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Utilizing Mechanical Linear Transducers for the Determination of a Mining Machine's Position and Heading: Underground Testing

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

a	ampere	mm	millimeter
A·h	ampere hour	mV	millivolt
deg	degree	mV/(V/in)	millivolt per volt per inch
ft	foot	oz	ounce
h	hour	pct	percent
Hz	hertz	rad	radian
in	inch	s	second
m	meter	V	volt
mA	milliampere	V dc	volt, direct current
min	minute	V/in	volt per inch

UTILIZING MECHANICAL LINEAR TRANSDUCERS FOR THE DETERMINATION OF A MINING MACHINE'S POSITION AND HEADING: UNDERGROUND TESTING

By Christopher C. Jobes[1] and Timothy J. Lutz[1]

ABSTRACT

Computer-assisted control of a mining machine can place the operator in a safe, remote location. A guidance system aids remote positioning of a mining machine by determining its position and heading. The mechanical position and heading system (MPHS) is one of several guidance systems being developed at the U.S. Bureau of Mines. The MPHS uses linear position transducers (LPT's) to provide navigation information during face maneuvers. This report presents an overview of the MPHS theory and implementation, including recent design modifications made for more successful underground testing. This report also presents the experimental setup and procedure for the underground test. The test showed that the MPHS provides reliable and accurate results and can, therefore, provide useful guidance information for face navigation.

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INTRODUCTION

Computer-assisted control of a mining machine can place the operator in a safe, remote location, thus reducing health and safety risks. An important requirement of computer-aided control of face operations under current continuous mining practices is the use of a guidance system.[2] Mobile mining equipment must be able to navigate when operating in the face area of an entry or crosscut. Continuous mining machines and roof bolters typify the types of equipment that perform such face navigation.[3] Sensing systems that provide machine position (X-Y coordinate) and heading (yaw) aid the operator in remote machine positioning. As part of its health, safety, and mining technology program, the U.S. Bureau of Mines has developed one such sensing system, the MPHS.

The MPHS was thoroughly tested aboveground at the Bureau's mining equipment test facility. Underground testing exposed some problems in the mechanical design of the MPHS. The MPHS was again tested underground after making the required engineering modifications. It is this second version of the MPHS that is presented in this report.

THEORY

The MPHS theory development was divided into three parts. The first step was to characterize the sensors used and their configuration. The next step was to select and define the navigation reference frames. The last step was to derive a closed-form solution to determine the position and heading from sensor information.

Sensors

Choosing the sensors and their measurement configuration required some thought. The constraints placed on a measurement system by the environment at the face severely limited the effectiveness of a rigid articulated link. Thus, angle measuring sensors were not appropriate. In order for distance-measuring tasks to perform the required task, they must be configurable as a six-degree-of-freedom mechanism. Thus, the logical sensor was an LPT (fig. 1) or wire pull. The LPT can measure fairly long distances, has an infinite degree of freedom, and is compliant enough to survive most contacts with obstructions.

[2]Schnakenberg, G. H., Jr. Computer-Assisted Continuous Coal Mining System—Research Program Overview. BuMines IC 9227, 1989, 15 pp.

[3]Anderson, D. L. Framework for Autonomous Navigation of a Continuous Mining Machine: Face Navigation. BuMines IC 9214, 1989, 23 pp.

Although three LPT's could yield position and heading, four LPT's provided redundancy for reliability. Any nondegenerate configuration of four LPT's allowed calculation of the position and heading. The selected configuration, however, affected the computation method and degree of required effort. Positioning the LPT's so that each mounting location and all wire attachment points were different resulted in a set of nonlinear transcendental equations.[4] These equations required an iterative solution. Configuring the LPT's by pairing their locations and attachment points (fig. 2) yielded a simple closed-form solution.

Navigation Reference Frame

Position and heading are crucial when navigating a mining machine. To derive the position and heading of a mining machine, one must know the attachment points on the mining machine, the transducer mount locations in the mine entry, and their relationship to each other. Attaching a machine reference frame (fig. 3) to the mining machine defined the location of points on the mining machine. Fixing a local reference frame to a stationary point behind the mining machine defined the location of points in the entry. By using standard, coordinate transformation techniques, it is possible to describe any point on the mining machine in the local reference frame. Knowing the location of the LPT mounts and attachment points makes it possible to describe the mining machine's position and heading.

[4]Jobes, C. C. Utilizing Mechanical Linear Transducers for the Determination of a Mining Machine's Position and Heading: The Concept. BuMines IC 9254, 1990, 16 pp.

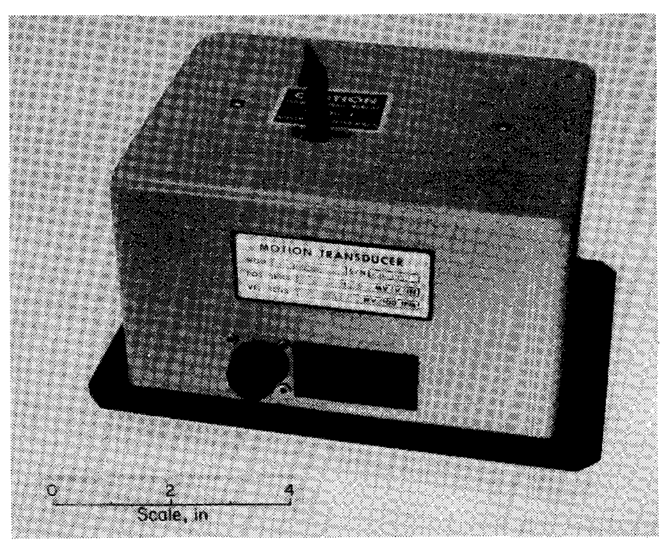

Figure 1.—LPT.

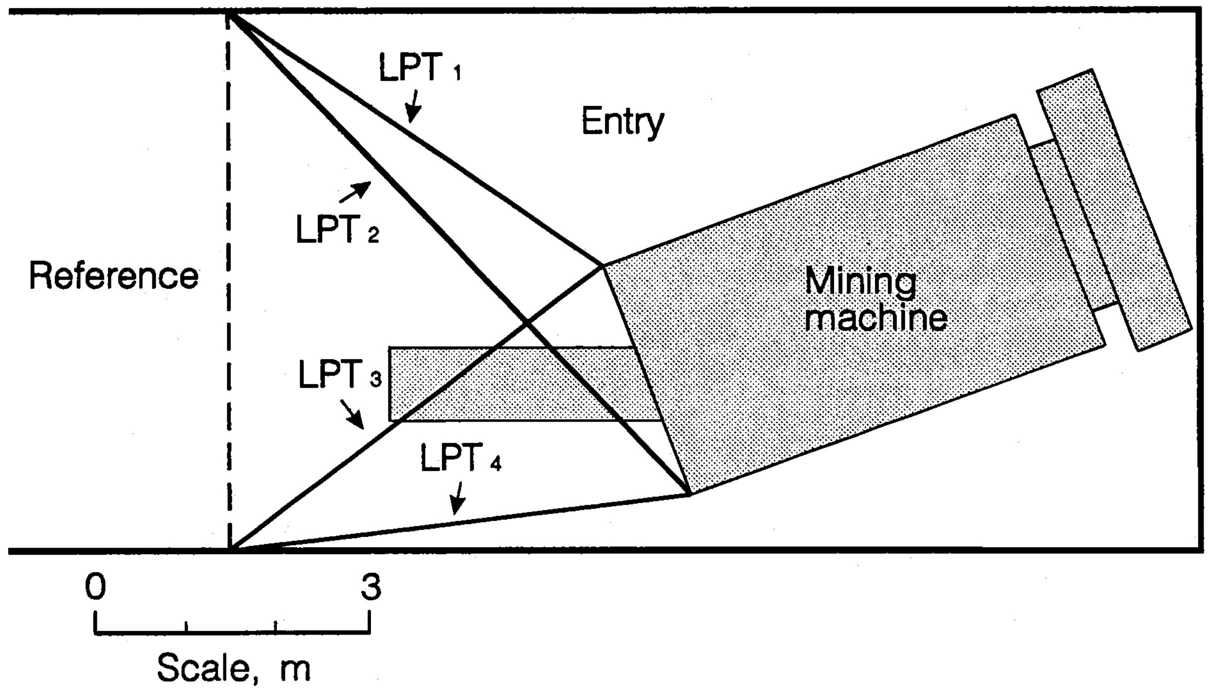

Figure 2.—Directly solvable, redundant four-transducer configuration.

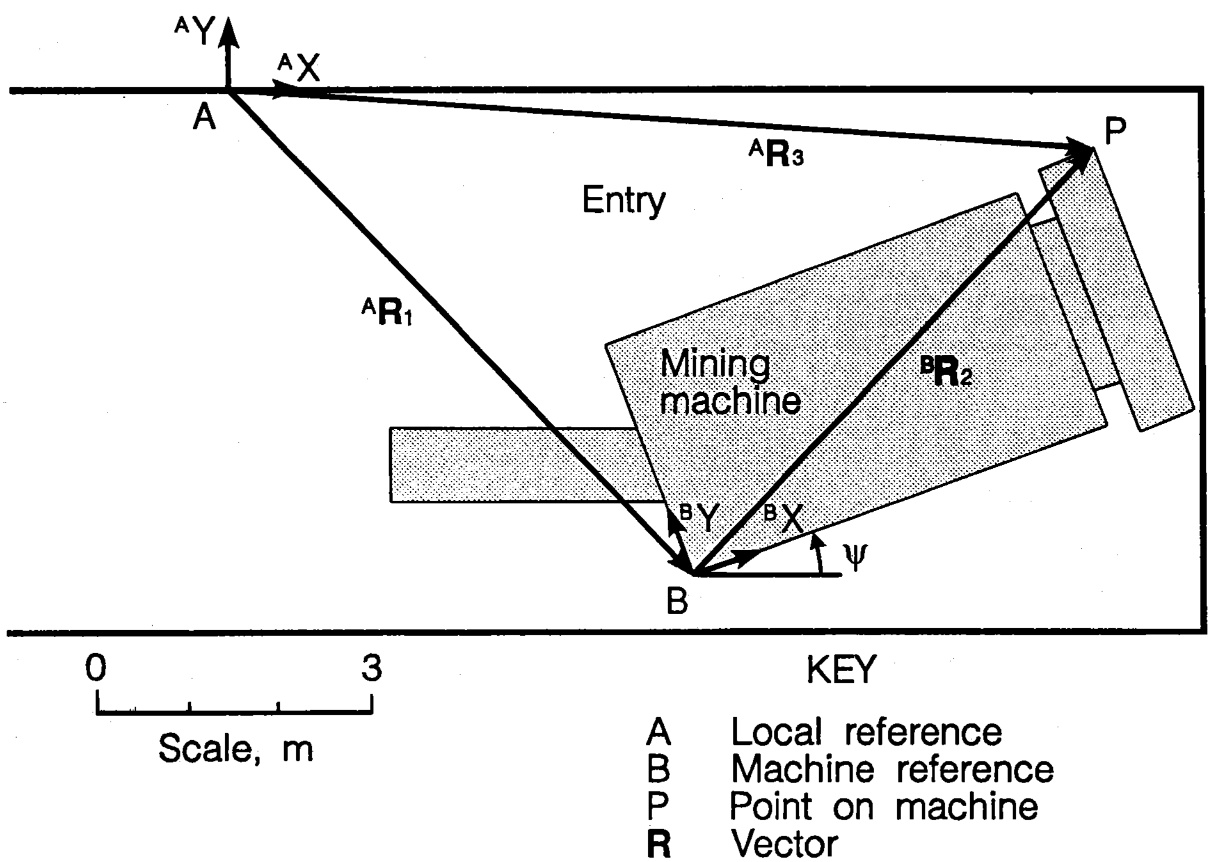

Figure 3.—Local and machine reference frames and position vectors.

