Mechanical Sensor Guidance of a Mining Machine

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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) developed at the Bureau of Mines provides such navigation information during face maneuvers. Formulating the required theory yielded a robust algorithm for calculating the position and heading. Implementing this theory through hardware and software design allowed testing. Analysis of the errors and test results showed that the MPHS provides reliable results.

NOMENCLATURE

$\mathbf{R}_i$	Position vector i
$^A\mathbf{R}_i$	Position vector $\mathbf{R}_i$ in the local (A) coordinate reference frame
$^B\mathbf{R}_i$	Position vector $\mathbf{R}_i$ in the machine (B) coordinate reference frame
x_i	X component of vector $\mathbf{R}_i$ in Cartesian coordinates
y_i	Y component of vector $\mathbf{R}_i$ in Cartesian coordinates
r_i	Magnitude of vector $\mathbf{R}_i$ in polar coordinates
θ_i	Argument (direction) of vector $\mathbf{R}_i$ in polar coordinates
π	Circular constant
ψ	Four-transducer solution for the heading of the mining machine
ψ_i	Three-transducer solution for the heading of the mining machine excluding transducer i
LPT_i	Linear position transducer i

I. INTRODUCTION

COMPUTER-assisted operation of equipment at the face increases worker health, safety, and efficiency. Autonomous navigation must be attained before computer-assisted control of face operations is possible under current continuous mining practices [1]. The mechanical position and heading system (MPHS) can provide guidance information for navigation of mining machines in the face area.

A. Background

Mobile mining equipment performs face navigation when preparing to operate in the face area of an entry or crosscut development. Continuous mining machines and roof bolters are types of equipment that perform face navigation.

Designing a navigation system for a self-guided mining machine is difficult. Current attempts are essentially electromagnetic, stress wave, and mechanical in nature. Much of this work is in the electromagnetic (optical, laser, radar, magnetic compass, etc.) and stress wave (ultrasonic) domains with very little attention paid to mechanical guidance methods. Some researchers believe that a mechanical method may yield a cheaper and more reliable system.

Mechanical guidance systems usually involve dead reckoning (chiefly machine motion relative to ground) or mechanical attachment. Errors are cumulative in dead reckoning; therefore, a system relying on dead reckoning alone is unreliable—particularly in a mining environment. Most designers of navigation systems, however, appear unwilling to sufficiently restrict their machines for mechanical attachment to be viable. The face area of an entry confines a mining machine, making it an ideal candidate for mechanical attachment.

B. Problem Definition

The MPHS is a mechanically attached system. To perform the mechanical design adequately, it is necessary to define the system's requirements and constraints.

One cannot consider a coal seam to be a smooth plane for even a short distance. Therefore, a mining machine has a spatial rather than planar nature of motion. An object with a spatial motion has six degree of freedom (x, y, z, roll, pitch, and yaw). The MPHS, since it measures the position and orientation of a spatial object, requires six degrees of freedom. Yet, for computational purposes, three of these degrees of freedom (z, roll, and pitch) are small enough to ignore. The position and heading (x, y, and yaw) are the important measured unknowns.

There are two types of mechanism design constraints: dimensional and inertial. These constraints check the feasibility of a mechanism found to satisfy the requirements. Dimensional constraints include a restricted working space, working around auxiliary equipment, a required long range, etc. The inertial constraints limit the mass of the MPHS and emphasize stiffness to enhance its accuracy.

II. MECHANICAL POSITION AND HEADING

The MPHS development has two parts. The first is to learn the theory governing the MPHS [2]; the other is to develop the enabling hardware and software.

