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Field Evaluation of the Modular Azimuth and Positioning System (MAPS) for a Continuous Mining Machine

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

°C	degree Celsius
ft	foot
ft^3	cubic foot
in	inch
lb	pound
m	meter
MHz	megahertz
min	minute
mm	millimeter
ppm	part per million
s	second
st	short ton
V dc	volt, direct current
W	watt

ACRONYMS USED IN THIS REPORT

CDU	control and display unit
DAS	data acquisition system
DRU	dynamic reference unit
MAPS	modular azimuth and positioning system
MTBF	mean time between failures
RLG	ring laser gyroscope
SDLC	synchronous data link control

FIELD EVALUATION OF THE MODULAR AZIMUTH AND POSITIONING SYSTEM (MAPS) FOR A CONTINUOUS MINING MACHINE

By John J. Sammarco[1]

ABSTRACT

This report details the testing and evaluation of a modular azimuth and positioning system (MAPS) to provide navigational information for a continuous mining machine. Vehicle navigation is part of the U.S. Bureau of Mines research program in computer-assisted mining serving as a tool to increase mining health, safety, and productivity. The Bureau is investigating other navigation systems, but MAPS seems to have the most promise.

MAPS was installed on a continuous mining machine. An operator used the machine to cut coal while researchers collected machine and MAPS data. A comparison of MAPS data for xy position and data obtained with an electronic transit showed an increasing error for MAPS. After 30 min of operation, the easting position error was −0.02 m, and the northing position error was 0.019 m; after 60 min of operation, the easting position error was −0.19 m, and the northing position error was −0.26 m. Modifications to MAPS software and to the operational procedure of the machine significantly reduced this error by a factor of 3.7. Researchers continue to reduce these errors.

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INTRODUCTION

The U.S. Bureau of Mines is continuing to research computer-assisted mining as a means of improving worker safety, especially by moving miners away from the dangerous face area. In doing so, the Bureau's Pittsburgh Research Center is investigating machine guidance and control of computer-assisted mining machines for underground and highwall mining applications (*1-3*).[2] The Bureau is researching machine guidance (*4-5*) since it is an important part of computer-assisted mining. A machine guidance system can be used to control the motion and position of the mining machine.

Considering the mining application possibilities of a land navigation system called MAPS,[3] the Bureau began testing its capability and accuracy under contract J0309018 with Honeywell Military Avionics Division, the manufacturer of MAPS. Appendix A contains the general specifications of MAPS. There were two planned phases of testing. Phase 1 involved evaluating MAPS' operation and accuracy on a Joy 14CM mining machine cutting a 20-ft lift of coal. MAPS was installed on a Joy 14CM modified by the Bureau to collect data on machine xy position, azimuth, pitch and roll, and vibration. Phase 2, now in progress, involves refinement of MAPS based on phase 1 results. All mine tests were conducted in an experimental mine section in West Virginia.

Honeywell has a 25-year record of involvement with inertial systems, including systems that employ ring laser gyroscope (RLG) technology, such as MAPS. For the last 10 years, RLG technology has been used in large-scale production of commercial aircraft, specifically the Boeing 757 and 767. RLG also has over 3,000 military applications, which include the F-15 Eagle fighter, the Army tactical missile system, and land-combat vehicles like the self-propelled Howitzer (*6*). With an aggregation of over 11 million hours of use, the RLG displays impressive mean time between failure (MTBF) data (*6*). Over the years, RLG's have established a positive history of experience and service.

The RLG is an optical gyroscope that differs from a mechanical or "iron" gyroscope in that it does not have any moving parts. Optical gyroscopes, such as the RLG, are laser-based, solid-state devices. Optical gyroscopes are small and lightweight, have low power consumption, have a fast response system level requiring less frequent system recalibration, and according to Honeywell, are very reliable in rugged environments.

ACKNOWLEDGMENTS

The author wishes to thank Timothy J. Matty, electronics technician, Pittsburgh Research Center, U.S. Bureau of Mines, and the personnel at Honeywell Military Avionics Division, St. Petersburg, FL, for testing and data analysis; Marrowbone Development Co., Naugatuck, WV, for providing a mine section for the evaluation, and, in particular, Michael Boutelle of Honeywell for his technical descriptions of MAPS incorporated into this report.

MAPS CONFIGURATION

MAPS has multiple configurations, making it adaptable to requirements of various applications. For instance, MAPS can operate with or without odometer input. In Phase 1 tests, no odometer input was used because the mining machine tracks can slip while traveling, thus giving inaccurate odometer information. Instead of odometer input, MAPS uses zero-velocity update (ZUPT). With ZUPT's, MAPS ignores the odometer signals. Instead, position errors are controlled by ZUPT's. When the system determines the machine has reached "zero velocity," a ZUPT automatically initiates and takes less than 30 s to complete error correction.

The dynamic reference unit (DRU) is the heart of the MAPS system. It contains three RLG's, three accelerometers, and a control and display unit (CDU). The CDU is a terminal that displays information to the user, and provides means to input control commands and data to the DRU since the CDU acts as a "bus master" on the DRU data bus. The CDU can be used to collect up to 50 data points. However, in Phase 1 tests, Honeywell replaced the CDU with two GRID portable computers. The computers operated with customized application software to display data types and formats most useful to Phase 1 tests. In addition, using two computers makes it possible to collect

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

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

data two ways: one computer constantly acquires data—two samples every second; the other computer gathers data at high speeds at select intervals during the tests (during the sump and shear cycle of the mining machine for Phase 1). The GRID computers can also collect data on floppy disks, far exceeding the memory capacity of the CDU. MAPS was also modified to time-stamp all recorded data with the system clock from the GRID computer. This time-stamp can be synchronized with clocks of other data-collecting devices, enabling comparison of data points used upon a single-time event.