Closed-Form Solution

A closed-form solution made calculating the position and heading easier than an iterative method.[5] (See work cited in footnotes 4 and 5 for a more detailed treatment of the closed-form solution derivation.) The solution process first included configuring the LPT's and defining all position vectors of interest. Second, applying coordinate transformation analysis of planar mechanisms to this configuration determined four pairs of three-transducer solutions. Finally, intermediate results yielded a four-transducer solution.

IMPLEMENTATION

Applying the MPHS theory required the development of hardware, software, and system interfaces. (See work cited in footnote 5 for a more detailed discussion of this topic.)

Hardware

The configuration for the MPHS measurement hardware consists of mounts, LPT's, cabling, a computer enclosure, and a data collection computer.

Mounts

The MPHS assembly shown in figure 4 is an exploded view of a portion of the MPHS measurement hardware. Items 1 through 4 are attached to the mining machine and items 5 through 10 are located in the mine entry. Two of these assemblies compose the MPHS measurement hardware.

The polycarbonate dome (item 1) allows the LPT wires (item 10) to cross over one another during a crosscut operation. The slotted opening allows the LPT wires to connect to the snap ring (item 2) encircling the dome-LPT wire attachment post (item 3). The machine mount (item 4) is height adjustable to keep the LPT wires close to the mine roof to avoid interference from other mining equipment. The machine-mounted portion of the assembly is referred to as the attachment post (fig. 5).

The adjustable post (item 8 of figure 4) supports the LPT mounts and is secured tightly against the mine roof. The U-bolts (item 9) connect the LPT mount (item 7) to the adjustable post. The LPT mount supports the LPT's (item 6) and the rollers (item 5). The rollers ensure that the LPT wires (item 10) exit the LPT's straight and keep the minimum bend radius to 44.5 mm (1.75 in). The portion of the assembly located in the entry is referred to as the LPT mount (fig. 6). From each LPT mount, one wire attaches to the left attachment post and the other wire to the right.

The described mount arrangement differs from the version presented in the previous aboveground tests[6] in several important ways. First, the LPT's are no longer located on the mining machine, but on stationary posts. This change enhanced the LPT's survivability by reducing the likelihood of the LPT mounts hitting the mine roof, being bent over by the conveyor, or run over by the shuttle car. Second, the LPT wires no longer pass over a small radius pulley and slide over a rounded metal lip. Fatigue failures previously experienced in the wires were eliminated by using the new configuration with the large radius pullies. Finally, the computer enclosure is no longer onboard the mining machine since the LPT's are under supported roof.

Linear Position Transducers

Each Rayelco[7] P-750A LPT has a housing; a constant force, spring-driven takeup drum; 19.05 m (750 in) of wire; a gear reducer; and a 500-ohm potentiometer. The potentiometer wiper resistance is proportional to the length of wire played off the takeup drum. By placing an excitation voltage across the potentiometer's resistor, this resistance is converted into an output voltage at the wiper.

Cabling

The LPT circuits are intrinsically safe (IS). Thus, riser-flame-tested, three-pair shielded cable with standard 97 series connectors was permissible. The LPT cables linked the LPT's to the computer enclosure (fig. 7). The LPT and communications cables enter the computer enclosure through five explosion-proof (X/P) packing glands. A Line Power 30-3301-25 X/P connector joined the user interface connector (UIC) cable to the BITBUS communication cable from the data collection computer in the control room. A 19.05-mm (3/4-in) mine conduit hose sheaths the UIC cable.

Computer Enclosure

The MPHS controller is enclosed in an Ocenco X/P 2387 computer enclosure (fig. 8). The computer enclosure contains the battery, battery charger, and power supply. A 12-V, 12 A·h gelled electrolyte battery allows the MPHS to operate independently during testing. A 12-V dc

[5]Jobes, C. C. Utilizing Mechanical Linear Transducers for the Determination of a Mining Machine's Position and Heading. BuMines RI 9364, 1990, 19 pp.

[6]Work cited in footnote 5.

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

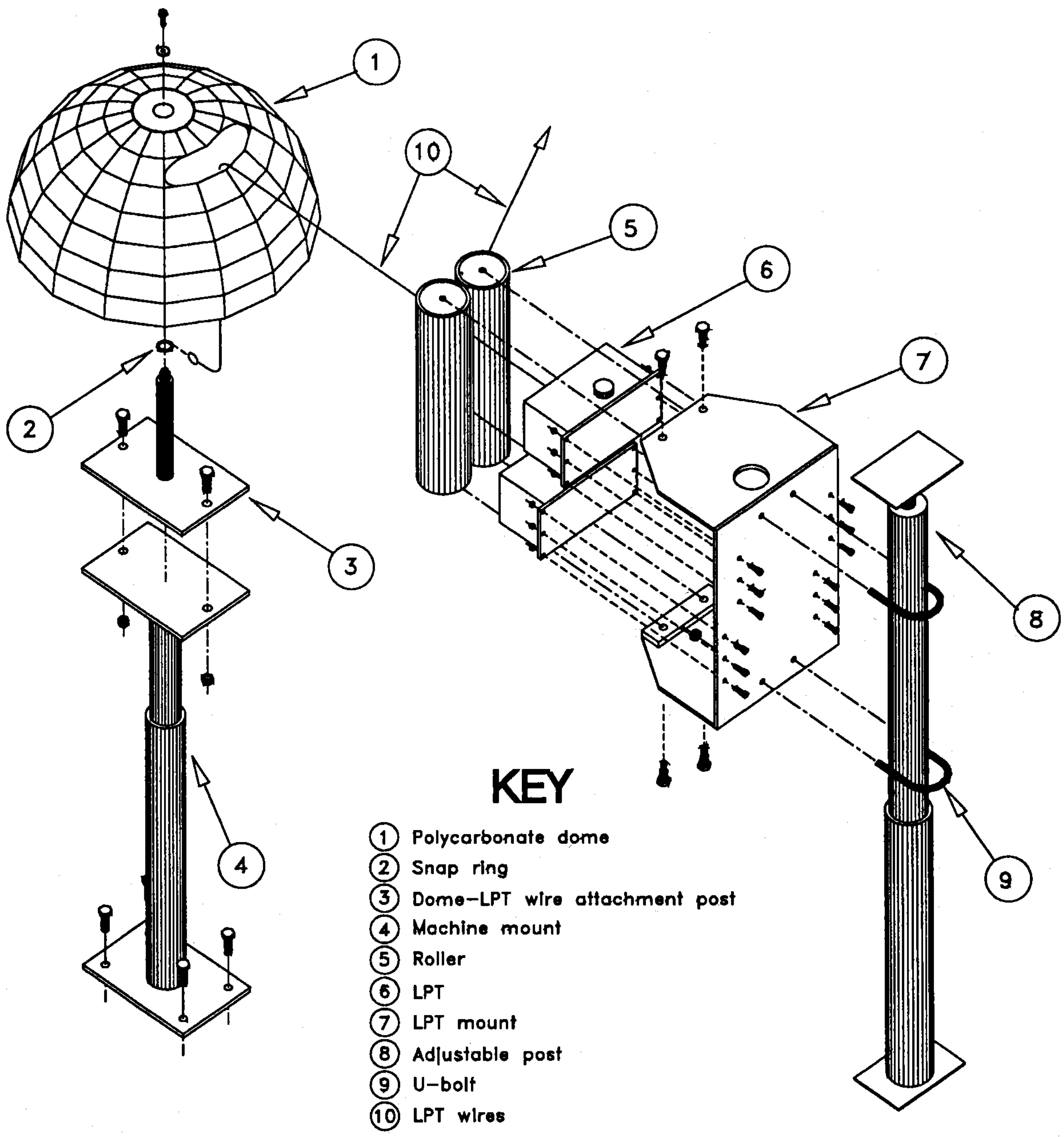

Figure 4.—Assembly drawing of MPHS mount-post pair.

to dc converter (rated at ±12 V at 310 mA and +5 V at 1.5 A) provides power to the controller and LPT circuits. Applying ac to two pins in the UIC provides power to the battery charger. An X/P switch on top of the computer enclosure controls the run, charge, and off states. An MPHS current draw of 1.26 A at 12 V limits operation to about 9 h of continuous use.

The MPHS enclosure also contains the IS barriers and controller. Twelve STAHL 9001/02-175-050-00 IS barriers make the four LPT circuits IS. The controller's analog-to-digital (A/D) converter reads the LPT output voltages ranging from -4.5 to +4.5 V. The MPHS controller is an Intel iRCB 44/20A analog input-output (I/O) controller. An Intel iSBX 331 fixed-floating point math multimodule board occupies the controller's ISBX connector. The math board lets the MPHS algorithm perform floating point calculations necessary to process the LPT analog data. The MPHS controller communicates using Intel's BITBUS network on a four-wire RS485 protocol interface.