A. Theory

The MPHS theory development divides into three parts. The first step is to characterize the sensors used and their configuration. The next is the selection and definition of
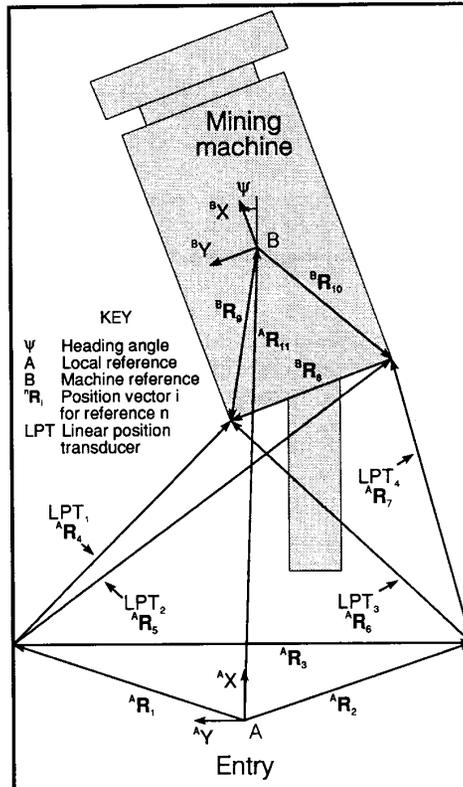
Fig. 1.   Configuration for directly solvable position and heading algorithm.

navigation reference frames. The last is to derive a closed-form solution determining the position and heading from sensor information.

1) Sensors: Choosing the sensors and their configuration requires much thought. Most transducers measure only one degree of freedom, and few have the linear range required by the MPHS. Thus, the logical sensor is a linear position transducer (LPT) or wire pull. Although it is possible to find position and heading using a configuration of three LPT's, four provide redundancy for reliability.

Any LPT nondegenerate configuration allows calculation of the position and heading. The configuration selected, however, does affect the computation method and effort required. Positioning the LPT's so their locations and wire attachment points differ results in a set of nonlinear transcendental equations. These equations require an iterative solution. Configuring the LPT's by pairing their locations and attachment points (see Fig. 1) yields trigonometrically solvable equations.

2) Navigation Reference Frames: When navigating a mining machine, its position and heading are crucial. Attaching a machine reference frame to the mining machine enables the location of points on the mining machine. Fixing a local reference frame to a stationary point behind the mining machine allows description of the mining machine's position and heading.

3) Closed-Form Solution: A closed-form solution allows easier calculation of the position and heading. First, the solution process requires configuring the LPT's and defining all position vectors of interest (see Fig. 1). Applying coordinate transformation analysis of planar mechanisms to this configuration determines four pairs of three-transducer solutions. Intermediate results obtained yield a four-transducer solution.

In the pair of three-transducer solutions excluding LPT_4 data, the direction of LPT_1's cable and the mining machine's heading are

$$\theta_4 = \theta_3 + \cos^{-1}\left[\frac{r_3^2 + r_4^2 - r_6^2}{2r_3r_4}\right] \qquad (1)$$

and

$$\Psi_4 = \pm\cos^{-1}\left[\frac{r_4^2 + r_8^2 - r_5^2}{2r_4r_8}\right] - \theta_8 + \theta_4 \qquad (2)$$

respectively, and the mining machine's position is

$$x_{11} = r_1\cos\theta_1 + r_4\cos\theta_4 - r_9\cos(\theta_9 - \Psi_4) \qquad (3)$$

and

$$y_{11} = r_1\sin\theta_1 + r_4\sin\theta_4 - r_9\sin(\theta_9 + \Psi_4). \qquad (4)$$

In the pair of three-transducer solutions excluding LPT_3 data, the direction of LPT_2's cable and the mining machine's heading are

$$\theta_5 = \theta_3 + \cos^{-1}\left[\frac{r_3^2 + r_5^2 - r_4^2}{2r_3r_5}\right] \qquad (5)$$

and

$$\Psi_3 = \pi \mp \cos^{-1}\left[\frac{r_5^2 + r_8^2 - r_4^2}{2r_5r_8}\right] - \theta_8 + \theta_5 \qquad (6)$$

respectively, and the mining machine's position is

$$x_{11} = r_1\cos\theta_1 + r_5\cos\theta_5 - r_{10}\cos(\theta_{10} - \Psi_3) \qquad (7)$$

and

$$y_{11} = r_1\sin\theta_1 + r_5\sin\theta_5 - r_{10}\sin(\theta_{10} + \Psi_3). \qquad (8)$$