DRU OPERATING MODES

The DRU has two operating modes. In the first mode, "**align**," the DRU **initializes** within 20 s after power goes to the unit or the DRU receives a restart command. During initialization, the DRU accepts and processes data when given the "accept position" or "accept geodetic data" command. For Phase 1 tests, the geodetic position of the DRU mounted on the mining machine was determined by a transit at mine survey mark 5895. The DRU position used during initialization was a northing of 307624.07 ft and an easting of 1622669.076 ft according to the localized West Virginia State Plane Grid Map. Once initial position coordinates are entered into the DRU, true north is determined by the DRU by "gyrocompassing." In the process of gyrocompassing, a gyroscope's spinning axis is confined to a horizontal plane such that the Earth's rotation causes the gyro to parallel itself to the Earth's axis, thus pointing to true north.

The second mode of operation is "survey." In this mode, the DRU provides position orientation and angular rate data. Two submodes exist under survey: the odometer mode and the exclusive ZUPT mode. Since mining machine tracks are prone to slip, Phase 1 tests configured the DRU without odometer input. Hence, the DRU was configured in the exclusive ZUPT mode.

DRU ELECTRICAL INTERFACES

The DRU has three connectors: J1 for electrical signals, J2 for electrical power connectors, and J3 for unit test functions. Phase 1 only deals with the J1 and J2 connectors.

Electrical power was supplied by an external Hewlett-Packard power system at 28 V dc. The DRU turns on if the steady-state voltage is 18.5 to 36.0 V dc. Once the DRU is on, steady-state voltage can be as low as 16.3 V dc. Between 16.3 and 15.0 V dc, operation of the DRU is unreliable. The DRU turns off if voltage falls to or below 15.0 V dc.

DRU data are serially transmitted on a binary coded digital data bus. The J2 connector provides access to the DRU data and the data bus. The electrical specifications of the data bus conform to the Electric Industry Association (EIA) standard RS-422, which applies to a balanced transmission line made up of two conductors. A binary value is encoded onto the line by creating a differential in voltage between the conductors. Balanced lines have the advantages of longer transmission distances up to 4,000 ft. Transmissions using electrical specifications meeting RS-422 are also less susceptible to electrical noise.

The data bus timing and data protocol conform to the normal synchronous data link control (SDLC) mode. The data link control defined in SDLC provides a reliable means to transmit data, and format standards and mechanisms for data flow and error control. The actual definition for the command and data message formats are in military specification MIL-D-70789 (AR).

DRU TEST SETUP SYSTEM

The general test setup is depicted in figure 1. The general test setup consists of a Joy 14CM mining machine modified to provide appendage sensor data for recording by the data acquisition system (DAS). The appendage actuation and position are under computer control. The mining machine is remotely controlled by an operator using a remote-control pendant. The radio control signals are also received and recorded by the DAS in the control room. The GRID computer is the primary control and display system for DRU data, and is located in a remote-control room. The GRID has been updated so that the display shows the parameters most critical, such as machine position, in real time. Operators control the DRU by using GRID personal computers (PC's).

The GRID's provide a quick data reference of the distance the mining machine moves along a given heading from a given reference point. To explain, a reference point is established at a survey mark near the beginning of an entry. "Along track" is defined as the distance along a centerline from the survey mark to the end of the entry, and "cross track" is the distance normal to either side of the centerline. Assume a survey mark established as 0 track and 0 cross track. A position at 10 ft of track and 3 ft in cross track then defines a position coordinate 10 ft down the centerline of the entry and 3 ft to the left of this centerline, both distances referenced from the survey mark. Negative values of cross track would be to the right or clockwise in reference to the centerline. This track-cross track display is helpful in evaluating the performance of the DRU in real-time.

