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# Laser Tracking and Tram Control of a Continuous Mining Machine

By Donna L. Anderson



# U.S. Bureau of Mines Spokane Research Center E. 015 Montgomery Ave. Spekano, VA - 90007 LIERALLY

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UN	UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT									
deg	degree	ms	millisecond							
ft	foot	pct	percent							
in	inch	r/s	revolution per second							
m	meter	S	second							
mg/m <sup>3</sup>	milligram per cubic meter									

# LASER TRACKING AND TRAM CONTROL OF A CONTINUOUS MINING MACHINE

By Donna L. Anderson<sup>1</sup>

# ABSTRACT

This U.S. Bureau of Mines report discusses the status of a laser-based guidance system to provide position and heading feedback and closed-loop control of tramming maneuvers for a continuous mining machine. The system has been developed and tested at the Bureau, and is now being prepared for underground experiments. The system hardware includes laser scanners, a sensor communication network, and host computer hardware. The system software includes a position and heading computation module and a tram control module. The description of the software includes discussions of laser data acquisition, error compensation methods, position and heading determination, safety checking for continuous miner tramming, and closed-loop tram control. The accuracy of the laser scanner's data, the reliability of the lasers in a dusty environment, and the system's accuracy on tracking the position and heading of the continuous mining machine are shown in the results of experiments performed at the Bureau. Conclusions are stated based on these experimental results, and further work to improve the system performance and prepare for underground testing is discussed.

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# INTRODUCTION

This report documents the status of the U.S. Bureau of Mines research into navigation in mines. The objective of this research is to support the Bureau's development of computer-assisted mining operations. Computer-assisted navigation will support the effort to relocate mine equipment operators further from hazardous areas. This will result in an increase in health and safety, and will provide a more controlled process for mining, thereby increasing mining efficiency.

The current research focuses on the guidance of a continuous mining machine as it is taking straight-ahead cuts and turning crosscuts during two-pass room-and-pillar type mining. The initial focus of the research was to develop a system to provide sensory feedback on the position and heading of the continuous miner.<sup>2</sup> The current focuses are to improve the accuracy of the position and heading determination system, to use the feedback to control continuous miner tramming, and to prepare the system for underground experiments.

A laser-based sensory system to provide feedback on the position and heading of a continuous mining machine was presented in previous Bureau work. The system includes laser-scanning sensors, which report the angular coordinates of retroreflective targets. The lasers, located on a stationary reference structure, horizontally scan a beam of laser light across targets mounted at fixed locations on the continuous mining machine. A conceptual drawing of the system is shown in figure 1. When the angular coordinates of at least three targets are given by a single laser (fig. 2), or the angular coordinates of the same two targets are given by two lasers (fig. 3), the position and heading of the continuous miner relative to the laser's reference location is determined.



Figure 1.-Laser scanners on reference structure viewing targets on continuous mining machine.

<sup>&</sup>lt;sup>2</sup>Anderson, D. L. Position and Heading Determination of a Continuous Mining Machine Using an Angular Position-Sensing System. BuMines IC 9222, 1989, 8 pp.



Figure 2.—Three targets (A, B, C) in field-of-view of single laser (L1).

This system has been revised and further developed to provide feedback for control of continuous miner tramming. The following is a description of the current



Figure 3.—Two same targets (A, B) in field-of-view of two lasers (L1, L2).

system for controlling continuous miner tramming using the laser-scanning sensors to provide feedback of machine position and heading.

## SYSTEM HARDWARE

Figure 4 shows the hardware components of the laser guidance system. They consist of laser-scanning sensors, retroreflective targets, hardware for the RS-485<sup>3</sup> sensor communication network, the Sun 3/160<sup>4</sup> host computer system, the BITBUS distributed control network, and the machine control computer testbed for autonomous mining

<sup>&</sup>lt;sup>3</sup>The standard for electrical characteristics of generators and receivers for use in balanced digital multipoint systems.

<sup>&</sup>lt;sup>4</sup>Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.



Figure 4.-Lasernet guidance system components.

machine experiments (TAMME). An overview of the hardware in the current system and revisions to the previous system are detailed.

## LASER-SCANNING SENSORS AND RETROREFLECTIVE TARGETS

The laser scanner used in the system is Lasernet, developed by Namco Controls, Mentor, OH (fig. 5). Lasernet contains an eye-safe class II laser light source, which is directed at a rotating mirror. The mirror sweeps a horizontal beam out the front window of the unit at a constant angular speed of 20 r/s. Lasernet has an angular field-ofview of approximately 105°.