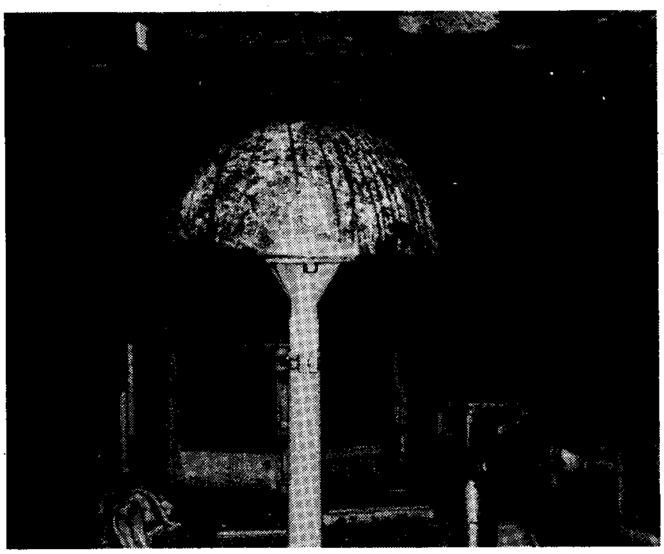

Figure 5.—MPHS attachment post on mining machine.

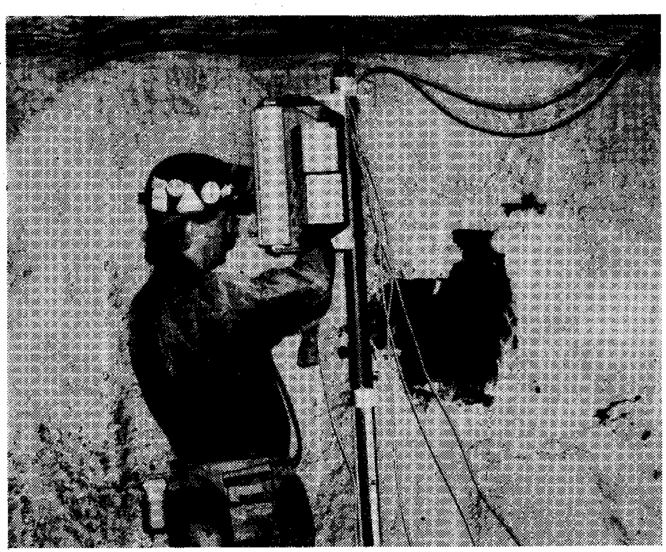

Figure 6.—MPHS transducer mount in mine entry.

Data Collection Computer

The MPHS position and heading data were collected in the underground control room (fig. 9) via a BITBUS network connection. The data collection software enabled the data to be stored for later analysis.

Software

Writing the controller software in the computer languages PL/M-51 and ASM-51 instead of a higher level language reduces the code size and increases code efficiency. The MPHS software has a node specification and task structure.

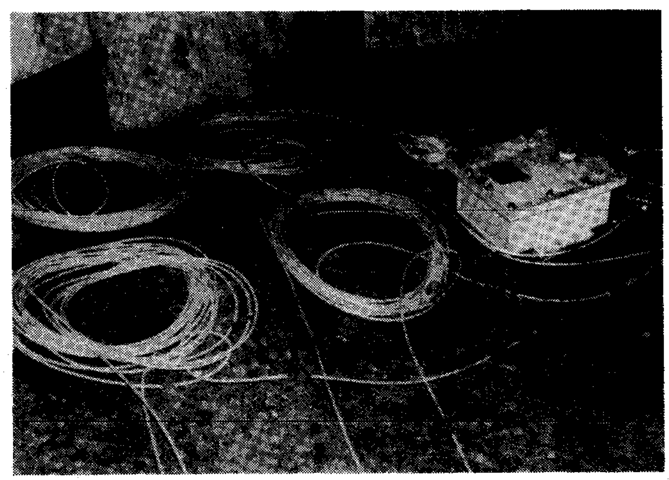

Figure 7.—MPHS computer enclosure and cables.

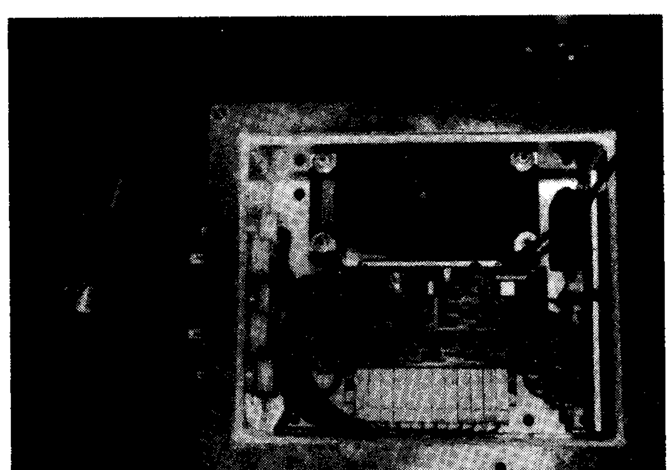

Figure 8.—MPHS computer enclosure chassis.

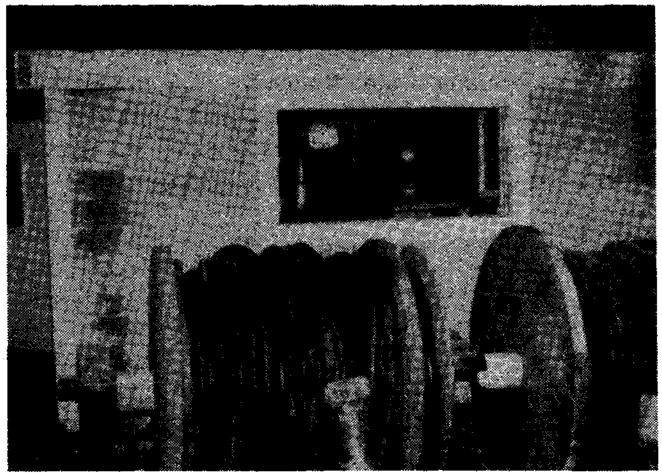

Figure 9.—Control room.

Node Specification

The node specification reflects the protocol, defined by the Bureau of Mines Network (BOM/NET), for communication with the MPHS node (see appendix A for more details). This node specification defines the syntax for requesting data or status, issuing commands, and interpreting responses. Communications with the MPHS contain data requests, control commands, and status requests.

Data requests let the requestor obtain data on any of three levels. The highest level returns the X position, Y position, heading, status, and confidence in engineering units. The next level returns the lengths of the LPT's in engineering units so the requestor may independently calculate the position and heading. The lowest level returns the raw A/D converter, 12-bit output for independent conversion into engineering units and calculation of position and heading by the requestor. The lower levels let the system operate if the ISBX 331 math board malfunctions by letting the requestor perform the necessary calculations.

Control commands let the requestor change the node's state or some of the variables used in calculating the position and heading. One command resets the node if it malfunctions; another updates calibration information (slope and intercept of the calibration curve) for each LPT. The calibration update command increases the system's flexibility and accuracy by using the individual calibration curves (see appendixes B and C for more information) instead of requiring a default generic calibration curve. A command is also available to determine the offset of the LPT to its zero position. Subtracting the offset from the LPT length accounts for offsets due to the LPT mounts. Finally, there are control commands that change the locations of the LPT's and attachment points in the mining machine and local reference frames. These commands provide flexibility in mount and attachment point locations depending on the constraints and configuration for operation or attachment to different machines.

The status requests let the requestor determine the status of the MPHS node. Issuing a communications status check determines if the MPHS node is in operation. Reading the status of the sensors determines if there is a range error or malfunctioning transducer. Reading the node status determines if a processing error occurred, the numeric coprocessor failed, or the A/D converter is inaccurate.

Task Structure

The MPHS node software operates in Intel's iDCX 51 real-time multitasking environment. Thus, three tasks can run simultaneously: Communications handling, command handling, and position and heading calculation (fig. 10).

The communications handler receives message packets addressed to the MPHS node. If the packet contains information for the MPHS node, the handler removes it and returns an empty message packet. The communications handler signals the command handler if there is information waiting for it to process. If no information is present in the message packet, the handler loads the message packet with outgoing information, if any. The communications handler then signals the command handler that it can send more information.

The command handler transfers information to and from both the communications handler and the position and heading calculator. It parses the information received from the communications handler to determine if it is a data request, control command, or status request. If it is a data or status request, the command handler queues the proper information from its data base for output to the communications handler. If the information is a control command, the command handler passes the proper information to the position and heading calculator. A control command calling for the reinitialization of the MPHS resets the MPHS parameters and restarts the software.

The position and heading calculator updates its data base with calibration, zeroing, attachment location, and transducer location information from the command handler. It continuously performs position and heading calculations and updates the position, heading, status, and confidence in the data base held in common with the command handler. If the position and heading calculator does not receive information from the command handler, it uses default settings. These settings let the MPHS calculate the position and heading at a rate of about 5 Hz.

System Interfaces

The MPHS is a BOM/NET node that can operate on either the Joy 14CM or 16CM networks. These mining machines are the Bureau's test beds for computer-assisted mining machine experiments. Figure 11 shows the MPHS node in BOM/NET as node 4—mechanical navigation. Other nodes perform tasks related to the computer-assisted operation of the mining machine (e.g., RODNE is the remote operator diagnostics node). The master node forms a pseudostar network by passing all traffic between the nodes. Thus, any node requiring position and heading information can obtain it from the MPHS quickly.

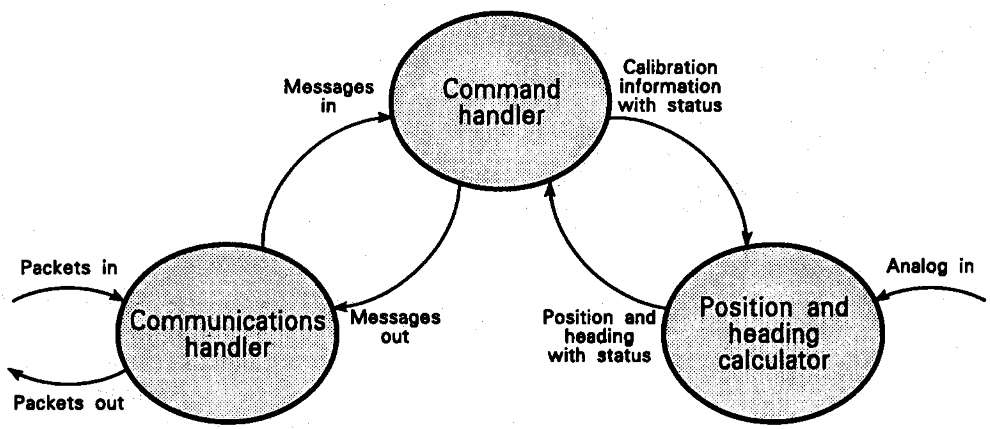

Figure 10.—Data flow diagram for BITBUS node tasks.