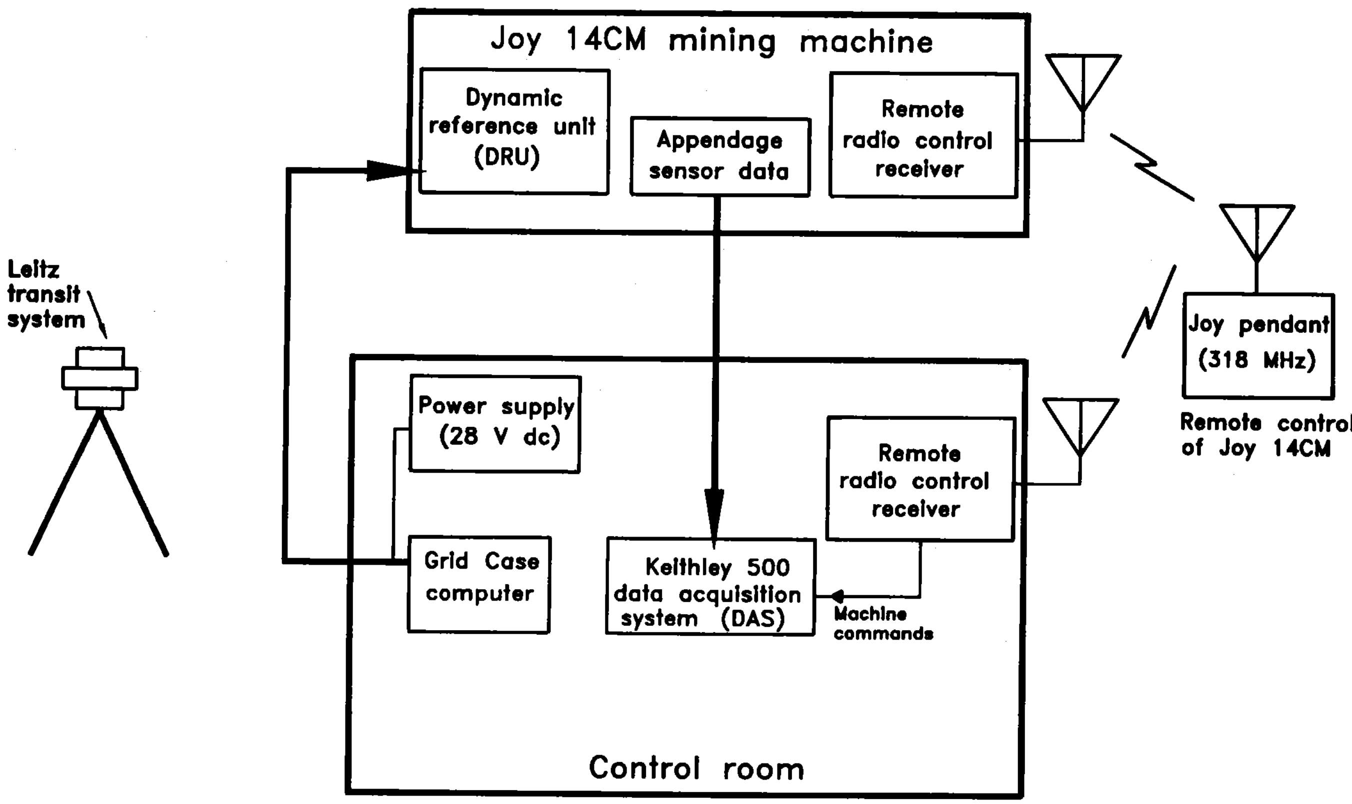

Figure 1.—General test setup.

TWO DATA ACQUISITION SYSTEMS

Phase 1 tests used two separate PC-based systems to acquire data. System 1 was configured and operated by the Bureau to acquire mining machine operation data. System 2 consisted of two GRID 386 PC's, and recorded DRU data and sent command messages to control the DRU as needed.

System 1 is a PC-based data acquisition system to collect the analog output voltage of each machine appendage sensor and the remote-control pendant radio signals that actuate the appendages and tram circuits. The main components of the Bureau's DAS are the Dolch 386 PC, the Joy radio remote-control pendant and receiver connected to the PC to obtain radio signals from the pendant, and the Keithley 500 DAS. System 1 collected all machine data and time-tagged it in synchronization with time-tagged DRU data obtained by Honeywell's GRID computers.

LEITZ TRANSIT SYSTEM

To determine the actual machine position, the Leitz Set 3 electronic transit station that automatically computes surveying information is used. The data obtained by transit are a baseline reference for the actual machine xy position and heading during Phase 1 tests. DRU data are compared to the transit reading to determine DRU accuracy. The Set 3 has an accuracy of 3 s and a range of 12,100 ft. The transit uses an infrared light beam to measure distance. Two retroreflective targets were placed at the rear of the mining machine to enable transit sighting to the machine. The accuracy of the transit for distance and coordinate determination is presented in appendix B.

TEST METHODOLOGY

Phase 1 experiments took place in a five-entry mine section in West Virginia. There, an operator used a Joy remote radio pendant to remotely control a Joy 14CM. Phase 1 tests were designed to be nonintrusive; the operator mined coal from the entries as he would in typical mining operations. Researchers collected both cutting-cycle sequence and machine-position data as the operator cut coal.

DESCRIPTION OF A MINING SEQUENCE

First, the mine operator aligns the mining machine at the face (lift 1) as seen in figure 2. Then the machine executes a "lift," as described below, at the face, removing coal from an 18-ft wide, 20-ft deep area. After completing the lift as position 1, the machine moves to lift 2 and performs another lift, cutting lifts sequentially.

Cutting a lift involves two major cuts, a "box cut" (section A), and a "slab cut" (section B) as shown in figure 2. The first cut is the box cut, in which the machine operator manually guides the machine during the operation, visually aligning a fixed point on the machine to a centerline point located at the entry. The second cut is the slab cut, where the operator repositions the machine to the other side.

ESTABLISHING ZERO VELOCITY

For accurate tests, researchers must establish "zero velocity" for the Joy 14CM. Initial zero-velocity characterizations are made when the machine's trams are not moving and when the shear is not cutting coal. These two conditions must be met at the same time. The cutting sequence provides multiple, predefined opportunities to establish zero velocity for the mining machine. Should the DRU detect any motion over a preset level defined as a zero velocity, it would terminate the ZUPT's. Zero velocity can be set at different levels so the DRU ignores insignificant movements. In the Bureau's tests, it is not desirable to take ZUPT readings during sumping or cutting since the machine moves during these operations: The machine trams forward to do a sump, and test data show slight position movements during cutting. Taking ZUPT's during these operations will cause erroneous MAPS data.