In the pair of three-transducer solutions excluding LPT_2 data, the direction of LPT_3's cable and the mining machine's heading are

$$\theta_6 = \theta_3 - \pi - \cos^{-1}\left[\frac{r_3^2 + r_6^2 - r_4^2}{2r_3r_6}\right] \qquad (9)$$

and

$$\Psi_2 = \pm\cos^{-1}\left[\frac{r_6^2 + r_8^2 - r_7^2}{2r_6r_8}\right] - \theta_8 + \theta_6 \qquad (10)$$

respectively, and the mining machine's position is

$$x_{11} = r_2\cos\theta_2 + r_6\cos\theta_6 - r_9\cos(\theta_9 - \Psi_2) \qquad (11)$$

and

$$y_{11} = r_2\sin\theta_2 + r_6\sin\theta_6 - r_9\sin(\theta_9 + \Psi_2). \qquad (12)$$

In the pair of three-transducer solutions excluding LPT_1 data, the direction of LPT_4's cable and the mining machine's heading are

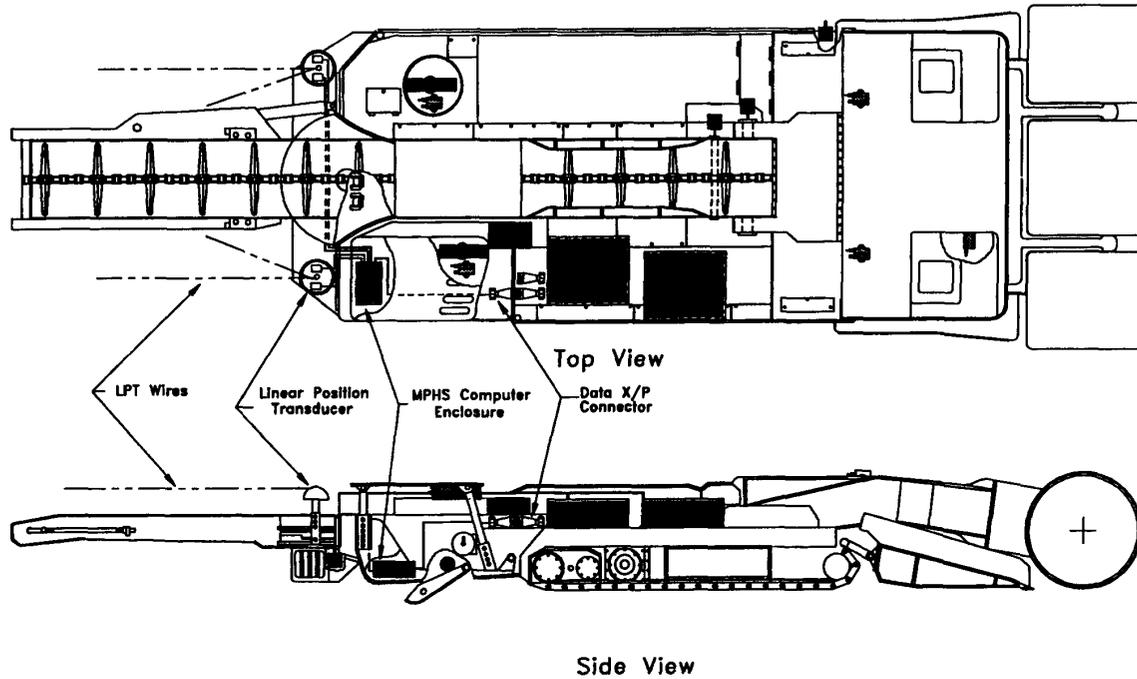$$\theta_7 = \theta_3 - \pi - \cos^{-1}\left[\frac{r_3^2 + r_7^2 - r_5^2}{2r_3r_7}\right] \qquad (13)$$