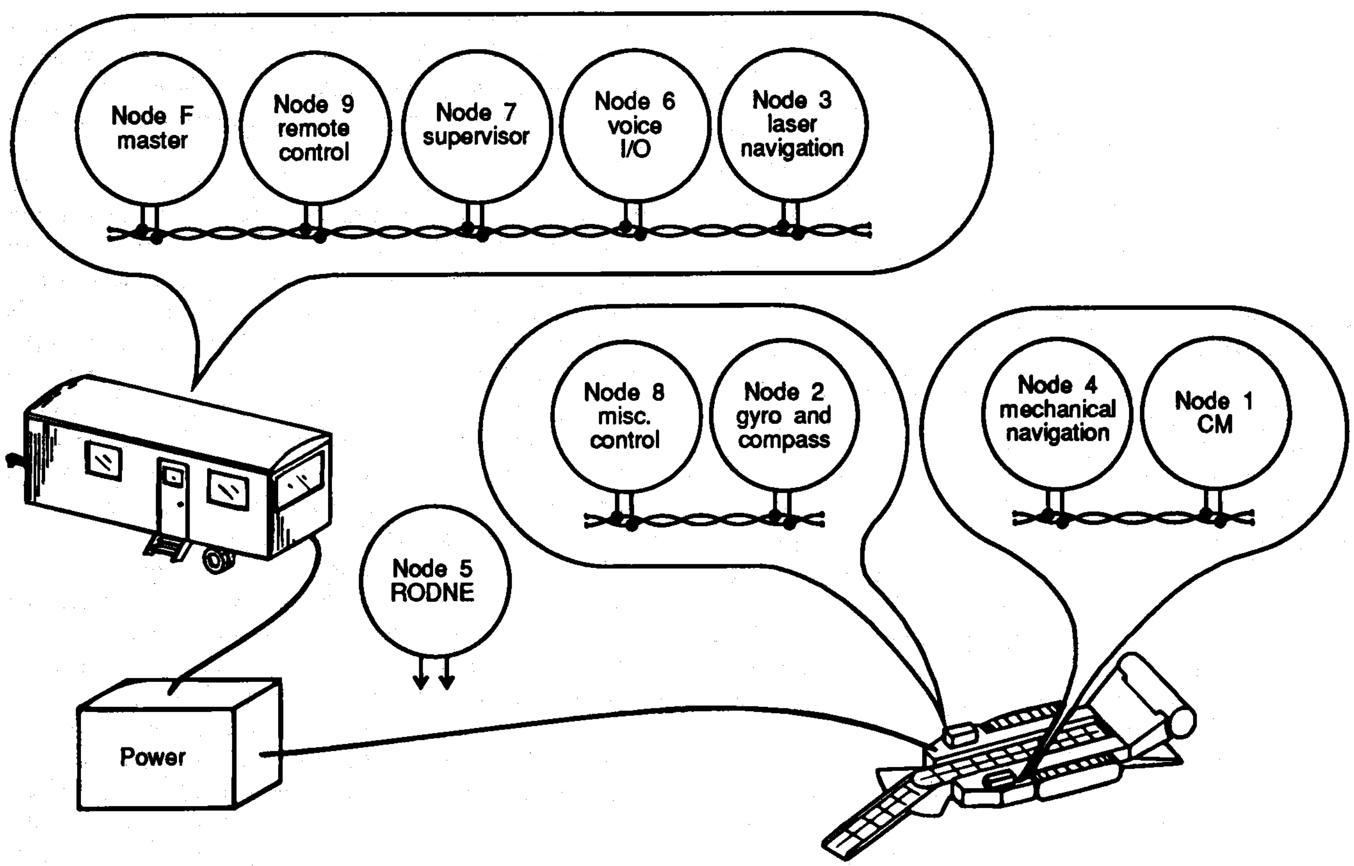

Figure 11.—BOM/NET for field trial system with Joy 14CM mining machine. (I/O = input-output; CM = continuous miner; RODNE = remote operator diagnostics node.)

MECHANICAL POSITION AND HEADING SYSTEM UNDERGROUND TEST

Testing the MPHS proved the validity of the concept, the adequacy of its implementation, and its feasibility under field conditions. Testing the MPHS underground involved designing the experiment, determining the experimental procedure, and collecting and analyzing the experimental test results. The MPHS underground tests occurred at a cooperating mine in West Virginia.

SETUP

In the experiment, the LPT wires from the LPT mounts set up in the entry behind the mining machine are connected to the attachment posts on the mining machine (fig. 12). IS cables connected the LPT's to the computer enclosure located in fresh air (fig. 13), then a communication cable connected the computer enclosure to the control room where the data collection computer resided. The X-Y orientation, as shown in figure 3, has the positive X axis pointing toward the face and parallel to the entry's axis. The positive Y axis points to the left side of the entry.

PROCEDURE

The experimental procedure examined the mining of a 5.5-m (18-ft) wide, 9.75-m (32-ft) deep cut block of coal. The miner performed the following cut sequence steps: (1) removed a 6-m (20-ft) deep box cut on the right of the entry, (2) repositioned and took a slab cut on the left, (3) proceeded to take a 3.75-m (12-ft) deep box cut on the left without repositioning, and (4) repositioned and took a slab cut on the right. These steps will be referred to as cuts 1 through 4, respectively.

The mining machine operator directed the mining machine in mining this block of coal with the radio-control pendant (fig. 14). The data collection computer took MPHS data during the mining operation at 1-s intervals. A laser transit took the mining machine position data during each pause in operation (fig. 15) by sighting reflectors on the attachment posts (fig. 16). Using the time stamps on both the MPHS and the transit data, the researchers compared the data to confirm the MPHS's accuracy.

RESULTS

Figures 17 through 20 show the results of the forward advance experiment. The top graph in each figure shows the position and heading information provided by the MPHS during each of the four cuts. The bottom portions of these figures show the MPHS-calculated confidence. Figure 21 shows the laser-transit-verified accuracy for the

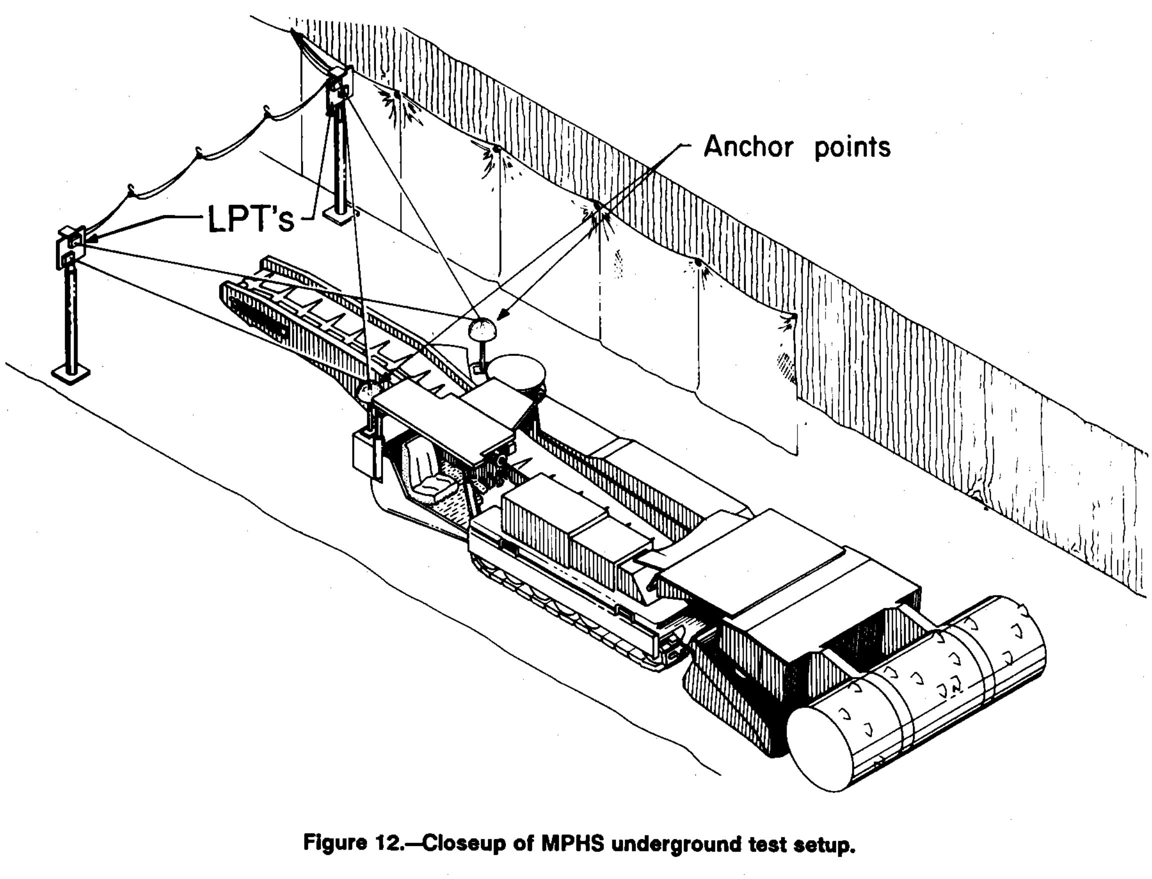

Figure 12.—Closeup of MPHS underground test setup.

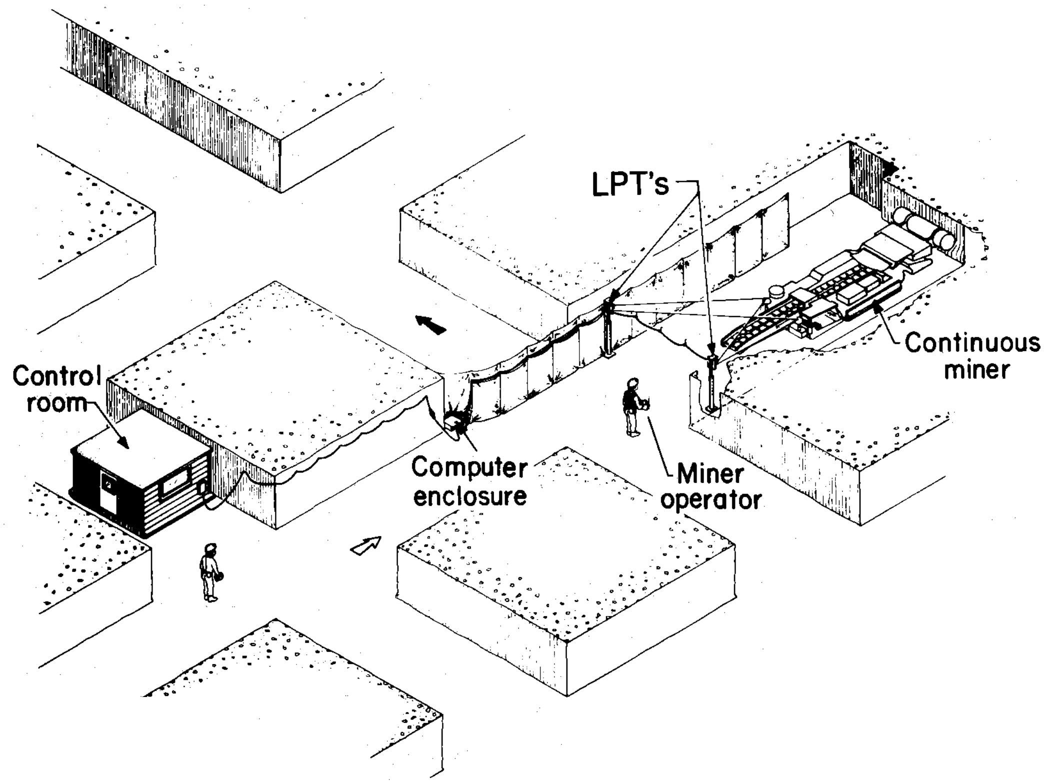

Figure 13.—MPHS underground test setup.