The targets are made of retroreflective tape attached to a 10-in-diameter 18-in-tall cylinder. When the Lasernet's beam crosses a target, the beam is reflected back to the unit and detected by a photodetector. The targets can be detected by the unit out to a range of 21 ft. Upon request, the unit returns raw angular data, which is proportional to the angular coordinates of the detected targets. Figure 6 shows the current system in the Bureau's test facility. Three targets are colinearly mounted at a 30-in center-to-center spacing on a Joy 16CM continuous mining machine, the Bureau's available testbed for continuous miner guidance experiments. Two Lasernet units are mounted on a mockup of a mobile control structure (MCS).

The MCS mockup is serving as a reference platform for the position and heading feedback. The conceptual design and functionality of the MCS is described in the literature.<sup>5,6</sup> The position and heading of the continuous miner relative to the MCS can be calculated when enough angular coordinates are reported by the Lasernet units. The coordinate system in which the position and heading of the continuous miner is referenced is defined with respect to one unit, which has been designated the reference laser.

<sup>&</sup>lt;sup>5</sup>Work cited in footnote 2.

<sup>&</sup>lt;sup>6</sup>Anderson, D. L. Framework for Autonomous Navigation of a Continuous Mining Machine: Face Navigation. BuMines IC 9214, 1989, 23 pp.



Figure 5.-Lasernet laser-scanning sensor with retroreflective targets.



Figure 6.-Two Lasernet units on MCS mockup viewing three targets on Joy 16CM.

#### **RS-485 COMMUNICATION NETWORK**

Raw angular data from the Lasernet units are requested by and delivered to the host computer over a RS-485 communication network. The RS-485 network replaced the RS-232 communications used earlier so that multiple Lasernet units can be addressed on one communication line, and to increase the length of transmission line and the noise tolerance. The new system takes advantage of the two-wire balanced differential signals and the multidrop features of RS-485 communications. All Lasernet units are attached to common send and receive lines. Transmission lines as long as 1,200 m are possible. Also, the host computer now requires only a single RS-232 serial port, which is tied into the network via a RS-232 to RS-485 interface converter developed by Namco Controls.

Each Lasernet unit on the network is assigned a unique address. The format and content of the requests from the host computer are the same as the previous RS-232-based system, except that an address precedes the request. All units on the network always operate in a passive listening mode and receive the request; however, only the one unit specifically addressed will respond.

Communication errors are detected by the host computer through the monitoring of a checksum provided by Lasernet. These errors can occur if multiple units were addressed and trying to respond. Lasernet has a variable communication response time, which is managed by the host computer to avoid any situation where a data collision could occur.

#### SUN WORKSTATION

A Sun 3/160 workstation is currently functioning as the host computer, and is being used for the software development of the system. The Sun's programming includes a position and heading computation module and a tram control module. The modules are coded in the "C" programming language, and run under the UNIX operating system.

The UNIX environment was used for the formation of this navigational software because it is a superb system for software development. However, it was not intended to be used as the final operating system for continuous miner tram control. UNIX lacks many features of real-time control systems, such as quick and predictable interrupt response, fast task context switching, and the ability to attach easily tasks (software) to interrupts (hardware). On the other hand, UNIX offers many advantages that make it a useful part of a distributed real-time system. For these reasons, the position and heading and tram control software will be directly loaded to a single-board microcomputer system that runs a real-time, UNIX compatible operating system. This new system will allow compatibility with the Sun-UNIX environment, portability for in-mine experiments, and most importantly, real-time control of tramming.

#### TAMME AND BITBUS DISTRIBUTED CONTROL NETWORK

TAMME, the on-board machine control computer, executes the Joy 16CM functions requested by the Sun's tram control module. TAMME has been programmed to accept Joy 16CM commands in the form of packets of digital information, decode the information, and actuate the appropriate functions on the Joy 16CM. When the function has been successfully actuated, TAMME returns an acknowledgment to the Sun.

The Sun workstation and TAMME communicate over the BITBUS distributed control network through BITBUS nodes. Commands and acknowledgments are coded in the BOMNET machine command protocol developed by the Bureau for the Joy 16CM. The BOMNET protocol, BITBUS network, and TAMME are documented in the literature.<sup>7</sup>

# SYSTEM SOFTWARE

The current software on the Sun includes a position and heading computation module and a tram control module. These modules are described in the following sections.

