Overview of the US Bureau of Mines' research in position and heading systems for mine machine guidance

J.J. Sammarco, D.L. Anderson and C.C. Jobes

Abstract — *Computer-aided control of a mining machine places its operator in a safe, remote location, thus reducing health and safety risks. Sensing systems that provide machine position (xy coordinates) and heading (yaw) are extremely useful in aiding remote positioning of mining machines.*

The US Bureau of Mines (Bureau) developed two sensing systems for position and heading information: a scanning laser system based on the Lasernet sensor and a mechanical position and heading system based on linear-position transducers. The Bureau is also investigating a system from Honeywell, the modular azimuth and positioning system (MAPS), that employs ring-laser gyroscopes (RLGs).

This paper presents a brief background and status of these sensing systems as applied to a continuous mining machine (CM). Included are field test results of each system operating in a room-and-pillar research section at a cooperating West Virginia mine.

Laser-based guidance system

The laser-based guidance system employs four laser scanning sensors at fixed locations in a mine entryway to report the angular coordinates of two cylindrical retroreflective targets mounted on a CM. Using triangulation, a real-time microcomputer system processes the sensor data and updates the xy position and heading (h) of the CM five times per second (Anderson, 1989). Using a simple control algorithm and communications interface to the CM control computer, the system also controls rotational and translational tram maneuvers.

Researchers first took the laser system underground in early 1991 and performed several experiments (Anderson, 1991). Figure 1 shows the experimental setup. The Lasernet sensors are mounted on two tripods located at fixed positions on both sides of a mock entryway. Two cylindrical retroreflective targets are mounted on the tail end of the CM. During underground experimentation, Lasernet sensors were housed in explosion-proof enclosures and mounted on two poles at fixed positions on both sides of the entryway (Fig. 2), 7.62 to 9.14 m outby the face.

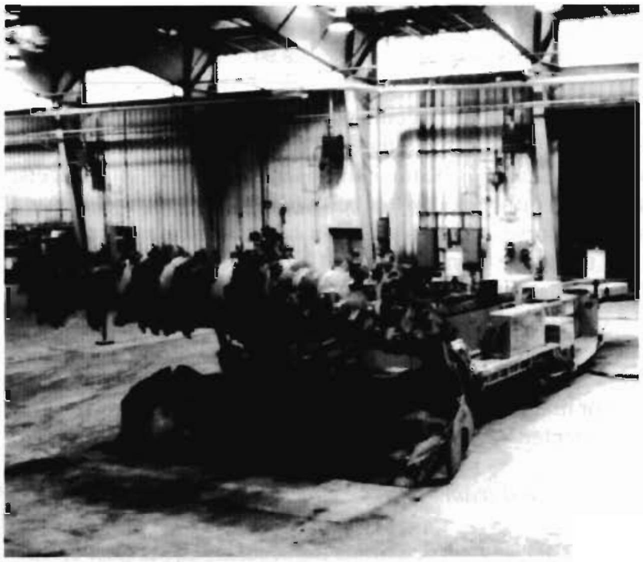


Fig. 1 — Experimental set-up at the Bureau's test facility, retroreflective targets on a Joy 16CM and Lasernet sensors on tripods.

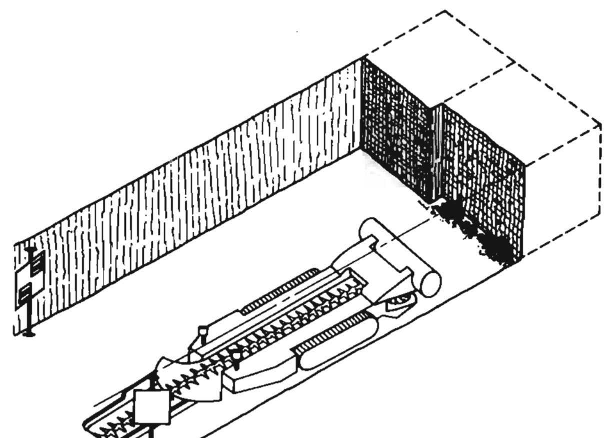


Fig. 2 — Lasernet guidance system, with targets on the CM and Lasernet sensors in the entryway.