Figure 14.—Miner operating Joy 14CM mining machine during MPHS underground test.

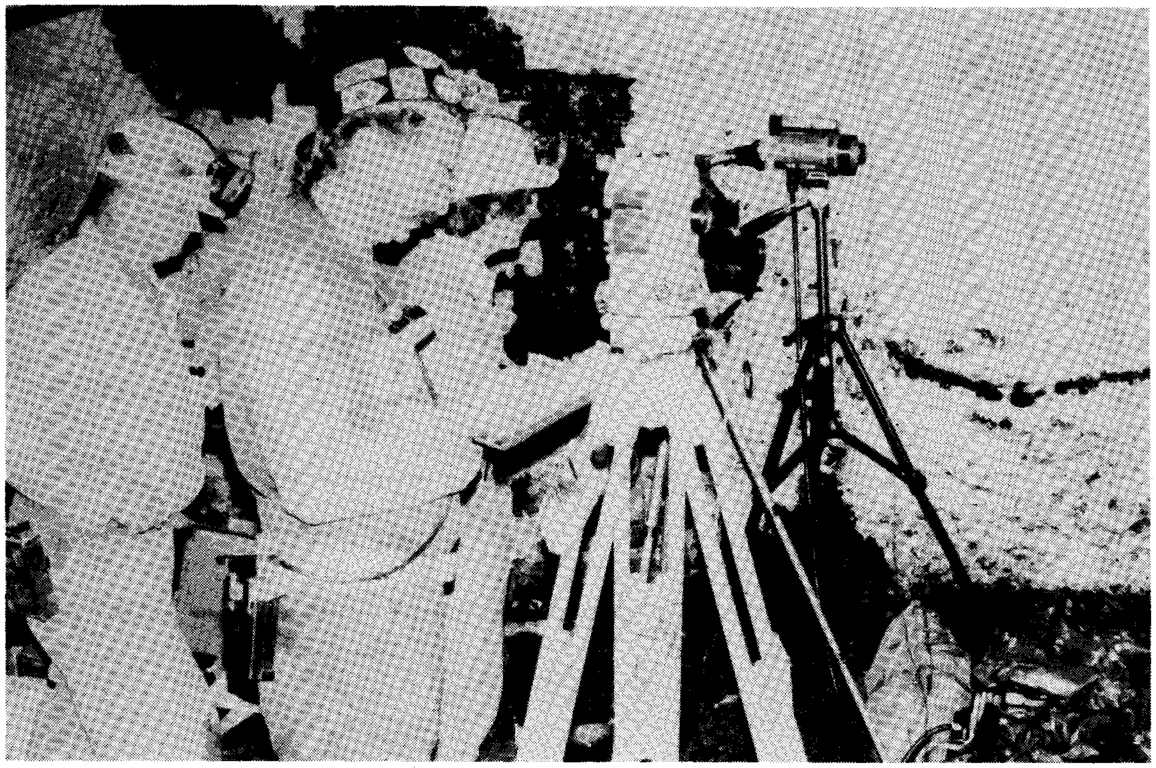

Figure 15.—Laser transit used for accuracy data collection.

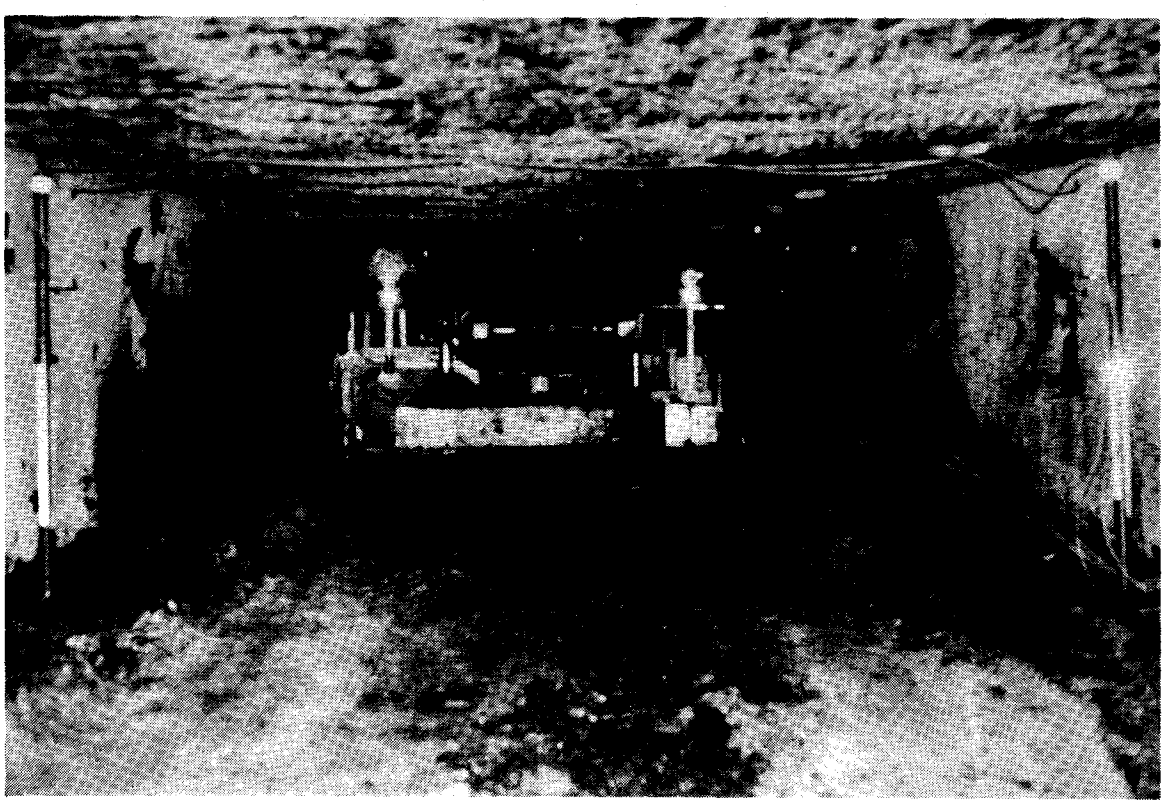

Figure 16.—Rear view of mining machine and MPHS.

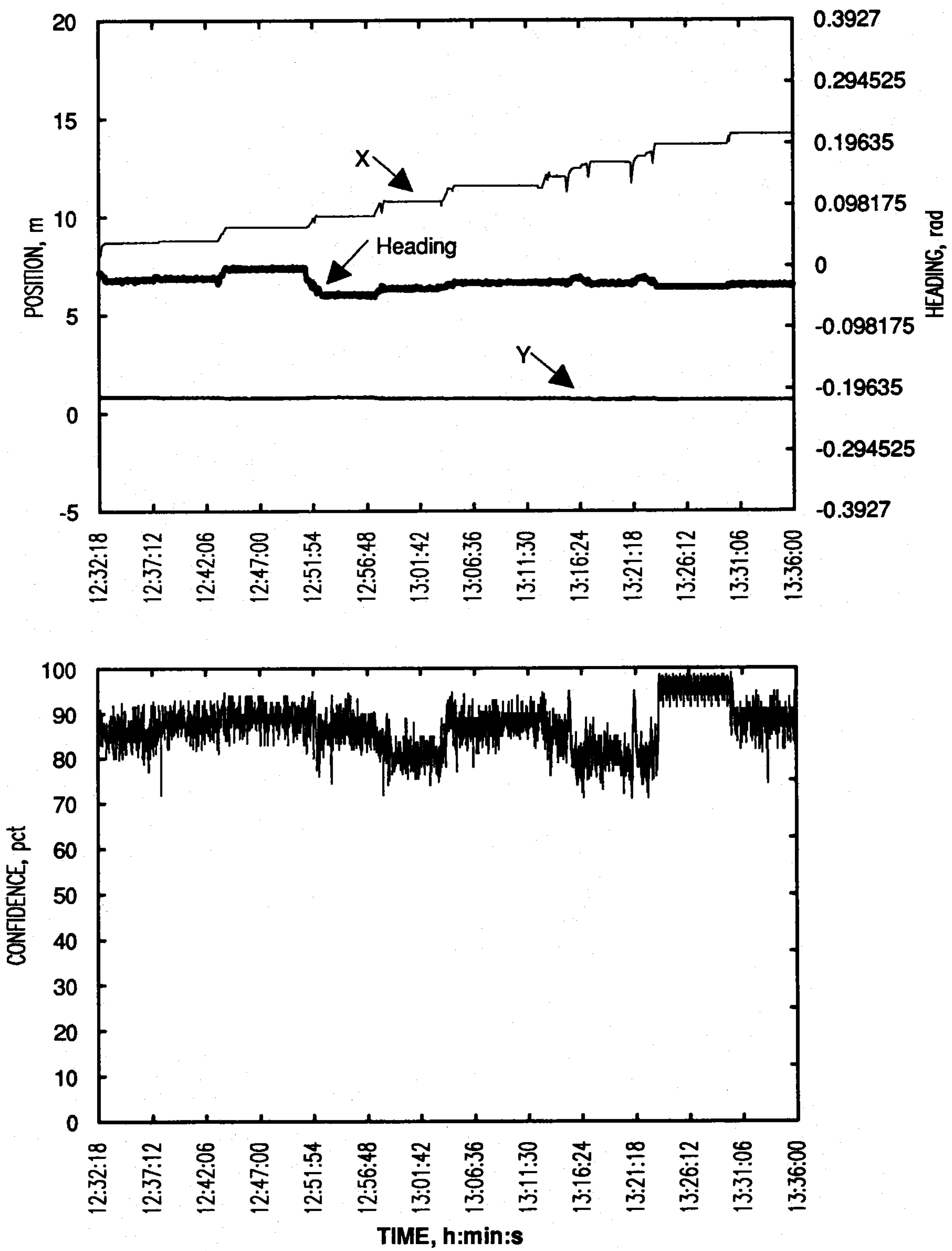

Figure 17.—Data for first cut of MPHS underground test.