## POSITION AND HEADING COMPUTATION MODULE

The position and heading computation module consists of routines for initialization of Lasernet and target parameters of the system, acquisition of Lasernet raw angular data, compensation of Lasernet angular coordinates errors, and calculation of position and heading. Figure 7 shows the order of processing.

<sup>&</sup>lt;sup>7</sup>Schiffbauer, W. H. A Microcomputer Network for Autonomous Mining Research. Ch. 85 in Proceedings of 21st International Symposium on Application of Computers and Operations Research in the Mineral Industry, ed. by A. Weiss. Soc. Min. Eng., AIME, 1989, pp. 928-935.





#### System Initialization

The system initialization routine reads a data file for system startup parameters. The data file includes information on Lasernet units and retroreflective targets. For each Lasernet unit, the data file includes the laser's location in the entry, field-of-view, range, communications address, error correction information, and polling status (indicating whether the unit is connected and active on the system, or a spare to be used at another time). For each target, the data file includes the target's location relative to the machine center.

This routine makes the system easily reconfigurable to suit different guidance tasks. To add or remove a particular Lasernet unit, the user changes the laser polling status; to relocate a unit, the user enters its new location. The other Lasernet parameters, such as field-of-view, range, communications address, and error correction data would be altered if a new unit is added to the system. If the targets were relocated on the machine, the user would also enter the new target locations relative to machine center.

#### Lasernet Data Acquisition

The data acquisition routine polls each Lasernet unit that is connected and operational on the RS-485 network and gathers the raw angular data. The routine also includes timeouts in the event of communication failures, disposal of any garbage data on the network, verifies checksums, and allows the option to take repetitive reads and average raw angular data to smooth out any erratic data.

The routine sequences through the list of lasers generated by the system initialization routine. If a laser is active, it reads the laser's address and sends a request for that laser's data in the form of "#," "address," and "< cr>". If no response is obtained in 60 ms, it is assumed that a communication failure has occurred and goes to the next active Lasernet. If a response is received, the routine looks for a valid data packet. Any garbage data are discarded until good data are received or no more data were returned. The routine verifies the data packet with a checksum comparison. Finally, the valid raw angular data are converted to radians and the angular coordinate is stored in memory.

#### Angular Coordinate Error Compensation

A compensation algorithm for angular coordinate errors is utilized once all angular coordinates have been acquired from a Lasernet. Extensive tests done at the Bureau on one of the units proved that the errors are a repeatable function of two parameters; the angular and the radial coordinates of the target.

These two parameters used by the error compensation algorithm are easily determined. The approximate angular coordinate of the target is given from the Lasernet unit. A trigonometric algorithm estimates the radial coordinate using two other angular coordinates given by the same Lasernet. The parameter values are then used by the error compensation algorithm to correct the angular coordinate, and the compensated angular coordinate is stored in memory. The test procedures, accuracy test results, and the error compensation algorithm are described in detail in the Test Results section of this report.

### **Position and Heading Updates**

The continuous miner's position and heading is calculated using the compensated angular coordinates. Two algorithms are employed and are documented in detail in the literature.<sup>8</sup> One algorithm calculates position and heading based on the compensated angular coordinates of three targets from one Lasernet unit, and the other on the coordinates of the same two targets from two Lasernet units.

When more than the minimum compensated angular coordinates for determination of position and heading are available, multiple determinations are computed. These multiple position and heading determinations are averaged together. Updates of continuous miner position and heading are provided five times per second.

### TRAM CONTROL MODULE

The tram control module consists of routines for checking the safety of requested tram commands before they are issued, monitoring the laser's position and heading updates to effect closed-loop control of Joy 16CM tramming, and interfacing to the Autonomous Mining Research and Development System (AMREDS) to utilize its user, graphical, and machine interface facilities. Figure 8 shows the order of processing.

#### Safety Checking on Tram Commands

The safety checking routine uses the machine's position and heading determinations to check the safety of each requested tram command, and, if determined safe, it issues the command to the machine. These safeguards are essential because computer-assisted operations will allow the continuous miner operator to be located farther away from the face, thereby limiting the operator's vision of the face area.