Fig. 2. Location of LPT's, cables, and the MPHS computer enclosure on the Joy 14 CM mining machine.

and

$$\Psi_1 = \pi \mp \cos^{-1}\left[\frac{r_7^2 + r_8^2 - r_6^2}{2r_7 r_8}\right] - \theta_8 + \theta_7 \qquad (14)$$

respectively, and the mining machine's position is

$$x_{11} = r_2 \cos\theta_2 + r_7 \cos\theta_7 - r_{10}\cos(\theta_{10} - \Psi_1) \qquad (15)$$

and

$$y_{11} = r_2 \sin\theta_2 + r_7 \sin\theta_7 - r_{10}\sin(\theta_{10} + \Psi_1). \qquad (16)$$

Equations (1) and (13) determine the mining machine's four-transducer solution's heading to be

$$\Psi = \tan^{-1}\left[\frac{r_4 \sin\theta_4 - r_7 \sin\theta_7 - r_3 \sin\theta_3}{r_4 \sin\theta_4 - r_7 \sin\theta_7 - r_3 \sin\theta_3}\right] - \theta_8 \qquad (17)$$

and position to be

$$x_{11} = r_1 \cos\theta_1 + r_4 \cos\theta_4 - r_9 \cos(\theta_9 - \Psi) \qquad (18)$$

and

$$y_{11} = r_1 \sin\theta_1 + r_4 \sin\theta_4 - r_9 \sin(\theta_9 + \Psi). \qquad (19)$$

Ambiguities in (17) caused by the inverse tangent function require special attention. Using quadrant information yielded by the x and y scalar equation components avoids multiple solutions.

B. Implementation

Implementing the MPHS theory required the development of hardware, software, and system interfaces.

1) Hardware: The hardware configuration consists of LPT's, mounts, cabling, and a computer enclosure (see Fig. 2).

Each Rayelco P-750A LPT[1] has a housing, a constant-force spring-driven take-up drum, 19.05 m (750 in) of wire, a gear reducer, and a 500-Ω potentiometer. The potentiometer wiper resistance is proportional to the length of wire played off the take-up drum. Placing an excitation voltage across the potentiometer's resistor converts this resistance into an output voltage at the wiper.

The two mounts pairing LPT's on either side of the mining machine's rear are roof-height adjustable. The mount design allows the LPT wires on one mount to slide over the top of the other when turning a crosscut. The wires attach in pairs to two stationary points behind the mining machine. Keeping these wires close to the roof reduces possible interference with haulage and other equipment. Locating the computer enclosure near the cab allows short lengths for the LPT connecting cables.

The LPT circuits are intrinsically safe (IS). Thus, riser flame-tested three pair shielded cable with standard 97 series connectors is permissible. The LPT cables link the LPT's to the computer enclosure. The LPT and user interface connector (UIC) cables enter the computer enclosure through five explosion-proof (X/P) packing glands. A Line Power 30-3301-25 X/P connector joins the UIC cable to the Bureau's Joy 14 CM or 16 CM mining machine. A 19.05-mm (0.75-in) MtP mine conduit hose sheaths the UIC cable.

The MPHS employs an Ocenco X/P 2387 as its computer enclosure. The enclosure contains the battery, battery charger,