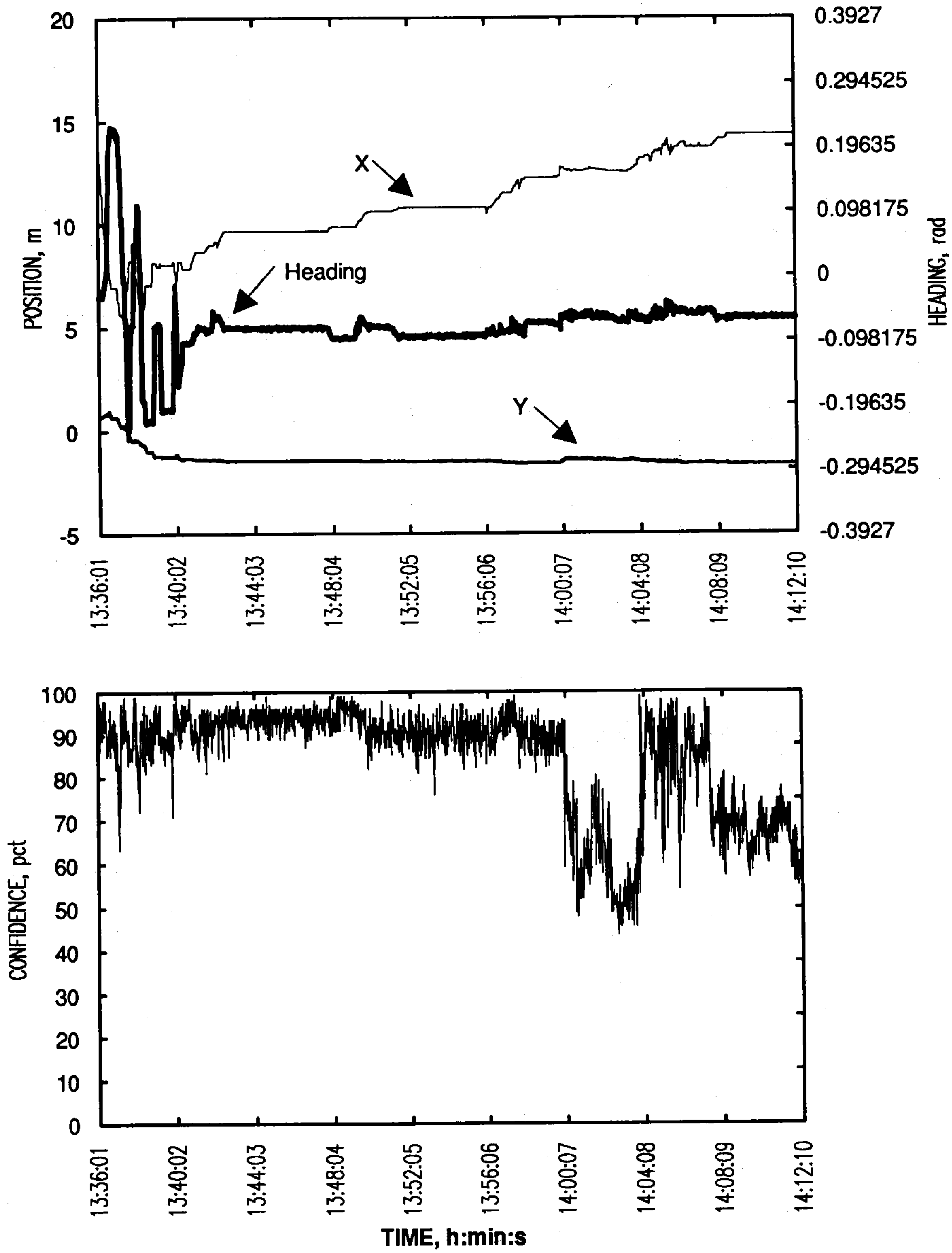

Figure 18.—Data for second cut of MPHS underground test.

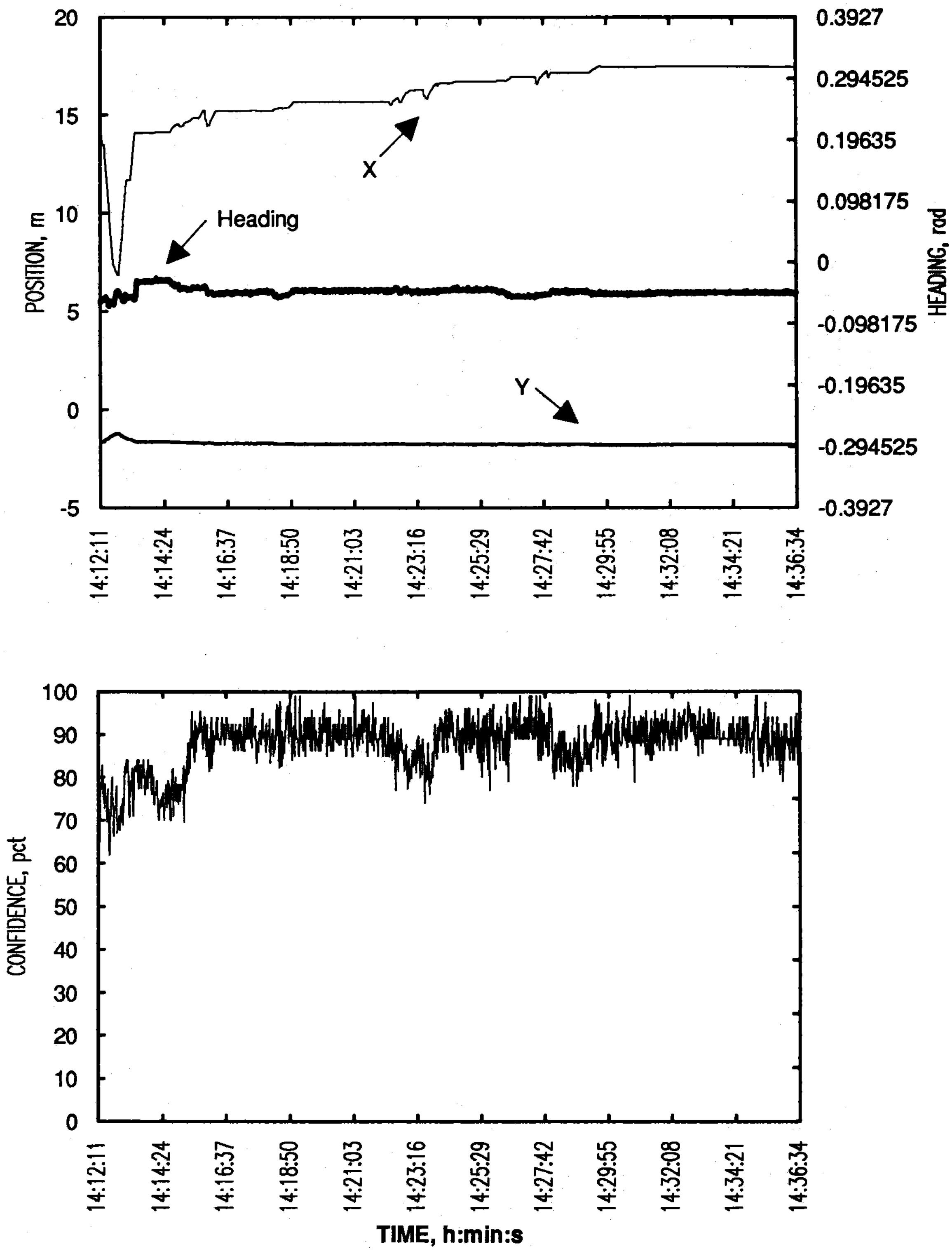

Figure 19.—Data for third cut of MPHS underground test.

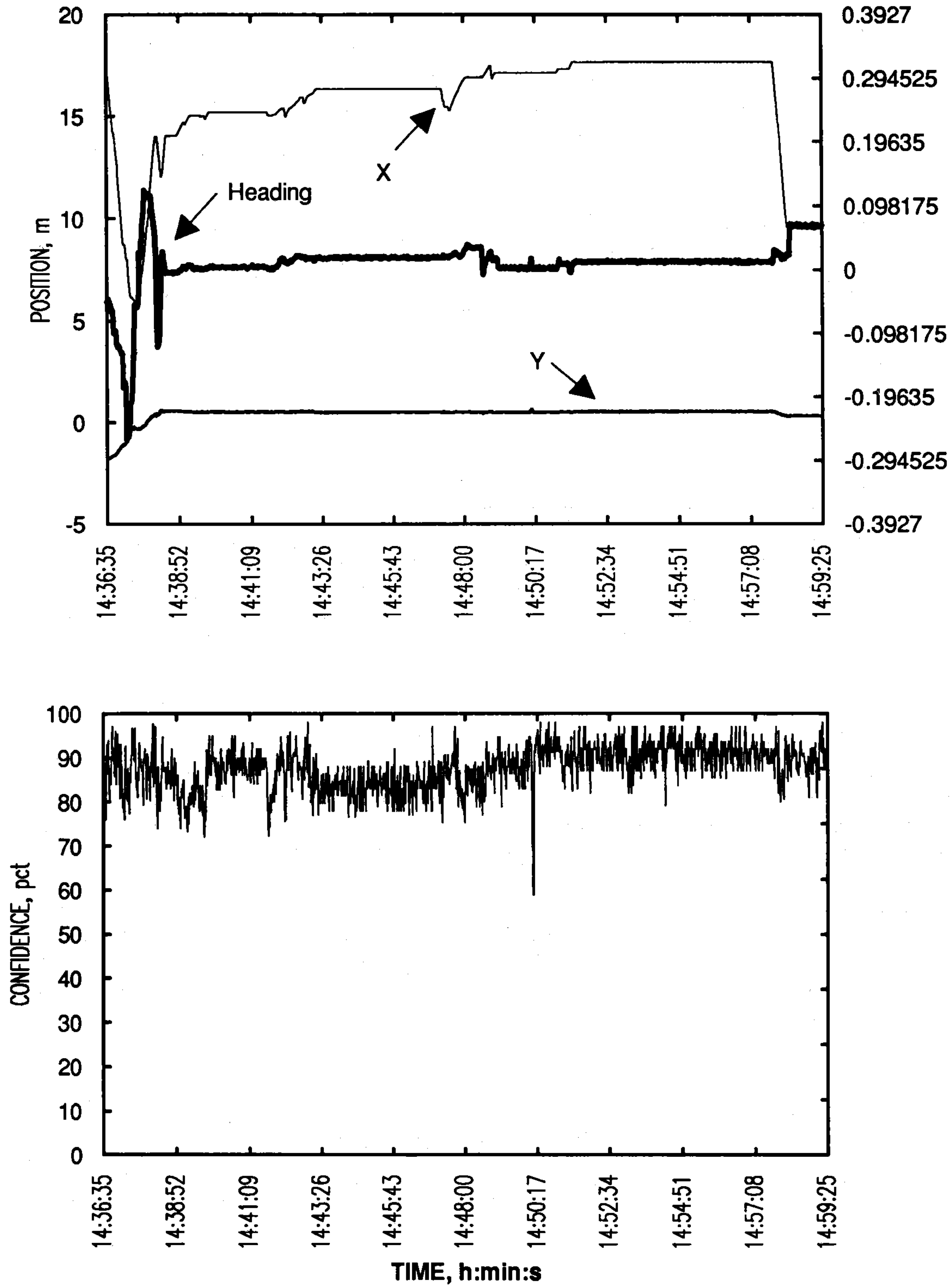

Figure 20.—Data for fourth cut of MPHS underground test.