Reliability

The most crucial factor in maintaining the laser system's reliability is keeping the targets within the Lasernet sensor's 110° field of view. While 110° easily covers an entryway, Lasernet sensor's target detection range has a 10.67-m limit. However, extended-range Lasernet sensors with a 30.48-m target detection range are currently available.

J.J. Sammarco, **D.L. Anderson** and **C.C. Jobes** are electrical engineer, electrical engineer and mechanical engineer, respectively, US Bureau of Mines Pittsburgh Research Center, Pittsburgh, PA. SME preprint 92-150, SME Annual Meeting, Feb. 24-27, 1992, Phoenix, AZ. Manuscript Dec. 6, 1991. Discussion of this peer-reviewed and approved paper is invited and must be submitted, in duplicate, prior to Oct. 31, 1993.

Table 1 — Lasernet tracking and tram control accuracy.

Tram maneuver	Translation, cm: Transit measurement	Lasernet measurement	Error, cm: Lasernet tracking	Lasernet control
Tram reverse 101.6 cm	97.43	97.16	0.28	4.17
Tram forward 91.44 cm	82.83	82.65	0.18	8.61
Tram reverse 101.6 cm	105.92	105.89	0.03	−4.32
Tram forward 91.44 cm	98.30	98.17	0.13	−6.86
Tram reverse 96.52 cm	98.58	98.40	0.18	−2.6
	Rotation, °		Error, °	
Pivot right 15°	13.10	12.83	0.27	1.9
Pivot left 12°	11.43	11.20	0.23	0.57
Pivot right 15°	13.04	12.52	0.52	1.96
Pivot left 15°	13.71	14.10	0.61	0.29
Turn reverse right 10°	10.67	10.43	0.24	−0.67
Turn forward left 10°	10.23	9.86	0.37	−0.23
Turn forward left 7°	6.92	6.78	0.14	0.08
Pivot left 10°	9.94	9.77	0.17	0.06

Another problem occurs with an unusually irregular floor. Position and heading updates of the CM become unavailable when the scanning beam of the laser doesn't cross the targets, scanning either above or below the target surface. As a solution, researchers used taller targets, increasing the vertical tolerance from 0.35 m to 0.46 m. They also added two Lasernet sensors, each mounted 0.15 to 0.30 m higher than the original two sensors, thus increasing the system's vertical tolerance from 0.35 m to 0.76 m. An alternative solution would be to add a mechanical mirrored assembly to the sensor that would sweep the beam vertically when no targets are detected.

Tracking and tram control accuracy

The data taken to determine the accuracy of the laser system in tracking position and heading and controlling the tram maneuvers of the Joy 14CM in both the Bureau's Mine Equipment Test Facility (METF) and underground were promising. The first experiment showed accuracy in tracking the position and heading of the CM as it performed a variety of maneuvers underground. After each move, a transit reading verified the xy position and h of the CM. Average errors were: h, 0.4°; x position, 1.65 cm; and y position, 0.51 cm.

The second experiment shows the accuracy in tracking and controlling the translations and rotations of the CM. Table 1 depicts the test results. Column 1 shows the desired tram maneuver. Column 2 shows the actual translation or rotation of the CM, calculated by using two transit measurements taken before and after the maneuver. Column 3 shows the translation or rotation measured by the laser system. The final columns show errors for determining Lasernet accuracy. Average measurement errors were 0.16 cm translation, 0.3° rotation. Average control errors were 5.2 cm translation, 0.7° rotation.

Supporting experiments

Related underground experiments on computer-assisted mining systems used the laser system to track and control the tramming of the CM. The laser system was an integral part of two experiments to test the first fully controlled, automatic execution of multiple sump-shear cutting cycles. The first experiment used a preprogrammed coal removal script created and executed by the autonomous mining research and development system (AMREDS), a window-based computer program developed by the Bureau and Carnegie Melon University (Ausefski, 1990). The second experiment used Carnegie Mellon University's MINENAV software to dynamically plan the maneuvers and appendage commands necessary during a two-pass mining sequence.