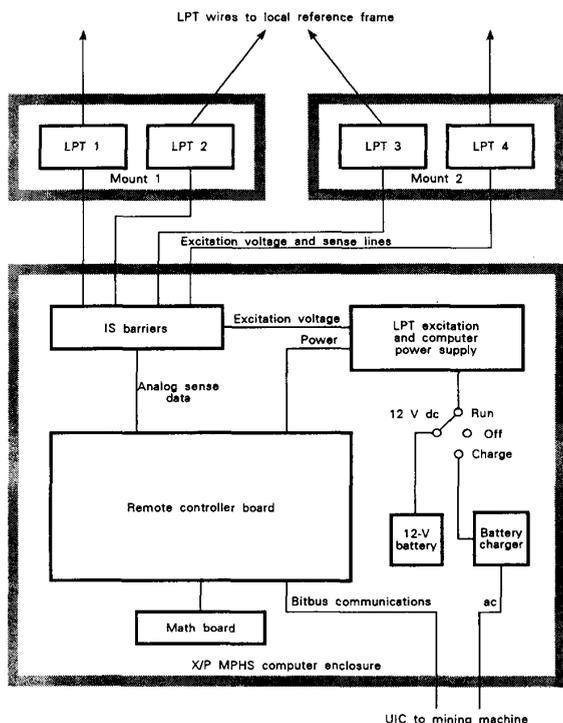[1] Reference to specific products does not imply endorsement by the Bureau of Mines.

Fig. 3.   Block diagram of the MPHS computer enclosure.

Fig. 4.   Data flow diagram for the Bitbus node tasks.

and power supply (see Fig. 3 for a block diagram of the MPHS hardware). A 12-V, 12-A-h gell cell allows self-contained operation of the MPHS during testing. A 12 V DC/DC converter (rated at ± 12 V @ 310 mA and +5 V @ 1.5 A) provides power to the controller and LPT circuits. Applying ac to two pins in the UIC while the mining machine is in fresh air provides power to the battery charger. An X/P switch on top of the computer enclosure selects the run, charge, and off states. An MPHS current draw of 1.26 A at 12 V limits operation to about 9 hr 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 V to +4.5 V. The MPHS controller is an Intel iRCB 44/20A Analog I/O Controller. An Intel iSBX 331 Fixed/Floating Point Math Multimodule Board occupies the controller's iSBX connector. The math board allows the MPHS algorithm to perform floating point calculations necessary to process the LPT analog data. The MPHS controller communicates through the UIC using Intel's Bitbus network on a four wire RS485 protocol interface.

2) Software: The MPHS software has a node specification, task structure, and algorithm.

The node specification reflects the protocol defined by the Bureau of Mines Network (BOM/NET) for communication with the MPHS node. This specification defines how to request data or status, issue commands, and interpret responses. These communications are data requests, control commands, and status requests. Data requests allow the requestor to obtain
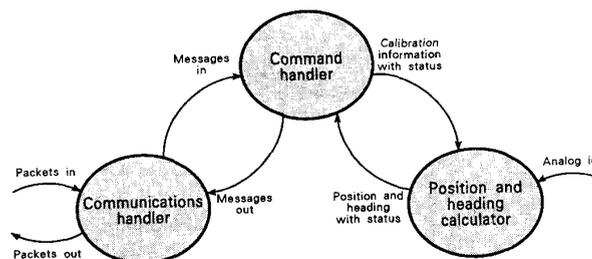
data on any of three levels of calculation complexity. Control commands enable modification of the node's state or variables. Status requests allow a requestor to determine the MPHS node status.

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 (see Fig. 4). The communications handler receives message packets addressed to the MPHS node and returns the requested information to the sender. The command handler transfers information between the communications handler and the position and heading calculator. The position and heading calculator receives calibration, zeroing, attachment location, and transducer location information from the command handler. The calculator program also reads the LPT analog data. The calculator returns the position, heading, status, and confidence to the command handler at a rate of about 5 Hz.

The MPHS algorithm is a subset of the calculator task and uses the theory already discussed. Using the four-transducer solution as an estimate allows the selection of the appropriate member of each pair of three-transducer solutions. *A priori* information (initial configuration, the sign of the angular rotation of the mining machine, mining machine commands issued, etc.) is available to assist this task. Using this information for error identification alone is, however, inefficient. Averaging the four remaining three-transducer solutions yields a usable position and heading solution.