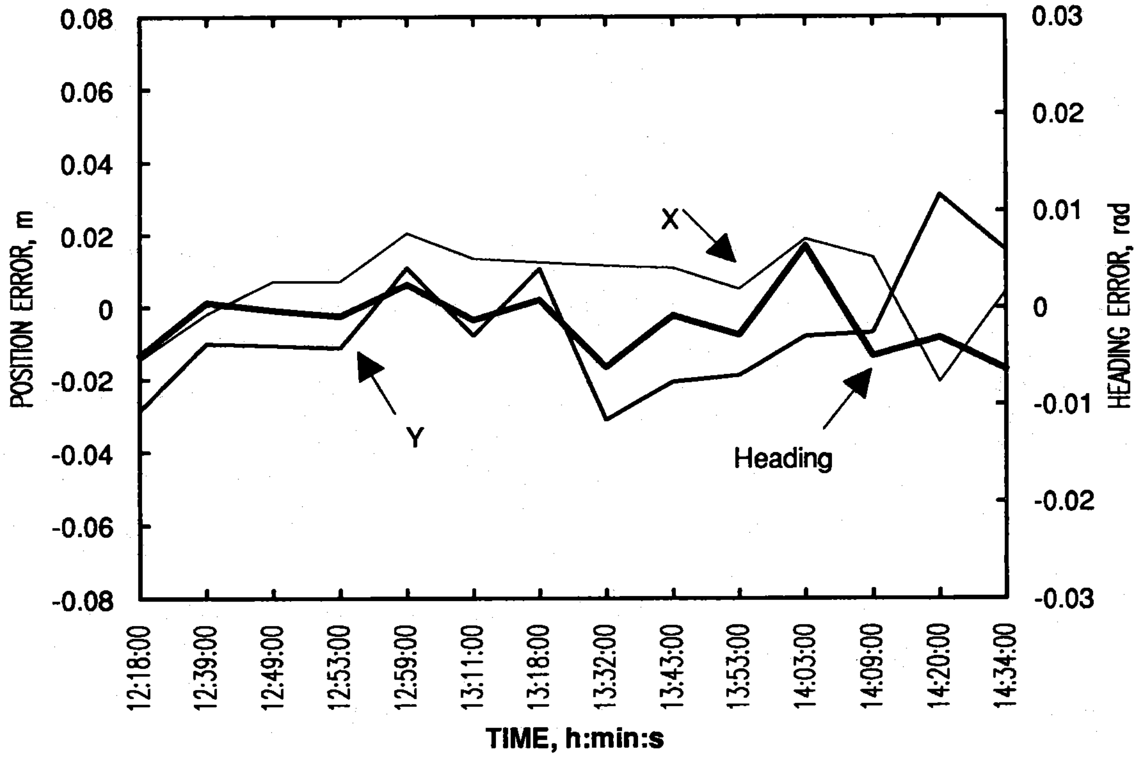

Figure 21.—Laser-transit-verified accuracy for first two cuts of MPHS underground test.

first two cuts of the underground test, which reach a depth of 6 m (20 ft).

An analysis of the accuracy data from the experiments shows several results of interest:

- The X and Y values change slightly during pivots because of slippage and the uncertain location of the continuous miner's center of rotation.
- The confidence supplied by the MPHS for the first two cuts averaged 86 pct, a much better accuracy than the allowable tolerances of ±76.2 mm (3 in) for X and Y position and ±0.026 rad (1.5°) for heading.
- Finally, the transit verified accuracy for the first two cuts supports the high confidence levels supplied by the MPHS (table 1).

These results compared favorably to those obtained in aboveground tests. They could not be directly compared, however, because of differences in the experimental procedure and data analysis method.

Table 1.—Transit versus MPHS data analysis of machine variables

	X		Y		Heading	
	mm	in	mm	in	rad	deg
Mean difference	6.37	0.25	6.07	0.24	0.00154	0.09
Maximum difference ..	20.5	.807	31.0	1.22	.00638	.365
3σ error limit	35.2	1.39	52.5	2.07	.0106	.61

CONCLUSIONS

The MPHS being developed by the Bureau works reliably under field conditions. The MPHS yields position, heading, status, and confidence data in response to LPT data. The confidence supplied with each position and heading calculation reflects the actual system accuracy. The system accuracy, obtained by transit measurement, is better than 35.2 mm (1.39 in) in X, 52.5 mm (2.07 in) in Y, and 0.0106 rad (0.61°) in heading. While the errors incurred by the MPHS may be acceptable in a mining environment, better LPT's are available to improve accuracy.

RECOMMENDATIONS

The researchers propose some recommendations for future study of the MPHS. First, either obtain more accurate LPT's or better characterize their inherent errors; better length data will yield more accurate results. Second, use a controller with more processing capability to proportionally decrease the calculation delay times and make the MPHS more suitable for real-time control applications. Finally, use a more accurate method to determine the exact position and heading of the mining machine to yield a more accurate representation of the MPHS's accuracy. The laser transit, while accurate enough for most tasks, showed some of its limitations, such as accuracy in distance and heading, during testing.

APPENDIX A.—NODE SPECIFICATION OF MECHANICAL POSITION AND HEADING SYSTEM

This sensory system determines the machine's X-Y position and heading. The sensors employed are four linear position transducers (LPT's) that report the distance between the transducer housing and the end of the cable.

HARDWARE

The hardware for this node will include a BITBUS analog control board IRCB 44/20A with an ISBX 331 numeric coprocessor.

SOFTWARE

The software to be used in this node will be PL/M-51 and ASM-51.

LOCATION

The node will be located off the mining machine with the four LPT's although they could be mounted onboard the mining machine and yield the same results.

DESCRIPTION

This multisensor system determines the machine heading and position. Four LPT's provide linear displacement information between the attachment points of the cables to the local reference frame to the LPT's onboard the mining machine. When combined with information known about the machine and the local reference frame, the information derived from the LPT's allow the calculation of the position and heading. The offboard system, designated as "the node" or node 4, utilizes a dedicated microcontroller BITBUS node with a numeric coprocessor and is connected to a BITBUS network.

The four-transducer system allows the accurate calculation of position and heading as long as certain requirements are met. The most important of these requirements is that the transducers attached to the machine should remain on one side of the reference line passing through the two attachment points. This is necessary because of the properties of the trigonometric solution that will provide two solutions to a given set of LPT values mirrored across the reference line. Sufficient redundancy is provided so that if one LPT fails, the error can be identified. The existence of an error will be returned in the status byte.

In addition to supplying sensor data, the node can respond to control commands and status requests. Control commands enable manipulation of the controlling software. The status request will indicate whether sensors are operating properly and provide information about the node status. A confidence can be generated for the average of the three-transducer solution based on the "spread" found in the spread of the three-transducer solutions about the average.

INTERACTION WITH OTHER NODES

Interaction with other nodes will involve receiving commands and sending responses.

The signals from the transducers are conditioned by calibration equations (which require scale and bias factors) and zero offsets (if the desired zero references have a nonzero value) in the following manner:

distance = (reading - bias)/slope - offset,

where reading = A/D converter value of transducer voltage, V,

bias = intercept of calibration curve, V,

slope = slope of calibration curve, V/in,

and offset = value that moves transducer zero reference, in.

The slope and the intercept are provided for each transducer via the "calibrate transducer" command. The zero offset is determined when the "initialize transducer to zero" command is executed.

Another node may request position and heading information from the node. If an error occurs, it may also be necessary for that node to inquire as to the node's status and make decisions accordingly. If an overrange error is about to destroy an LPT (i.e., pull the wire off the LPT's takeup drum), then that node may be required to take some action.

SENSOR DATA CHECKS

The node is responsible for verifying sensor data output. It uses overrange and underrange detection and utilizes the designed redundancy to determine the validity of its data. Items checked by the node are overrange and underrange errors for the linear transducers, and the validity of the solution with respect to the four possible pairs of three-transducer solutions.

When a request for data is initiated while an error exists, a command execution failure packet (CEFP) will be sent in response from the node. The requesting node then has the option to request the node status and to proceed accordingly.

In addition to these software checks, several hardware checks are made by both the 8044 BEM firmware and the node application software. The hardware checks made are—

1. 8044 instruction set test (firmware),
2. Internal read only memory (ROM) checksum test (firmware),
3. Internal random access memory (RAM) test (firmware),
4. External RAM test (firmware),
5. Numeric coprocessor instruction set test (software), and
6. Analog I/O test (software).

NODE COMMANDS

It is necessary for the node to receive commands and issue responses. The node commands enable access to three areas—data, control, and status. The commands to access these areas and the type of responses from the node are listed below following BOM/NET protocol.[1]

Data Commands

Data commands are used by other nodes on the network to obtain information derived from the LPT's.

Commands

Command	Definition
#4A1<cr>	request X position
#4A2<cr>	request Y position
#4A3<cr>	request heading
#4A4z<cr>	request LPT z value
#4A5z<cr>	request LPT z raw data

where z = LPT identification number.

Responses

CEFP	Definition
#dFEA1eee<cr>	failed to obtain X position
#dFEA2eee<cr>	failed to obtain Y position
#dFEA3eee<cr>	failed to obtain heading
#dFEA4eee<cr>	cannot read LPT z length value
#dFEA5eee<cr>	cannot read LPT z raw data

[1]Bureau report in preparation; for information, contact W. H. Schiffbauer, Pittsburgh Research Center, Pittsburgh, PA.