Tram commands are requested and delivered to the safety checking routine via the AMREDS tram control menu (described in the Interface to AMREDS section of this report). A command is depicted as a Joy 16CM tramming option with a target value. Continuous miner tramming options include tram forward (both tracks forward, high or low speed), tram reverse (both tracks reverse, high or low speed), pivot (one track forward, one track reverse, low speed), turn forward (one track forward), and turn reverse (one track reverse). The target values are expressed in inches or degrees.

When a new tram command is requested, the safety checking routine first predicts the destination position and heading of the machine, and then checks for any potentially hazardous situations. The first check determines whether the machine would hit any Lasernet units while tramming to the destination. Because the continuous miner is in close quarters with the Lasernet units, this safeguard is essential. Secondly, a check is made to determine if the command will result in the targets going out of the lasers' detectable range. In this situation, the position and heading of the continuous miner would become unknown, and the tram command cannot be controlled properly. Finally, a check is made to see whether the machine will hit the ribs. Although there are no sensors to indicate the precise location of the ribs, an estimate can be obtained from the Lasernet system's position. Since the Lasernet is initially placed in the entry with its position calibrated relative to the mine plan, it can define two lines, i.e., the presumed location of the rib, and 20 ft (or any designated distance) away, the location of a parallel rib. These estimated locations are used by the safety routine to check if the machine would hit the ribs.

Any tram commands determined safe are issued to the machine. Any dangerous commands will not be executed, and a warning will be sent back to the user via AMREDS.

#### **Closed-Loop Tram Control**

The closed-loop control algorithm controls machine translational and rotational movements. Once a tram command has been determined safe and issued to the machine, this routine monitors the position and heading feedback from the Lasernet system, and issues a stop tram when the target value of the tram command has been achieved.

The actuation delays associated with a stop tram for each tramming option have been measured on our Joy 16CM. To improve control precision, a stop tram is issued early to compensate for these delays. For example, a stop command issued during a pivot left command has a time lag of 0.46 s. The angular velocity of a pivot left is 3.230° per second. Therefore, the rotational lag is 1.49°. During a command such as pivot left 10°, a stop tram will be issued when the machine has rotated 8.51°. The Joy 16CM actuation delays and tram velocities are documented in the literature.<sup>9</sup>

#### Interface to AMREDS

AMREDS was designed by Carnegie Mellon University, Pittsburgh, PA, under a Bureau contract for supporting

<sup>&</sup>lt;sup>8</sup>Work cited in footnote 2.

<sup>&</sup>lt;sup>9</sup>Sammarco, J. J. Closed Loop Control for a Continuous Mining Machine. BuMines RI 9209, 1988, 17 pp.



Figure 8.-Tram control module.

continuous miner automation research. Through the interface to AMREDS, the continuous miner guidance system has access to many useful routines that facilitate software development. The AMREDS user interface includes a tram control menu for easy selection of tram commands and a sensor-driven graphical display of the Joy 16CM continuous miner in an entry. A BITBUS network interface routine in AMREDS converts the machine commands issued by the safety checking routine into packets of digital information, and issues them onto the BITBUS distributed control network to be actuated by TAMME. The AMREDS skit executor mode allows a user to compose, edit, and execute a sequence of continuous miner commands.

Figure 9 shows how the Lasernet data processing and tram control software fit into AMREDS. Tram commands are either selected from the tram control menu by a user, or read from a script automatically by the skit executor. The tram control module receives the tram command, analyzes it to determine whether it is a safe command, and sends the safe command to the BITBUS network interface, which forwards the commands to TAMME.

The updates of machine position and heading are produced by the position and heading computation module, monitored by the tram controller, and are also delivered to the AMREDS graphical display, providing remote visual feedback of the movement and location of the machine in the entry.



Figure 9.--Lasernet control of Joy 16CM using AMREDS interface.

# **TEST RESULTS**

Experiments have been performed on the Lasernet system to improve its effectiveness and characterize its performance for tram control of a continuous mining machine in the mine environment. The reliability of Lasernet in a dusty environment was tested. The accuracy of Lasernet's angular coordinate reports was determined and used in the formation of error correction equations to increase the accuracy of the position and heading determinations. Also, the system's accuracy in tracking the position and heading of the continuous miner was determined.

#### LASERNET DUST GALLERY EXPERIMENTS

The effect of dust concentration on the Lasernet's ability to detect targets was tested in the experimental dust gallery at the Bureau. A target was placed in the field-ofview of a Lasernet unit at a range of 12 ft. Three dust monitors were located so they could sample the dust along the path from the Lasernet to the target.