In the first experiment, AMREDS automatically executed sump-shear cycles by a preprogrammed script of fully-controlled CM functions, first with a Joy 16CM cutting coalcrete in METF, then with a 14CM cutting coal underground (Anderson, 1989). Underground, seven scripts ran sequentially with human intervention limited to "pauses" to let the shuttle car empty and to issue the script start command. Each sump was fixed at 0.56 m. The average error in sump distance was 1.93 cm, and the average sump rate was 2.79 cm/s (Table 2).

In the second experiment, researchers tested MINENAV software for dynamic planning and executing a two-pass (box and slab cut) mining sequence. The MINENAV software includes algorithms for controlling the CM and its appendages' maneuvers during the mining sequence. MINENAV used Lasernet to track xy and h, and to characterize the Joy 14CM's tram velocities underground. Using Lasernet xy and h updates and controlled translational and rotational maneuvers, MINENAV successfully maneuvered the Joy 14CM through the transition from box to slab cut.

Laser system conclusions

Results of the underground experiments show promise.

Table 2 — Tram control and rate during sump.

Distance traveled, cm	Error, cm	Sump rate, cm/s
56.64	0.89	3.91
58.57	2.69	3.23
55.58	− 0.31	4.01
53.34	−2.03	2.29
54.41	−1.47	2.21
53.54	−2.34	1.93
54.41	−1.47	4.09
51.51	−4.37	2.85
54.05	−1.83	2.03
53.77	−2.11	1.40

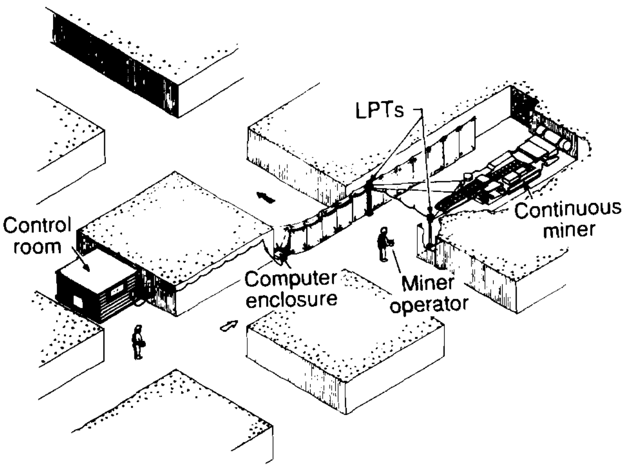
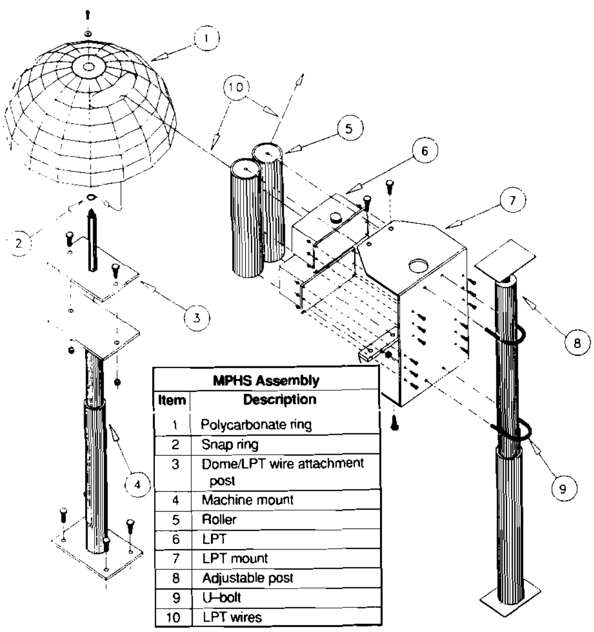


Fig. 3 — Setup for MPHS underground test.



Item	Description
1	Polycarbonate ring
2	Snap ring
3	Dome/LPT wire attachment post
4	Machine mount
5	Roller
6	LPT
7	LPT mount
8	Adjustable post
9	U-bolt
10	LPT wires

Fig. 4 — Assembly drawing of MPHS mount\post pair.