Determining the average magnitude of difference between the average and the four three-transducer solutions allows the calculation of a confidence. The average magnitude of difference generates the confidence for the variables x, y, and heading:

$$confidence = \left[\frac{tolerance - avg.\ mag.\ of\ diff.}{tolerance} \right]. \qquad (20)$$

The tolerances determining the confidence are 76.2 mm (3 in) for x and y and 0.0262 rad (1.5°) for the heading. These same tolerance values, which will be used later, determine an accuracy value for the calculated position and heading.

If the confidence calculated for a variable is less than zero, the associated confidence is set to zero. The RMS value of the three confidences yields system confidence. If any of the confidences are zero, the system confidence is defined as zero. If any processing errors occur during operation, the
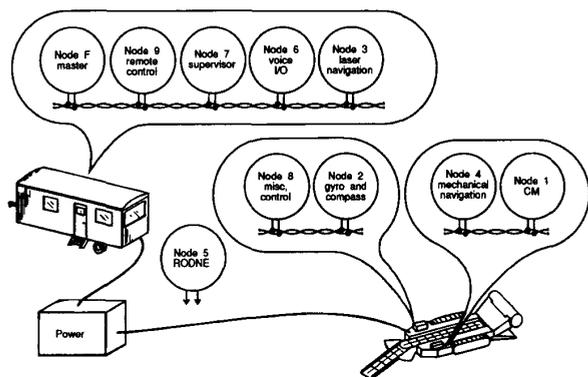
Fig. 5.   BOM/NET for the field trial system with the Joy 14 CM.

Fig. 6.   Data for advance. Top: position and heading; bottom: confidence and accuracy.

math module returns a system confidence of zero and an error status. If the confidence is nonzero, the position and heading calculator supplies its results to the command handler.

3) System: The MPHS is a BOM/NET node that can operate on either the Joy 14 CM or 16 CM networks. These mining machines are the Bureau's testbeds for autonomous mining machine experiments. Fig. 5 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. The master node forms a modified star network by passing all traffic between the nodes. Thus, any node requiring position and heading information can obtain it from the MPHS quickly.

III. TESTING THE MECHANICAL POSITION AND HEADING SYSTEM

Testing the MPHS proved the idea and its feasibility. Testing the MPHS involved setting up experiments, devising experimental procedures, and obtaining and analyzing experimental test results.

A. Setup

The experiment required that the LPT wires connect to a wood mockup of a mobile control structure (MCS). The MCS provided an attachment point for two pairs of wires and a stationary local reference frame for the MPHS. The LPT mounts attached to the rear of the Joy 14 CM mining machine (as shown in Fig. 2). The operator's cab of the mining machine housed the computer enclosure. A laser transit providing accurate position and heading data supplied a benchmark for the MPHS data.

B. Procedure

The experimental procedure devised examined two cases. The first case examined the mining machine executing a 12.192-m (40-ft) forward advance (as if traversing an entry). In the second case, the mining machine turned a 1.571 rad (90°) left crosscut and advanced 6.096 m (20 ft). Manually tramming the mining machine for about 1 s at a time while modeling each case allowed data collection. Data collection via a transit and the MPHS occurred during each pause.
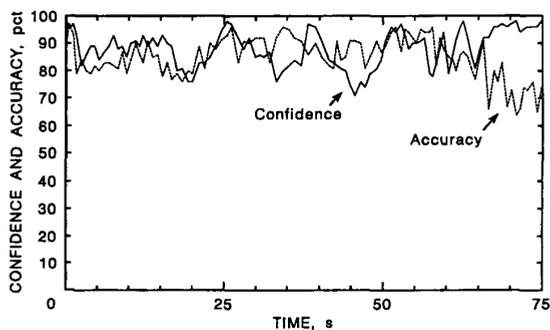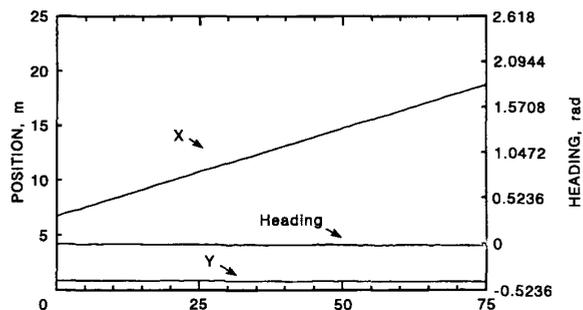
C. Results