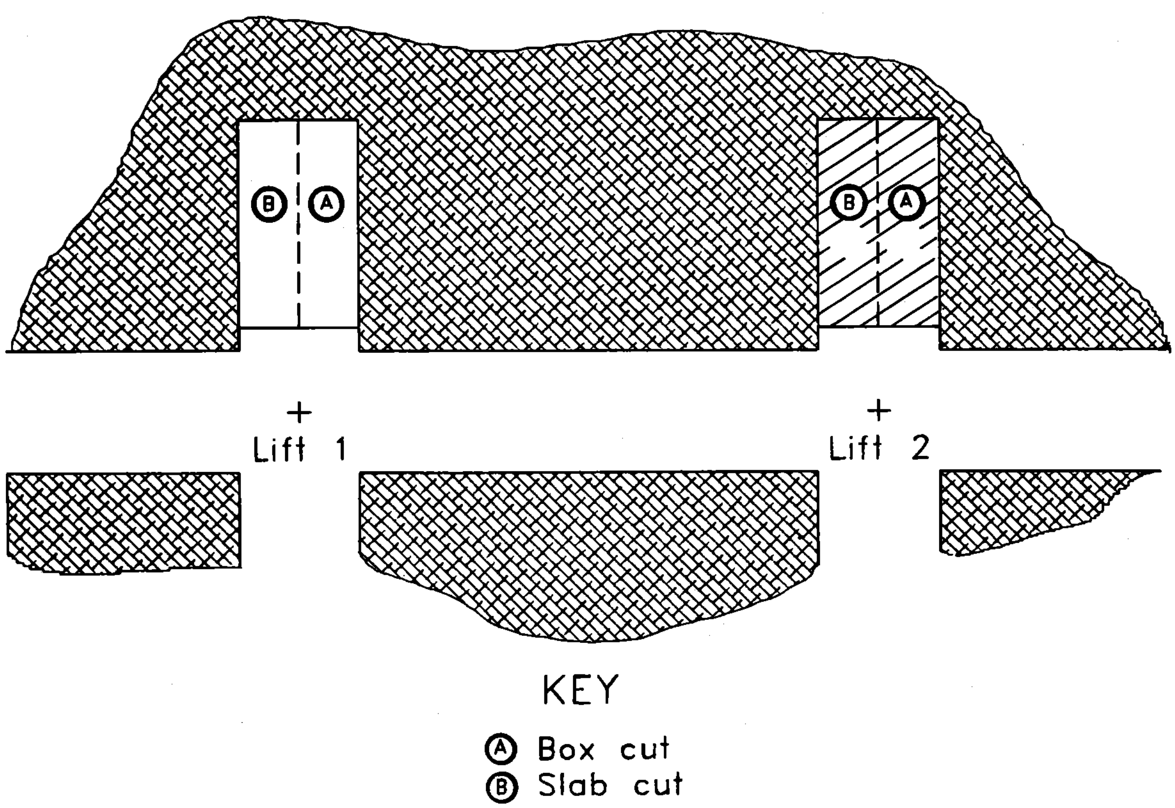

Figure 2.—Lift containing box and slab cuts.

DRU TEST RESULTS

With a system of this type, the error sources are generally not distinct. Certain types of errors, such as software coding errors, may have an effect only under certain conditions. Typically, error sources are always present but are more dominant under certain conditions. The discussion below documents the error sources found during Phase 1. While only one source of error is discussed on a given graph, other error sources may also be active. A given graph addresses only that error best characterized by the given conditions.

The transit expresses the xy position of the mining machine by east and north axis data as referenced to the West Virginia State Plane Grid Map. The transit data are the baseline reference for the machine position. Figure 3 is the delta plot between DRU and transit data. A delta of 0 indicates that DRU and transit data are equal. The data plot shows the transit and DRU tracking together until about 34 min. Thereafter, the delta values become significant. The maximum north axis delta was −43.95 cm at 77.9 min, while the maximum east axis delta was −54 cm at 79 min.

Figure 4 shows one of the significant sources of error during the demonstration. It shows approximately a 2-min period during which the continuous mining machine was stopped several times for 2 to 3 s. The plots have been annotated with circles indicating three points during this time period with such a stop occurring. If any of the stops had been increased to 6 s, the DRU would have collected sufficient data for a ZUPT, thus improving system accuracy.

Data analysis indicates the system is abnormally sensitive to vibration, thus preventing ZUPT's at various times. This vibration, normal for the operation of the machine, should not have been high enough to prevent a ZUPT, thus contributing to the observed position errors. The vibration sensitivity was attributed to a software error and is probably the single largest source of position error during the demonstration. The software determines when a ZUPT can be taken. ZUPT activity can be monitored by observing "COUNT." Each time data are acquired for a ZUPT, COUNT increases by one. Analysis of the data showed that, in cases of high machine vibration, the software did not allow a ZUPT when it was acceptable to do so.

The errors due to vibration sensitivity are also generally evident in figure 5. During the elapsed time period from 0 to 35 min, the mining machine was experiencing relatively low levels of vibration since only about 75% of the cutting head was in contact with the coal face. In the remaining time period from 35 to 90 min, the cutting head was in full contact with the coal face. High levels of vibration were experienced. One could see the machine "bouncing" during sump and shear operations.

Other programs within Honeywell documented vibration sensitivity, thus reinforcing conclusions of abnormal

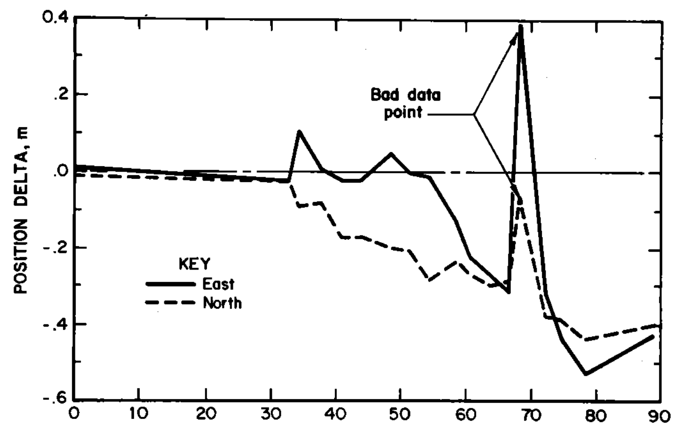

Figure 3.—Position deltas for east and north axes.