The system tracks the CM's position to better than 2.5-cm accuracy and the heading to better than 0.5°. Tram control accuracies are better than 10.2-cm translation and better than 2° rotation. For more extensive and practical use of Lasernet, an extended-range Lasernet sensor with a 30.48-m detection range is recommended. A mechanical device for vertically sweeping the beam could be added to the sensor to best combat problems with irregular floors. In addition, the laser system can be applied to other mining equipment, such as shuttle cars and roof bolters. Simple alterations would make the system capable of tracking any vehicle equipped with retroreflective targets.

MPHS

The MPHS is based on linear position transducers (LPTs) and operates on principles of triangulation to provide machine position (xy coordinates) and orientation in the xy plane (yaw or heading). These data are needed to keep the CM in proper alignment before and during the cutting cycle. The MPHS measurement hardware configuration consists of mounts, LPTs, cabling, a computer enclosure and a data

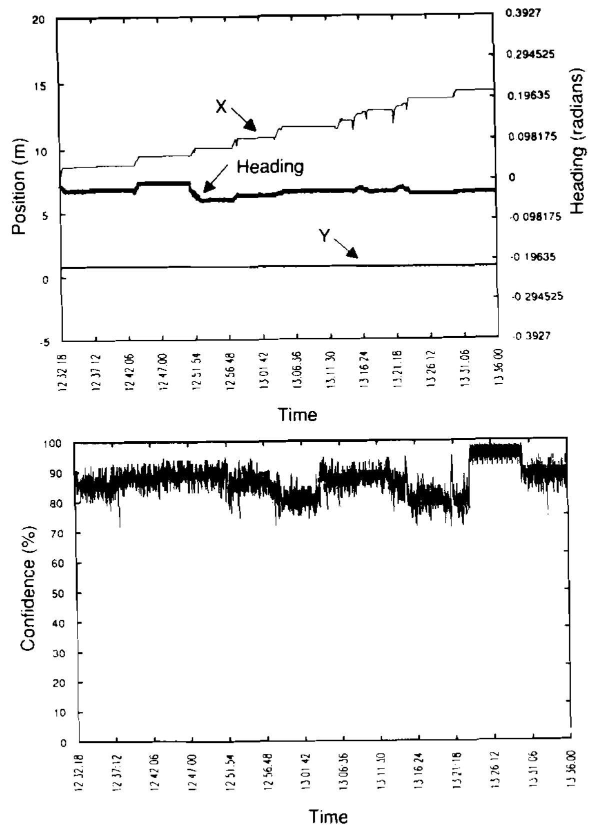


Fig. 5 — Data for first cut of MPHS underground test.

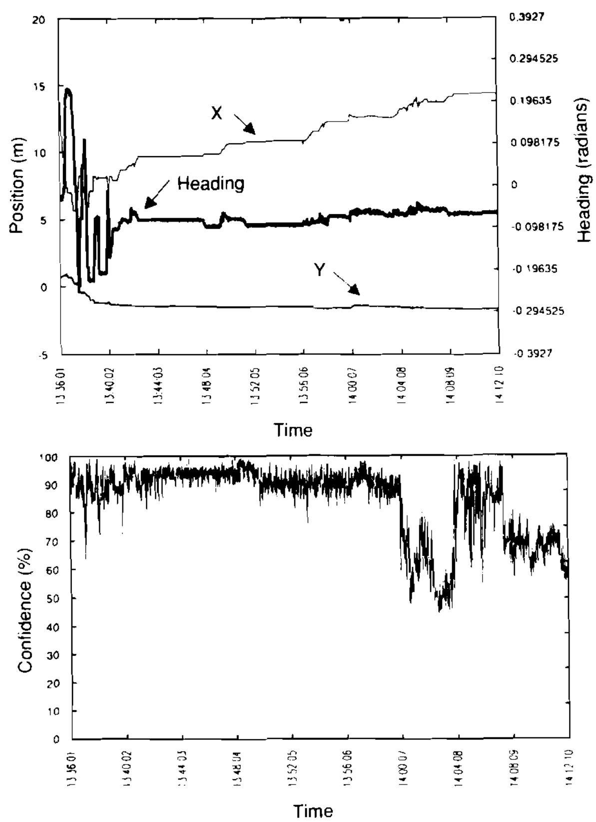


Fig. 6 — Data for second cut of MPHS underground test.

