment mentioned here is available from the author.

IX. AUTOMATED TRACKING TRANSIT (ATT)

An ATT is a geodetical surveying instrument that can permit hands-off surveying from a remote point. It is equipped with an automatic search/aim function, employing servo drives and a telemetric link. The object to be tracked must have a special prism mounted on it.

ATT's are a relatively new development in surveying instruments. They have been used in many applications where tracking of a moving target is required. The accuracies provided by ATT's is in the millimeter range, which more than exceeds the INS test requirements. Additionally, the vehicle being tracked does not have to stop for measurements to be made. Fig. 6 shows how the
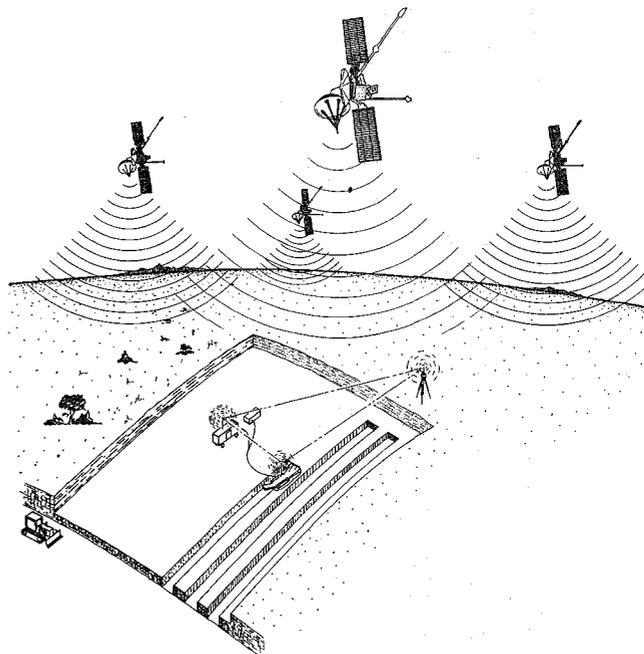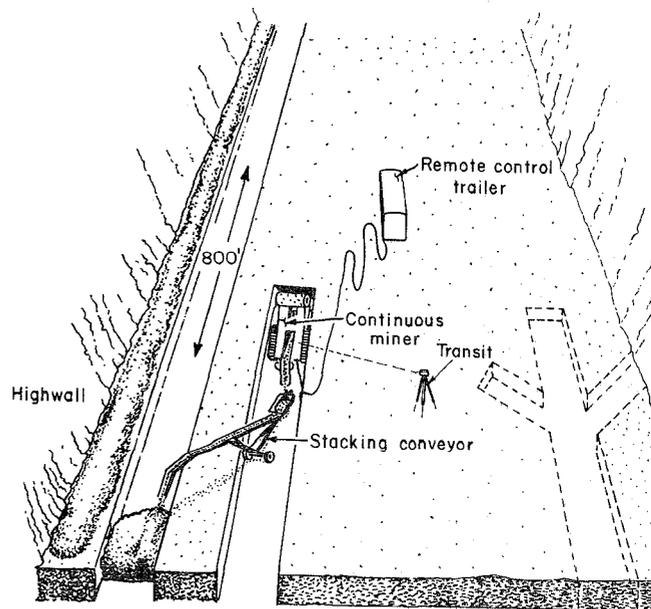
[8]Walter K. Utt, Global Positioning System Applications in Surface Mining. U.S. Bureau of Mines, Minneapolis, MN, published in the Engineering and Mining Journal, August/September 1995.

Fig. 5. Global positioning system

Fig. 6 Automated tracking transit.

system will be configured for the tests. The ATT will be placed at a previously surveyed point, near the open-pit site. A prism will be placed on the CM. Data collected by the ATT will be radioed to the control hut. In the hut the data will be used as described in the GPS example. A list of a few vendors capable of supplying the equipment mentioned here is available from the author.

At the time of writing this paper, the decision of whether to use GPS or an ATT has not yet been made. However, the decision is leaning heavily toward the ATT due to the simplicity of the system, its accuracy, and the cost to employ it. A complete critique of the pros and cons of using either system would be too lengthy to include here.

X. INS ACCURACY

Honeywell, the maker of the INS, indicates that the position accuracy is 10 to 15 cm/hr and the azimuth accuracy is 0.028°. We have obtained nearly as accurate numbers during underground testing; however, testing conditions were not optimal. At least

three other groups, presently using the Honeywell INS for mining situations, have verbally indicated that they are finding results that verify Honeywell's claims. The actual test conditions and implementation methods used to obtain these results is unknown at this time. At the conclusion of the PRC tests, all test conditions, implementation methods, and final test results will be published.

XI. SUMMARY

A PRC health and safety research program has developed technology that permits remote-controlled operation of coal mining equipment. The technology developed permits operators to effectively work at distances up to 150 m from the coal production area. The system created (hardware and software) is modular and can be assembled incrementally to satisfy the specific needs of a particular mining scenario. Much research has been done to verify the accuracy of the primary CM navigation device called the INS. Results so far with the INS have been promising. Continued, more valid, tests are planned in the very near future. Results of these tests will be made available at that time.