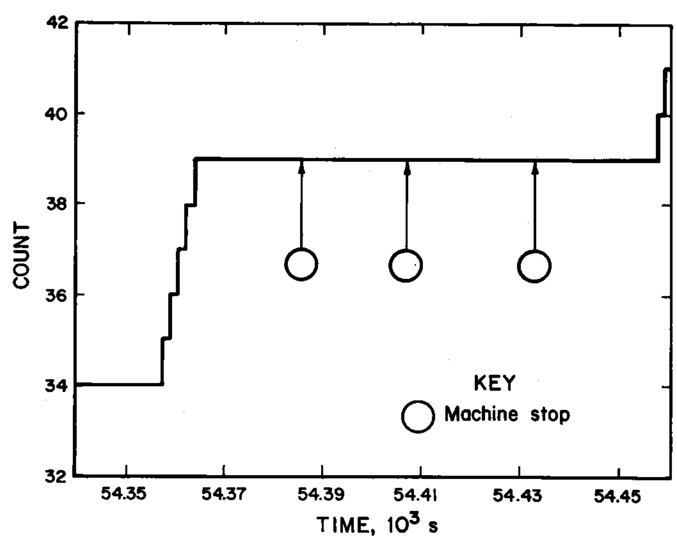

Figure 4.—Count versus time for machine file M22L3.

vibration sensitivity. Around the same time as Phase 1 data analysis of this project, the U.S. Army was testing MAPS under controlled vibration conditions. The vibration test failed, and an internal team of investigators sought the cause of the problem. They identified and corrected the MAPS software to change the way vibrational data are used. The software used for the Bureau's demonstration is identical to the software originally used by the U.S. Army; therefore, a verified solution exists.

System vibration can also cause errors in taking ZUPT data during the mining machine's sump and cutting actions. ZUPT data should not be taken during sump since the machine advances forward half the cutting drum's diameter, about 22 in. Advancing 22 in during a sump occurs at a very slow rate; hence, the DRU must be able to recognize this and not take ZUPT data (no increment in COUNT). Test results show that no data for ZUPT were taken during sump actions since the machine's position changes during sumps. In addition, no data should be taken during the cutting action since the machine experiences minor translations that would accumulate as position errors if data were taken. Figure 6 depicts the status of COUNT during the sump and cutting actions. The position of the shear is shown on the graph along with annotations for the sump and shear actions. Note that COUNT does not increment during the sump or the cutting; hence, no ZUPT data were acquired.

Careful comparison of COUNT shows a minor, correctable source of error; the mining machine had not been stopped for 5 s when COUNT was incremented. Thus, velocity data containing motion were contained within calculations for ZUPT. This was due to a minor software logic error within the ZUPT control portion of the code that failed to reset a timer used in determining when the vehicle has been stopped long enough to warrant a ZUPT. This error was then corrected.

The manual operation of the mining machine was analyzed to be somewhat erratic and nonrepeatable. The operator does not control the machine to a repeatable, set pattern. An overall sequence of sump and shears may take place but each action contains minor deviations. MAPS accuracy would improve if a set pattern of machine operations was established.

Other Bureau projects in computer-assisted mining involve using a computerized script of cutting actions. Such a cutting cycle was submitted to Honeywell for evaluation (fig. 7). Phase 2 tests successfully used this cutting cycle to help improve MAPS accuracy.

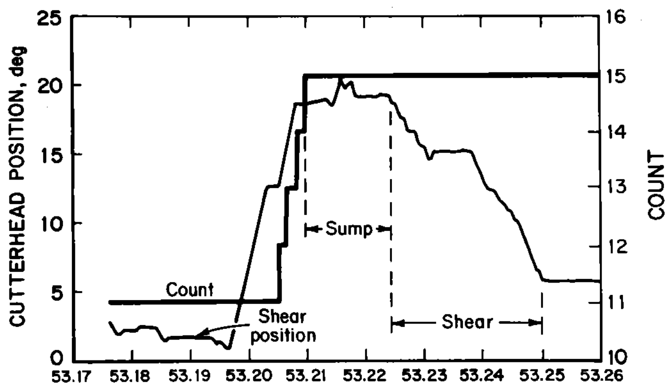

Figure 6.—ZUPT data during sump and shear.

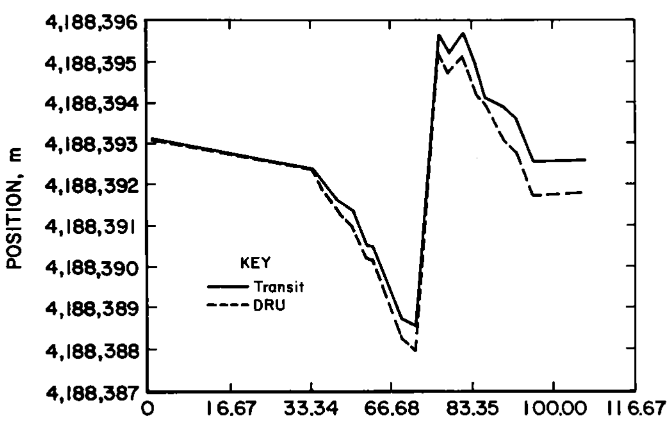

Figure 5.—North-axis position versus elapsed time.

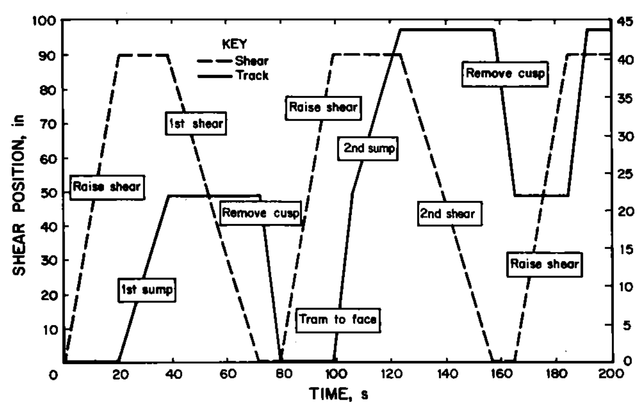

Figure 7.—Computer-controlled cutting cycle.