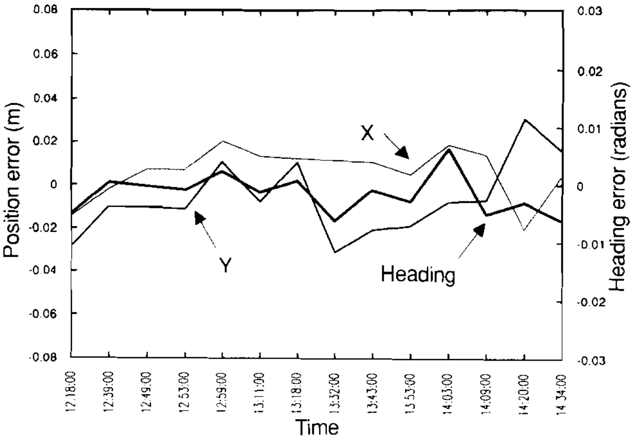


Fig. 7 — Laser transit verified accuracy for first two cuts of the MPHS underground test.

collection computer. The MPHS software was written in computer languages PL/M-51 and ASM-51. The MPHS system interfaces to a distributed computer network that the Bureau integrated to a mining machine for computer-assisted control.

The MPHS's sensory system has four LPTs in stationary positions. The wires of these LPTs attach to two points on the CM (Fig. 3). The MPHS controller processes the linear distance sensor data in the computer enclosure, giving the CM's position and heading. Sensor redundancy allows constant testing of the guidance system accuracy and generation of a position and heading confidence as reported by Jobes (1990). A nonzero confidence means that the solution is within tolerance. With higher confidence comes higher accuracy. Analysis of the surface test results shows that the MPHS is reliable and can, therefore, provide useful guidance information for in-mine navigation (Jobes, 1991).

The MPHS underground test

The LPTs are mounted in pairs on stationary posts (Fig. 4) on each side of the entry. The LPT wires connect to the CM, keeping close to the roof to avoid obstacles. Intrinsically safe (IS) instrument cables connect the LPTs to the computer enclosure located in fresh air. All cables in traffic areas hang from the roof or ribs to minimize cable damage. A communication cable connects the computer enclosure to a control room behind the operation. The data collection computer, located in the control room, operates and collects data from the MPHS.

The experimental procedure examined a two-pass, two-cut advance (only the first cut is presented here). The entry width and depth were 6 m and 9.75 m, respectively. The mining machine operator directed the mining machine to mine this block of coal with the radio control pendant. The data collection computer took MPHS data during the mining operation at one-second intervals. A laser transit took the mining machine position data during each pause in operation by sighting reflectors on the attachment posts. Using the time stamps on both the MPHS and the transit data, the researchers compared the data to confirm the MPHS's accuracy.

Figures 5 and 6 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 cuts. The bottom portions of these figures show the MPHS calculated confidence. Figure 7 shows the MPHS vs. transit position and heading accuracy for the first two cuts.

Table 3 — Transit vs. MPHS data analysis.

Variable	Mean difference	Maximum difference	3σ error limit
x	0.637 cm	2.05 cm	3.52 cm
y	0.607 cm	3.10 cm	5.25 cm
h	0.09°	0.365°	0.61°

The accuracy data resulting from the experiments show several interesting results:

- The x and y values change slightly during pivots due to slippage and the uncertain location of the CM's center of rotation.
- The confidence supplied by the MPHS for the first two cuts averaged 86%, a much better accuracy than the allowable tolerances of ±76.2 mm for x and y position and ±0.026 rad for heading (h).
- Table 3 shows the transit-verified accuracy for the first two-pass cuts, which supports the high confidence levels supplied by the MPHS.