Data from the dust monitors were correlated to data from the Lasernet to determine the maximum level of dust at which the Lasernet can detect and accurately report the angular coordinate of the target.

Table 1 shows the results of the tests. The respirable dust level dictated by Mine Safety and Health Administration (MSHA) requirements is  $2 \text{ mg/m}^3$ . The Lasernet's angular coordinate reports are extremely reliable up to a concentration of 13 mg/m<sup>3</sup>. Since the targets will be located at the back of the machine, and the Lasernet units will most often be located outbye the targets, dust is expected to have little effect on the Lasernet's ability to detect targets.

Τa	able	1	-Du	st	tes	t	7 e	s	ul	ts
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Dust concentration, mg/m <sup>3</sup>	Target-in-view time, pct
0 to 5	100
5 to 10	96.2
10 to 15	76.2
15 to 20	15
20 to 25	0

### ANGULAR COORDINATE ACCURACT TEST

The effect of a target's angular and radial coordinates on Lasernet's angular coordinate accuracy were characterized with two tests: angular tests and range tests.

## **Angular Test Procedure**

First, angular tests were performed to determine the effect of a target's angular coordinate on Lasernet error. Angular coordinate data were gathered as a target was moved in 2.5° increments across the 105° field-of-view of Lasernet. A Lietz Set 3 transit (accurate to  $\pm 0.001^{\circ}$ ) was used to take angular coordinate measurements to compare with the Lasernet's data. Figure 10 (left) shows the results of these angular tests performed at constant ranges of 8 and 16 ft.

The maximum error is on the edges of the scan. The errors are mostly linear across the angular field-of-view of

the unit, and most importantly, they are repeatable, so corrections can be made.

A linear regression analysis was performed on the data to determine the correction formula. The Lasernet's angular coordinate errors are estimated with the following equations:

8-ft range,

$$\Delta \Theta = -0.00687 \times \Theta - 0.0292$$

16-ft range,

	Δ <del>Θ</del>	$= -0.00805 \times \Theta + 0.0144$
where	θ	= lasernet angular coordinate
and	ΔΘ	<ul> <li>estimated lasernet angular coordinate error.</li> </ul>

Figure 10 (right) shows the result when these correction formulas are applied to the data from figure 10 (left). A



MEASURED TARGET ANGLE, deg

Figure 10.—Effect of target angular coordinate on Lasernet accuracy before (left) and after (right) correction. A, 8-ft range; B 16-ft range.

 $\pm 0.15^{\circ}$  error is maintained over most of the field-of-view of the unit. The worst case was a 0.3° error on the edge of the scan.

#### Range Test Procedure

The effect of a target's radial coordinate on Lasernet's angular coordinate accuracy was determined in a second series of tests. Figure 11 shows the results of one of these tests. A target was placed in the field-of-view of a Lasernet unit at a constant angular coordinate. The target was then moved throughout the range of the Lasernet from 3 to 21 ft.

Analysis of all the range experiments showed that the Lasernet's accuracy was only slightly affected by range up to 10 ft, with an error of  $\pm 0.05^{\circ}$ . The worst errors, approximately 0.2°, were found at ranges of 15 and 21 ft.

#### **Error Compensation Algorithms**

An algorithm to compensate for the repeatable errors was developed based on the results of the angular and range tests. This algorithm requires two input variables; i.e., the target's angular coordinate and the target's radial coordinate. An estimation of the target's angular coordinate is given directly from the Lasernet unit, and an estimation of radial coordinate is calculated using two other angular position reports from the same Lasernet unit.

The error compensation algorithm uses the formulae determined in the angular test procedure to estimate the Lasernet angular coordinate error. At ranges less than 10 ft, the 8-ft error correction formula is used; between



Figure 11.--Effect of target range on Lasernet accuracy.

ranges of 10 and 16 ft, a linear interpolation between the 8- and 16-ft formulae is used; at ranges of greater than 16 ft, only the 16-ft formula is used. Lasernet's angular coordinate is then adjusted by this estimated error to yield a compensated angular coordinate.

Spot tests were performed to check the success of this error correction method. A target was randomly placed in the range and angular field-of-view of the unit. Transit measurements of the target's angular coordinates were compared with the Lasernet's compensated angular coordinates. Table 2 shows the results of these tests. The overall errors reported by the Lasernet unit were reduced by 53 pct, and each range region shows a significant amount of error correction.