ENTRY PROFILE TEST RESULTS

Profile tests show the potential amount of coal that could be mined if machine operators know the exact machine position, and if operators control the machine to cut the lift precisely at a width of 20 ft. A navigation system for computer-assisted mining is important because with proper machine position data, as obtained from MAPS, an operator could use computers to control the continuous miner accurately, thus achieving the precise geometry of a cut. Of course, productivity is secondary to health and safety benefits, which a navigation system also achieves. The more accurate a navigation system, the more miners can depend on remote guidance of a mining machine, and the less exposure they will have to the dangerous face area. Profile tests are of interest to researchers to evaluate how well manual operation can guide a machine. This provides a relative comparison for the accuracies of MAPS positioning data.

The entry profile tests for entries 1 and 2 gave researchers data to calculate the amount of raw coal removed. The test profile data were imported to AutoCad software, which calculated the theoretical volume of coal removed for a 20-ft-deep entry. Table 1 compares actual and theoretical amounts of coal removed for entries 1 and 2, and shows the actual short tons of coal not removed based on coal density of 104 st/ft^3.

Table 1 shows that in entry 1 there is a difference of 16.1 st between the theoretical value and actual value of removed coal. In entry 2 the difference is 12.2 st. The profile of entry 1 is shown in figure 8.

Table 1.—Comparison of actual coal removed and theoretical maximum volume of coal removal from entries 1 and 2

	Entry 1	Entry 2
Actual coal removed:		
Volume . . . . ft^3 . .	4,239.6	4,304.6
Weight . . . . st . .	202.5	223.8
Theoretical coal available:		
Volume . . . . ft^3 . .	4,549.3	236.6
Weight . . . . st . .	4,539.0	236.0
Coal not removed . . . . st . .	16.1	12.2

PHASE 2

As mentioned earlier, Phase 1 tests were to assess the feasibility of MAPS for determining the position and heading data for a continuous miner. Results of Phase 1 tests warrant further investigation to arrive at more competent conclusions. The DRU's accuracy proved less than desirable, and Honeywell identified many sources of error. However, there are immediate solutions to these errors as well as improvements for the test setup to increase accuracy. The following items for Phase 2 testing were incorporated to improve DRU accuracy.

- Use computer control to give sufficient time for ZUPT's and to control the machine's movement so that the time between ZUPT's is less than 1 min. Using the Bureau-developed computer-assisted control of a Joy 14CM during a cutting cycle (fig. 8), the machine operations are predictable and repeatable. This contrasts with the erratic, nonrepeatable set of machine operations resulting from manual control used in Phase 1. As Phase 1 test results prove, manual control is detrimental to DRU accuracy since irregular machine movements can prevent necessary ZUPT's. A computer-controlled cut cycle provides sufficient time to complete a ZUPT, while prohibiting excessive time elapses between ZUPT's.
- Modify the DRU baseline software to address vibration sensitivity and software logic problems. Then, using the computer-controlled cutting cycle, run tests with the DRU mounted on the Joy 14CM.
- Analyze the DRU software under high-vibration environments at Honeywell prior to any field testing.

Phase 2 tests were run using the computer-controlled cutting cycle. Analysis of the data shows that the accuracy has improved by a factor of 3.7 as compared with Phase 1 results. Figure 9 depicts the northing and easting errors as compared with transit data. This corresponds to the errors as depicted in figure 6 for Phase 1 tests. The