MPHS Conclusions

The Bureau-developed MPHS works reliably under field conditions. The MPHS yields position, heading, status and confidence data in response to linear position transducer (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 for x, 52.5 mm for y and 0.0106 rad for heading. While errors incurred by the MPHS are acceptable in a mining environment, there exist better LPT transducers that could further improve accuracy.

MAPS

MAPS is an RLG-based inertial system providing azimuth reference from true north, elevation, pitch, roll and xy position data. Unlike Lasernet and MPHS, MAPS is a self-contained system and can mount directly on the mining machine, thus making MAPS a simpler, more flexible system. MAPS consists of a dynamic reference unit (DRU) and a control and display unit (CDU). The DRU is the heart of the system and contains three RLGs and accelerometers. The CDU provides a means to input control commands and data to the DRU. In addition, MAPS can survive harsh conditions with significant reliability.

The Bureau began two phases of testing MAPS' capability and accuracy under contract JO309018 with Honeywell Military Avionics Division. Phase I, now completed, involved evaluating MAPS operation and accuracy on a Joy 14CM cutting a 6-m lift of coal at an experimental mine (Sammarco, 1991). MAPS was installed on a Joy 14CM, modified by the Bureau to collect data on machine appendage motions, pitch, roll, vibration and radio commands from pendant-control of machine operation. Phase II involves refinement of MAPS based on Phase I results.

Establishing zero velocity

For accurate tests, researchers must establish "zero velocity" (when the machine remains relatively stationary) for the Joy 14CM as it cuts a lift of coal. While the machine is

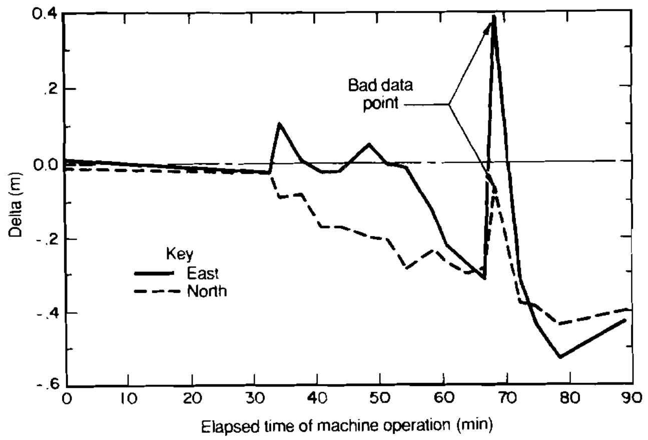


Fig. 8 — Position deltas during elapsed time of machine operation.

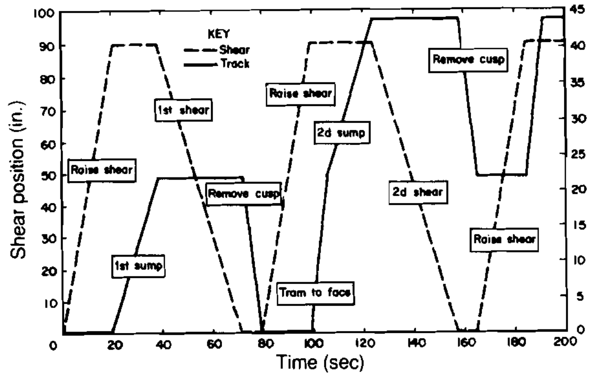


Fig. 9 — Computer-controlled cutting cycle.

stationary, MAPS takes zero velocity update (ZUPT) data used for MAPS correction purposes. Should the DRU detect any motion over a preset level defined as a zero velocity, it would terminate the ZUPT. Zero velocity can be set at different levels so that the DRU ignores insignificant movements. To determine that the DRU has stopped, Honeywell passed delta velocity accumulation (data for the accelerometers) through a least-squares filter and calls these data VELOCITY NOISE. When this filtered value falls below 3.0e–5 m**2/sec**2, the DRU acquires data.