Table	2Error	correction	test	results

	Average e	Error cor-		
Target range	Before correction	After correction	rection, pct	
Less than or equal to 10 ft	0.17	0.07	58.8	
Between 10 and 16 ft	.25	.10	60	
Greater than or equal to 16 ft	.21	.13	38.1	
Overall	.21	.10	53.1	

The reduction in target angular coordinate errors is very significant since these errors induce machine position and heading errors. When propagated through the position and heading algorithms, errors in target angular coordinates will, on average, double in machine heading errors. For example, a  $0.2^{\circ}$  error in a target's angular coordinate will, on average, result in a  $0.4^{\circ}$  error in the heading determination. The position determination is less affected; nevertheless, a  $0.2^{\circ}$  error in a target angular coordinate would result in an average of  $0.2^{\circ}$  in error in position. Average position and heading errors are stated because there are many factors that affect the propagation of angular coordinate errors. A primary factor influencing error propagation is the distance to the targets.

## POSITION AND HEADING TRACKING AND TRAM CONTROL ACCURACY

The precision of the position and heading computation module in tracking, and the tram control module in controlling Joy 16CM translations and rotations were tested. A series of tram commands were issued to the Joy 16CM and, at the completion of each command, transit data were gathered and compared with the updates from the position and heading computation module.

	Target	Transl	ation, in	Erro	r, in		Target	Rotatio	on, deg	Error,	deg
Command	valve, in	Transit measure- ment	Lasernet report	Lasernet tracking	Tram control	Command	value, deg	Transit measure- ment	Lasernet report	Lasernet tracking	Tram control
Tram forward	40 48 36 34	38.88 46.52 34.04 31.78	40.63 49.79 35.17 35.35	-1.75 -3.28 -1.13 -3.57	1.12 1.48 1.96 2.22	Pivot left Pivot right Turn forward	7 9 5	7.44 9.08 4.70	6.79 9.18 4.39	0.65 11 .31	-0.44 08 .03
Tram reverse	48 24 36 32.5 30	47.18 22.57 35.38 30.80 28.32	50.11 24.43 37.40 33.90 31.98	-2.93 -1.86 -2.02 -3.10 -3.66	.82 1.43 .62 1.70 1.68	Turn reverse right	4.5	3.38	3.74	.14	.12

Table 3.-Lasernet tracking and tram control test results

Table 3 shows the results of the first series of tests. Each tram command listed was issued three times and the data averaged. Tracking results showed an average 2.59 in. error in translation, and an average 0.25° error in heading. Tram control results showed an average 1.45 in. error in translation, and an average 0.21° error in heading.

Both the tracking and tram control results are promising; however, the tram control results are inconclusive. Since a real-time computer is not yet being used for control, the actual control precision is not yet shown with these data. Further experiments will be conducted to further prove the tracking accuracy, and the tram control precision will be tested when the real-time computer system is operational.

# CONCLUSIONS

The status of a system to provide position and heading feedback and closed-loop control of tramming maneuvers for a continuous mining machine has been described. The system includes Lasernet laser-scanning sensors, which report the angular coordinates of three retroreflective targets. The Lasernet sensors are mounted on a reference structure, and the Lasernet targets are mounted onboard the continuous mining machine. The machine position and heading computation and tram control modules are programmed on a Sun 3/160 workstation, and include routines for Lasernet data acquisition, error compensation, position and heading determination, safety checking for continuous miner tramming, and closed-loop tram control.

Dust tests on the Lasernet sensor demonstrated that dust in the face area would pose little, if any, restrictions on system reliability. The results of tests on a Lasernet's angular coordinate accuracy is used in an algorithm for error compensation, which maintains a  $\pm 0.15^{\circ}$  target angular position accuracy over most of the 21 ft range and 105° angular field-of-view of the sensor. The systems accuracy in tracking the position and heading of a continuous mining machine was also investigated, and errors were found on average to be 0.25° in heading and 2.59 in. in position.

The system has been developed and tested at the Bureau on a Joy 16CM continuous mining machine. An update of the position and heading of the continuous miner is provided approximately five times per second. The system allows a user to select tram commands with target values from a tramming menu, which will then be executed by the continuous miner. This system is being prepared for underground experiments.

Further work to improve the system performance and prepare for underground testing is planned The position and heading computation and tram control module will be loaded to a real-time computer system to allow for more precise and reliable real-time tram control and portability for in-mine experiments. Further experiments will be conducted at that time to determine the system's performance.