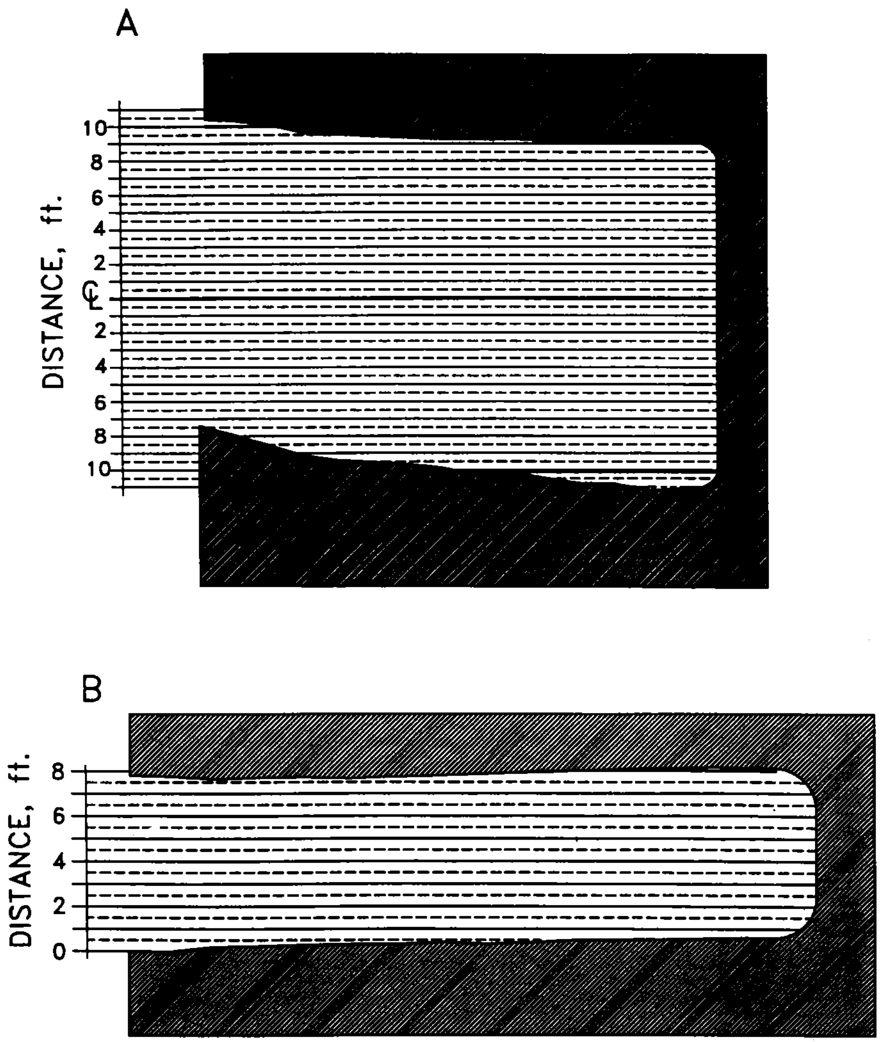

Figure 8.—Entry 1 profile. A, Top view; B, side view.

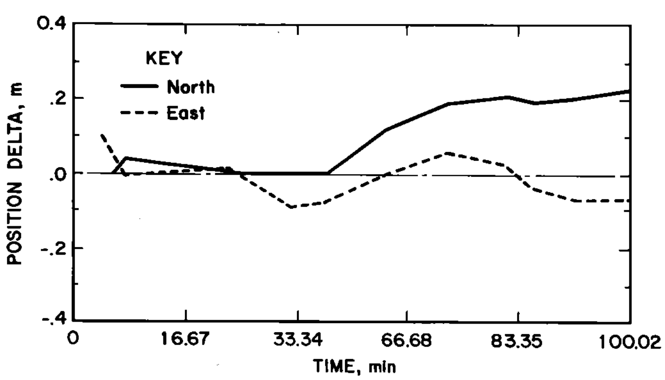

Figure 9.—Phase 2 northing and easting errors.

northing and easting positions can be translated to along track and cross track. Figure 10 depicts these errors with respect to measurements made by the transit.

Machine heading information from the DRU was compared with data from the transit. Figure 11 depicts the heading errors based on transit data. As Phase 2 progresses, other data from the DRU such as pitch and roll will be analyzed. Phase 2 refinements will continue in order to improve MAPS's accuracy for mining applications.

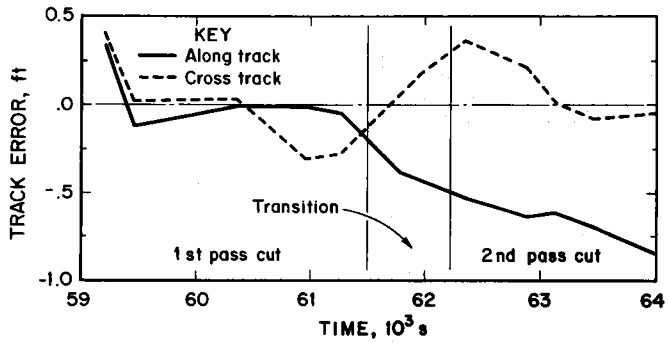

Figure 10.—Phase 2 along track and cross track errors.

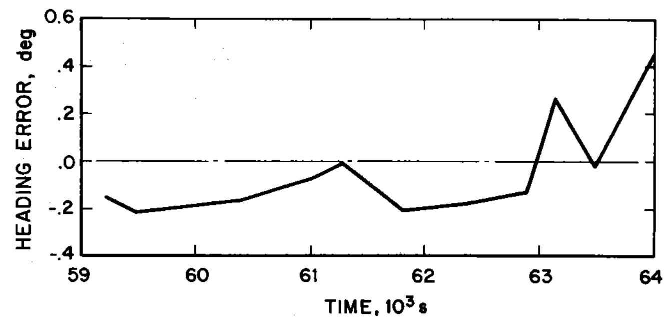

Figure 11.—Phase 2 heading (azimuth) errors.

FUTURE WORK

Phase 2 testing has led to a deeper understanding of DRU operation and has given weight to operational modifications that will facilitate future tests and accommodate other applications. As a result of Phase 1 and Phase 2 work with Honeywell, the basic application of a DRU to mining equipment has proved to be feasible. Thus, the Bureau will initiate a purchase of a DRU, modified with software from Phases 1 and 2. This Bureau-owned DRU will be used to support continuing work in computer-assisted mining and will also serve as the navigation system for research into other applications such as highwall mining. The entire MAPS system is not needed since the Bureau's existing computer system can be used with the DRU.

Specific areas of modification for DRU software have been identified. Modifications and subsequent testing have been designated for a Phase 3. These software modifications have been divided into two groups—those that facilitate the operation of the DRU and those that will enhance the DRU's accuracy.

CONCLUSIONS

The first phase of the program was to determine the general feasibility of using MAPS for mining machine navigation. MAPS was deemed feasible to use for mining, but certain performance problems have been identified that can be corrected by software modifications. The first problem is that the time between the continuous mining machine's stops necessary to perform ZUPT's exceeded 1 min; a ZUPT should occur at least once every minute. The Bureau's solution was a computer-assisted mining sequence that includes sufficient time for ZUPT's.

Second was the problem of vibration sensitivity, which according to Honeywell, occurs in other programs using MAPS baseline software as well. The solution by a Honeywell research team was a minor change to the software. The third problem deals with the erroneous data collections for ZUPT's. This was solved by a minor logic change in the DRU software.

Since the identified errors have workable solutions, the basic operating characteristics and basic philosophy of using the system as a self-contained, inertial land navigation unit merits more investigation. Phase 2 tests, which encompass the detailed recommendations presented in this report along with the proper software modifications, are now in progress. The first test under Phase 2 has yielded an accuracy improvement by a factor of 3.7 as compared to Phase 1 results. Phase 2 will continue to reduce positional errors.