DRU test results

With MAPS, error sources are generally not distinct. Certain types of errors, such as software coding errors, may have an effect only under certain conditions. The discussion below documents the error sources found during Phase I. While only one source of error is discussed in a given graph, other error sources may also be active. A given graph addresses only that error that can be 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 8 is the delta plot between the DRU and the transit data. A delta of 0 indicates that the DRU and the 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. Note that these are scalar components. The total error, which is a vector quantity, was determined to be 71.12 cm in magnitude, with an angle of 62° after about 1 hr of operation.

Data analysis indicates the system is abnormally sensitive to vibration, as evident in Fig. 8. During the elapsed time from 0 to 35 min, the mining machine was experiencing relatively low levels of vibration since only about 70% of the cutting head was in contact with the coal face. In the remaining time from 35 to 90 min, the cutting head was in full contact with the coal face, and the machine experienced high levels of vibration. One could see the machine "bouncing" during sump and shear operations.

Other programs within Honeywell document vibration sensitivity, thus reinforcing conclusions of abnormal vibration sensitivity. Around the same time as Phase I data analysis of this project, the US Army was conducting tests under controlled vibration conditions as part of the acceptance testing for the MAPS software. The vibration test failed. Since then Honeywell has identified and corrected the failure in the MAPS software.

Related to system vibration and translation is the taking of ZUPT data during sump and cutting actions. ZUPT data should not be taken during sump since the machine advances half the cutting drum's diameter, about 55.88 cm. Advancing 55.88 cm during a sump occurs at a very slow rate, hence the DRU must be able to recognize this and not take ZUPT data. Test results show that no data for ZUPT were taken during sump actions. 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.

Careful comparison of COUNT and VELOCITY NOISE shows a minor, correctable source of error: the mining machine had not stopped for 5 s when COUNT was incremented. This means that velocity data containing motion were included within calculations for ZUPT. This is 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 stopped long enough to warrant a ZUPT.

The Bureau informed Honeywell about other projects concerning computer-assisted CMs. One project was the computer control of the CM through a cutting cycle. The Bureau submitted the sample cutting cycle to Honeywell for evaluation (Fig. 9). One observation was that the mining machine only stopped during the shear-up operation. The demonstration data were analyzed to determine if a similar event had occurred, and it had. However, it is not identical because there was some motion during the early part of the shear operation.

MAPS conclusions

The first phase of the program determined the general feasibility of using the MAPS for this application. The DRU's combined track and cross-track position error was 63.5 cm/hr. Certain performance problems have been identified and can be corrected by software modifications.

The first problem is that the time between the CM's stops necessary to perform ZUPT exceeded 1 min; a ZUPT should occur at least once every minute. The solution comes from the Bureau — a computer-assisted mining sequence that includes sufficient time for ZUPT. Testing is recommended to assure the success of the Bureau's system.

The second problem is vibration sensitivity, which, according to Honeywell, also occurs in other programs using MAPS baseline software. The solution is a minor change to the software, on which a Honeywell research team is currently working. Further testing should confirm their findings.

The third problem deals with the erroneous data collections for ZUPT. This can be solved by a minor logic change in the DRU software.

In conclusion, since the identified errors have workable solutions, the basic operating characteristics and basic philosophy of using the DRU as a self-contained, inertial land navigation unit merits another phase of investigation. Phase II tests should, at least, encompass the detailed recommendations presented in this report, along with the proper software modifications.

Conclusions

All three of the navigation systems show promise. With proper implementation each can perform the navigation task assigned to it. The accuracy and applicability of each system do, however, vary.

The Lasernet guidance system tracks the CM's position to better than 2.54-cm accuracy and the heading to better than 0.5°. The MPHS 3σ accuracy is better than 3.52 cm for x, 5.25 cm for y, and 0.61° for h. The MAPS unit accuracy, after one hour of operation without the Phase II software corrections, was 71.12 cm in magnitude and 62° in heading.

To varying degrees, these guidance systems can be applied to CMs, roof bolters, shuttle cars and other mobile mining equipment. The MAPS unit is the most flexible and the MPHS is the most restrictive in their application.

The effort to find a usable guidance system for underground mining equipment is continuing at the Bureau. The guidance systems reported here are the best found to date; several more await testing. Reports on these, and the later phases of the documented guidance systems, are forthcoming.♦

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