Fig. 6 shows the results of the forward advance experiment. The results shown in Fig. 7 are from the crosscut experiment. The top chart in each figure shows the position and heading information obtained from the MPHS during each experiment. The bottom portions of these figures show the transit measured accuracy versus the MPHS calculated confidence.

The MPHS system accuracy is calculated in much the same manner as the confidence at each data point. The difference between the estimated and actual values for variables x, y, and heading generates a normalized accuracy:

$$accuracy = \left[\frac{tolerance - |estimated\ pos. - actual\ pos.|}{tolerance} \right].$$
(21)

If the resulting normalized accuracy for any of these variables is less than zero, the associate normalized accuracy is defined as zero. The RMS value of the three accuracies yields the system accuracy. If any of the normalized accuracies are zero, then the system accuracy is defined as zero.

The confidence and accuracy data resulting from the experiment shows several results of interest:

• The first result of interest is that the system confidence in the calculated position and heading is within 10% of the system accuracy. This relationship shows the confidence generator and uses a viable computation method.

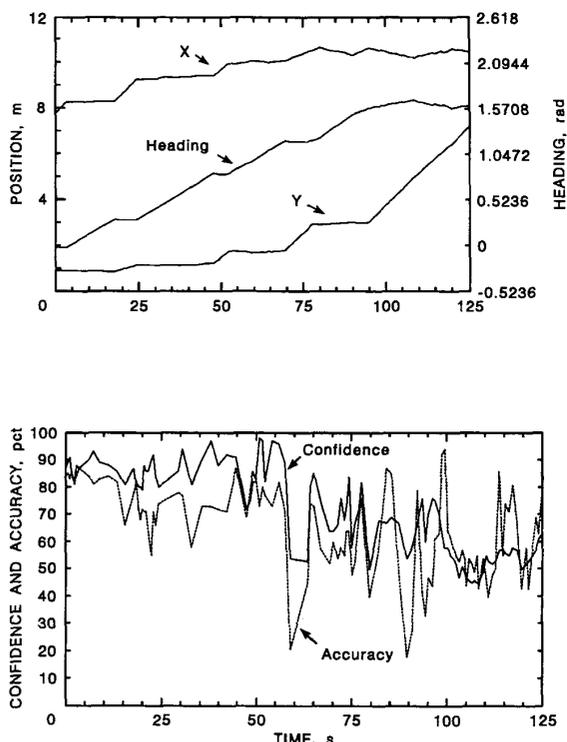• Next, there is a greater sensitivity to transducer errors at

Fig. 7.   Data for crosscut. Top: position and heading; bottom: confidence and accuracy.

headings far from zero. This expected sensitivity is due to the coupling of the sensor input values in the position and heading equations.

• Finally, the results show that the confidence of the MPHS is nonzero, confirming reliable operation.

IV. ERROR ANALYSIS

When performing measurements of any kind, it is usually more important to know the data's reliability than the actual data itself. Safety of personnel is extremely important in mining operations; therefore, ignorance of data reliability makes data less than useless (that is, dangerous). Sensor redundancy reduces the probability of an undetectable error to an insignificant level; however, the detectable errors affect the solution's accuracy.

Measurable, inherent errors exist in the sensors, A/D converter, and sample rate of the MPHS. The LPT's typically have a 0.1% full scale (FS) accuracy translating into ±9.53 mm (0.375 in) for the LPT's used. The A/D converter used has a 0.035% FS error. Combining the A/D error with the LPT error in a root sum squared (rss) manner yields a 0.106% FS error of ±10.1 mm (0.397 in). A sampling rate of 5 Hz yields a 32.9 mm (1.30 in) and 0.0113 rad (0.646°) error for the mining machine used.