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APPENDIX A.—MAPS GENERAL SPECIFICATIONS

Physical:

Size:	8.7 by 10.75 by 15 in
Weight:	45 lb nominal
Power:	100 W nominal from power-on to shutdown at 24 V dc supply
Input voltage:	18.5 to 36 V dc

Environments:

Temperature:	−46° to 60° C
Vibration:	track vehicles
Shock:	Howitzer gunfire

Full water immersion
Radiation hardened

Communications interface:

RS422
1553B (optional)

APPENDIX B.—LEITZ SET 3 TRANSIT ACCURACY

The Leitz Set 3 transit system electronically measures angles and distances by using an infrared light beam. The transmitted light beam reflects off the target and is received by the system, which calculates the distance to the target. Angle measurements employ an increment-coded glass circle. A diode light transmission passes through the glass, and a photo diode on the other side detects how many increments pass by.

The basic specifications of the transit system, as supplied by the manufacturer, are as follows.

Specifications	*Set 3*
Angle accuracy	±3"
Minimum angle display ..	1"/5"
Maximum distance	12,100 ft
EDM accuracy	±(5 mm + 3 ppm)

Since the transit is the baseline reference to which the DRU is judged, it is important to discuss the sources of errors. Leitz provides detailed discussion of error sources and error budgets. Atmospheric condition errors can be arithmetically corrected by entering temperature and barometric pressure. Other sources of error are internally compensated by the transit system. Refer to figure B-1 for the calculations to determine distance accuracy and coordinate accuracy.

Distance Accuracy: ±[5 mm + (3 ppm × distance)].

Example: Let distance (d) = 30 ft.

Accuracy = ±{0.01625 ft + (3×10^{-6} × 30 ft)}.

Accuracy = ±(0.6134 ft)
or Accuracy = ±0.545% of reading at 30 ft.

Coordinate Accuracy

COORDINATE POINT Y_A:

Let Y coordinate error = E_{Y_A}
Let distance d = 30 ft.

E_{Y_A} = ±5 mm + (3 ppm × distance).
E_{Y_A} = ±(0.6134 ft).

COORDINATE POINT X_A:

Let X coordinate error = E_{X_A}
Given: Angle accuracy = 3" = 0.0008333°.
Let horizontal distance = 10 ft.

E_{X_A} = horizotnal distance × tan (angle accuracy).
E_{X_A} = 10 ft × tan (3").
E_{X_A} = 10 ft (0.0000145).
E_{X_A} = ±0.000145 ft.

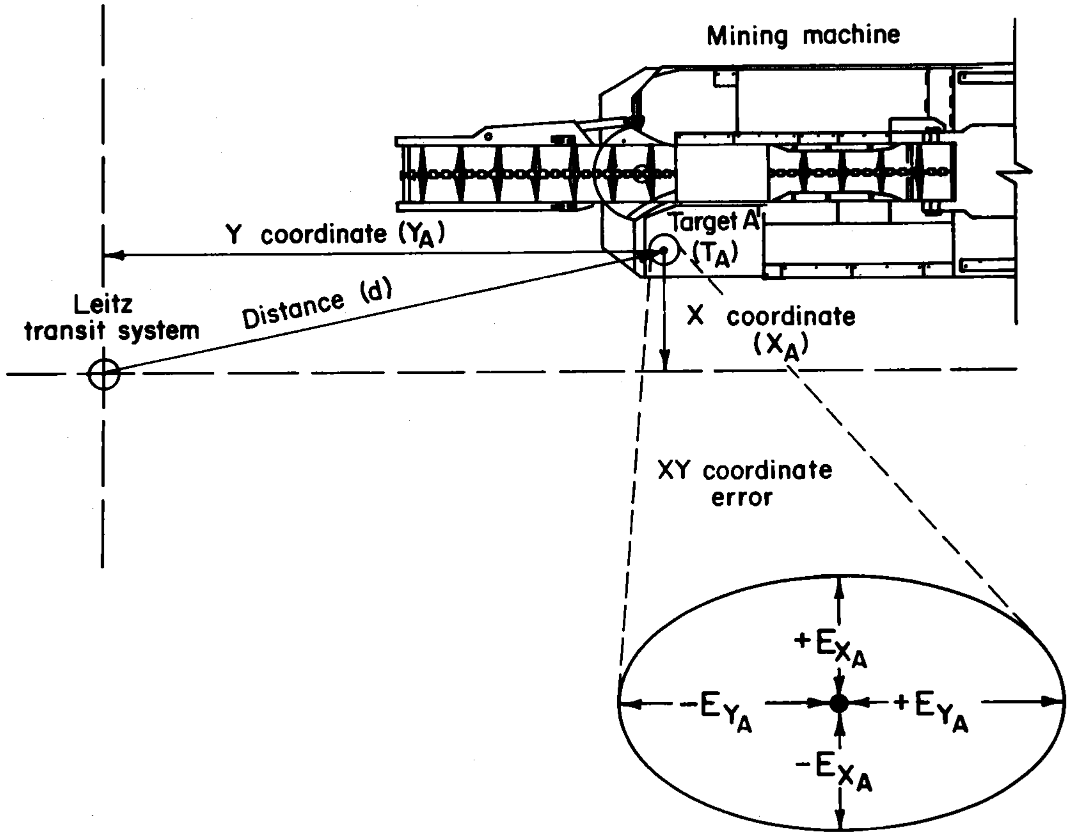

Figure B-1.—Transit xy coordinate errors.

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*U.S.G.P.O.: 1993--709/008/80019