CECP	Definition
#dFCA1xxxxspp<cr>	X is xxxx with status s and confidence pp
#dFCA2xxxxspp<cr>	Y is xxxx with status s and confidence pp
#dFCA3yyyyspp<cr>	heading is yyyy with status s and confidence pp
#dFCA4zxxxxs<cr>	LPT z is xxxx with status s
#dFCA5zvvvs<cr>	LPT raw value z is vvv with status s

where d = destination node identification (ID),

eee = error code:

001 = node not ready,

002 = illegal destination reference,

003 = node hardware error,

004 = operand out of range,

005 = invalid command, and

006 = invalid hex character,

FE = command failure (NAK),

FC = command success (ACK),

vvv = 12-bit A/D value of LPT input,

xxxx = position or length in tenths of an inch,

yyyy = heading in ten thousandths of a radian,

s = status nibble,

pp = percentage confidence,

and z = LPT identification number (1 to 4).

X and Y position data are expressed in tenths of an inch. X and Y range from 8001H to 7FFFH (-3276.7 to 3276.7 in. in 2's complement) since it depends on the LPT range (750.0 in) plus the distance to the local reference origin (defined in the initial configuration) and the machine reference origin (usually less than 288 in).

Heading information is expressed in ten thousandths of a radian. Heading ranges from 8548H to 7AB8H (-3.1416 to 3.1416 rad in 2's complement).

Length data are expressed in tenths of an inch. Lengths range from 0000H to 1D4CH (0 to 750.0 in) for the LPT's used.

Raw data are expressed in 12-bit form. Raw data values range from 0000H to 0FFFH (0 to 750.0 in) for the LPT's used.

The status is expressed as the nibble (usually four bits) s composed of four status bits.

0	twf	oef	btf
msb			lsb

where msb = most significant bit,

lsb = least significant bit,

twf = transition warning flag,

oef = other errors,

and btf = bad transducer reading.

Example: s = 1H would indicate that there is a bad transducer reading and that the solution is incorrect.

Percentage confidence is expressed as percent. The percentage confidence ranges from 00H to 64H (0 to 100 pct).

Control Commands

The sensor control commands allow other nodes to alter the performance of the node.

Commands

Command	Definition
#4B1<cr>	initialize node
#4B2zmmmmbbbb<cr>	calibrate transducer z
#4B3zffff<cr>	determine transducer z offset
#4B4axxxxyyyy<cr>	attachment point a wrt local reference frame
#4B5txxxxyyyy<cr>	transducer point t wrt machine reference frame

where mmmm = slope of calibration equation,

bbbb = intercept of calibration equation,

a = attachment point number (1 or 2),

t = transducer point number (1 or 2),

and ffff = offset for transducer.

Slope information is expressed in volts per inch. The sensitivity will be in the range of 0.01 to 0.02 V/in with 0.011663 V/in being the default (2D8FH). To obtain the hex value, multiply 0.0sssss V/in by 1,000,000 and convert.

Intercept information is expressed in millivolts. The intercept will be in the range of -5.0 to -4.0 V with -4.473 V being the default (EE87H). To obtain the hex value, multiply i.iii V by 1,000 and convert.

Offset information is expressed in tenths of an inch. The offset will be in the range of 0.0 to 36.0 in with 0.0 in being the default (0000H). To obtain the hex value, multiply fff.f in by 10 and convert. If the most significant bit of the offset is set to 1, then the current value of the LPT becomes the offset (provided it is in the specified range).

Responses

CEFP	Definition
#dFEB1eee<cr>	node not initialized
#dFEB2eee<cr>	transducer z not calibrated
#dFEB3eee<cr>	transducer z not initialized to zero
#dFEB4eee<cr>	attachment point a not defined
#dFEB5eee<cr>	transducer point p not defined

CECP	Definition
#dFCB1<cr>	node initialized
#dFCB2z<cr>	transducer z calibrated
#dFCB3z<cr>	transducer z initialized to zero
#dFCB4a<cr>	attachment point a defined
#dFCB5p<cr>	transducer point p defined

Status Commands

System status commands are used to isolate sensor faults in the node. These commands allow the examination at a general level for all the node sensors and solution method parameters.

Commands

Command	Definition
#499<cr>	communication status check
#4C1<cr>	sensor status check
#4C2<cr>	node status check

Responses

CFP	Definition
#dFF<cr>	CFP for communication check

CEFP	Definition
#dFEC1eee<cr>	sensor status not available
#dFEC2eee<cr>	node status not available

CECP	Definition
#dFC99<cr>	communication check
#dFCC1bour<cr>	sensor status
#dFCC2n<cr>	node status

where FF = command failure packet (CFP),

b = bad transducer status nibble,

o = overrange status nibble,

u = underrange status nibble,

r = transition status nibble,

and n = node status nibble.

The format of the b status nibble is—

lb3	lb2	lb1	lb0
msb			lsb

where lbx = linear transducer x data bad.

The format of the o status nibble is—

or3	or2	or1	or0
msb			lsb

where orx = linear transducer x overrange.

The format of the u status nibble is—

ur3	ur2	ur1	ur0
msb			lsb

where urx = linear transducer x underrange.

The format of the r status nibble is—

tr3	tr2	tr1	tr0
msb			lsb

where trx = internal angle to machine associated with transducer x in transition.

The format of the n status nibble is—

0	ope	ncp	adc
msb			lsb

where 0 = unused,

ope = other processing error,

ncp = numeric coprocessor error,

and adc = A/D converter error.

COMMANDS

Command	Definition
#4A1<cr>	request X position
#4A2<cr>	request Y position
#4A3<cr>	request heading
#4A4z<cr>	request LPT z value
#4A5z<cr>	request LPT z raw data
#4B1<cr>	initialize node
#4B2zmmmmbbbb<cr>	calibrate transducer z
#4B3zffff<cr>	determine transducer z offset
#4B4axxxxyyyy<cr>	attachment point a wrt local reference frame
#4B5txxxxyyyy<cr>	transducer point t wrt machine reference frame
#499<cr>	communication status check
#4C1<cr>	sensor status check
#4C2<cr>	node status check

APPENDIX B.—CALIBRATION DATA FOR LINEAR POSITION TRANSDUCER

(Range, 750 in; cable tension, 24 oz; potential resistance, 500 ohms; excitation, 10 V dc)

Calibration step	Travel, in	Output, V	Ideal, V	Delta, mV
		TRANSDUCER[1]		
1	0.00	0.035	0.035	0
2	187.50	2.463	2.463	0
3	357.00	4.889	4.891	2
4	562.50	7.314	7.319	5
5	750.00	9.747	9.747	0
		TRANSDUCER 2[2]		
1	0.00	0.028	0.028	0
2	187.50	2.462	2.460	2
3	357.00	4.891	4.893	2
4	562.50	7.321	7.325	4
5	750.00	9.758	9.758	0
		TRANSDUCER 3[3]		
1	0.00	0.034	0.034	0
2	187.50	2.454	2.461	7
3	357.50	4.887	4.888	1
4	562.50	7.314	7.316	2
5	750.00	9.743	9.743	0
		TRANSDUCER 4[4]		
1	0.00	0.030	0.030	0
2	187.50	2.461	2.465	4
3	357.50	4.898	4.901	3
4	562.50	7.339	7.336	3
5	750.00	9.771	9.771	0
		TRANSDUCER 5[3]		
1	0.00	0.026	0.026	0
2	187.50	2.448	2.452	4
3	357.00	4.877	4.878	1
4	562.50	7.298	7.305	7
5	750.00	9.731	9.731	0

[1]0.05 pct full scale, 1.29 mV/(V/in) position.
[2]0.05 pct full scale, 1.30 mV/(V/in) position.
[3]0.07 pct full scale, 1.29 mV/(V/in) position.
[4]0.04 pct full scale, 1.30 mV/(V/in) position.

APPENDIX C.—CALIBRATION EQUATIONS AND ERROR FREQUENCY DISTRIBUTION

Output (Qo), in volts, for the five linear position transducers as described in appendix B was used to calculate the slopes, intercepts, and standard deviations of the calibration equations for each of the five linear position transducers and for all five combined. The general calibration equation was determined to be

$$Qi = \frac{Qo - 0.02944}{0.012959} \pm 2.050786 \text{ in}, \qquad \text{(C-1)}$$

where Qi = quantity input, in,

with maximum error = 1.694514 in.

The calibration equation for transducer 1 was determined to be

$$Qi = \frac{Qo - 0.03460}{0.012947} \pm 0.89625 \text{ in}, \qquad \text{(C-2)}$$

with maximum error = 0.239444 in.

The calibration equation for transducer 2 was determined to be

$$Qi = \frac{Qo - 0.02820}{0.01297} \pm 1.014279 \text{ in}, \qquad \text{(C-3)}$$

with maximum error = 0.223591 in.

The calibration equation for transducer 3 was determined to be

$$Qi = \frac{Qo - 0.03080}{0.012948} \pm 1.120895 \text{ in}, \qquad \text{(C-4)}$$

with maximum error = 0.35526 in.

The calibration equation for transducer 4 was determined to be

$$Qi = \frac{Qo - 0.02780}{0.012992} \pm 3.201727 \text{ in}, \qquad \text{(C-5)}$$

with maximum error = 0.246305 in.

The calibration equation for transducer 5 was determined to be

$$Qi = \frac{Qo - 0.02580}{0.012940} \pm 2.772926 \text{ in}, \qquad \text{(C-6)}$$

with maximum error = 0.030911 in.

The error frequency distribution for the general calibration equation is shown in figure C-1.

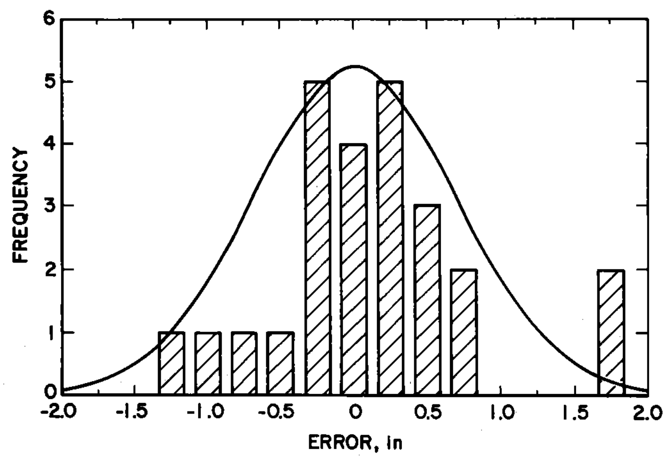

Figure C-1.—Error frequency of general calibration equation.