Due to the nature of the MPHS algorithm, these errors affect the solution's accuracy, depending on the mining machine's position and heading. Therefore, a simple method is not available to determine the system accuracy. System error determination employs three techniques: numerical analysis, algebraic analysis, and experimental analysis.

A. Numerical Analysis

A program written in C simulating the MPHS with its inherent errors performs several tasks. The program first simulates the motion of the mining machine using the appropriate tramming commands and calculating the actual position and heading. Next, the simulator calculates the expected lengths of the LPT's for the mining machine's position and heading. A random error within calibration limits introduced into the simulated LPT readings provide realistic data. The MPHS algorithm uses these simulated LPT readings to compute the mining machine's position and heading. The calculated position and heading when compared with the actual position and heading yield a system error.

Using this method for many positions and headings show the system error to depend on the mining machine position, heading, and configuration. The system error determined is usually within the tolerances used for the calculation of the confidence. These tolerances are ±76.2 mm (0.25 ft) in the x and y position and ± 0.026 rad (1.5°) in the heading.

B. Algebraic Analysis

The standard method for computing the combination of component errors in system-accuracy calculations for the MPHS algorithm is complex [3]. This method requires taking the partials of the x, y, and heading equations with respect to each of the four LPT lengths. Thus, space does not permit including the resulting equations in this paper. The method itself, however, is simple:

1. Make a table of all data points, each with its plus-or-minus error attached.
2. To compute the x position determined by a three-transducer solution, where $x = f(r_1, \theta_1, r_3, \theta_3, r_4, r_5, r_6, r_8, \theta_8, r_9, \theta_9)$, take the partial derivatives $\partial f / \partial r_4$, $\partial f / \partial r_5$ and $\partial f / \partial r_6$ and evaluate the function by substituting the values of r_4, r_5, and r_6.
3. Compute

$$E_{a_{rss}} = \sqrt{\left(\Delta r_4 \frac{\delta f}{\delta r_4}\right)^2 + \left(\Delta r_5 \frac{\delta f}{\delta r_5}\right)^2 + \left(\Delta r_6 \frac{\delta f}{\delta r_6}\right)^2}.$$

(22)

Here, $E_{a_{rss}}$ is the systemic error in rss absolute terms for the configuration described by r_4, r_5, and r_6. The systemic error is close to the error predicted by the numerical method and varies with the position and heading.

C. Experimental Analysis

Figs. 6 and 7 show an experimental analysis of the system error. The nonzero confidence and accuracy shows the system error falls within the tolerance parameters set.

V. CONCLUSIONS

The mechanical position and heading system (MPHS) developed works reliably. The MPHS yields position, heading, status, and confidence data in response to linear position transducer (LPT) inputs. The confidence supplied with each position and heading calculation reflects the actual system accuracy. The system accuracy is better than ±76.2 mm (3 in) in the x and y position and ±0.026 rad (1.5°) in the heading. The advance and crosscut tests performed verified this accuracy. The system accuracy depends on the position and heading of the mining machine and the LPT input errors. Although the errors incurred by the MPHS may be acceptable in a mining environment, better LPT transducers are available to improve accuracy.

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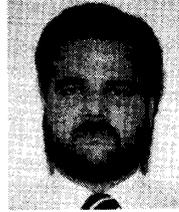
Christopher C. Jobes received the Bachelor's degrees in engineering and mechanical engineering from Geneva College in 1982 and 1983, respectively. He then received the Master's and Ph.D. degrees in mechanical engineering from West Virginia University, Morgantown, in 1985 and 1987, respectively.

In 1988, he joined the Electrical and Electronic Systems Group of the U.S. Bureau of Mines' Pittsburgh Research Center as a Mechanical Engineer, where he performs research into computer-assisted mining. He has been working on navigation systems for in-mine use and, most recently, on the controller architecture to be used to attain autonomous control of a mining machine.