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Mining Machine Orientation Control Based on Inertial, Gravitational, and Magnetic Sensors

By John J. Sammarco

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

°/h	degree per hour	hp	horsepower
°/min	degree per minute	in	inch
°/s	degree per second	min	minute
ft	foot	pct	percent
ft/s	foot per second	rpm	revolution per minute
h	hour	s	second

MINING MACHINE ORIENTATION CONTROL BASED ON INERTIAL, GRAVITATIONAL, AND MAGNETIC SENSORS

By John J. Sammarco[1]

ABSTRACT

The U.S. Bureau of Mines seeks to increase safety and efficiency in U.S. coal mines. One approach is to develop technology for automation of a continuous mining machine. Realization of an autonomous mining machine requires development of subsystems for machine intelligence, navigation-positioning, and computer control. This report focuses on investigation of one subsystem, an onboard heading system, which would be responsible for determining and controlling machine heading.

The onboard heading system investigated is a multisensor system to determine machine heading, pitch, and roll. A directional gyroscope provides heading (yaw), fluxgate sensors provide a compass heading, and gravity-referenced clinometers give machine pitch and roll. The system utilizes a dedicated microcontroller networked to an external system of computers. Tram commands, supplied to the network from external computers, are executed by the onboard system. Sensor feedback is employed for closed-loop control of machine heading by controlling pivots and turns.

The report discusses operating limitations and error sources of system sensors and presents test results of closed-loop control of machine heading. Results of tests with a mining machine are used to exhibit various sensor shortcomings and to evaluate control of pivots and turns.

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[1] Electrical engineer, Pittsburgh Research Center, U.S. Bureau of Mines, Pittsburgh, PA.

SYSTEM DESCRIPTION

The basic task of a navigation-positioning system is to manipulate a continuous mining machine through various positions and headings for computer-assisted mining. The system must guide the machine in a straight path, determine machine distance from known survey marks, and negotiate turns for room-and-pillar mining.

Typically, a mining machine operator guides the machine according to visual inspection of a survey mark and observation of the mine ribs. Reference lines may be painted on the roof and reflectors are sometimes used to help in alignment (fig. 1). The machine navigation-position system under investigation by the Bureau is composed of two parts: a laser-based position and yaw system mounted on a mobile control structure (MCS) and an onboard heading system for short-term heading data and control at the mine face (fig. 2). The laser-based system can provide a heading reference to the onboard system (*1*).[2]

The onboard system is used in conjunction with a Lasernet[3] system and also provides redundancy for machine heading data. Primarily, the onboard system is used for short-term situations where heading information is used. The onboard system data can also be fused with Lasernet data to obtain a higher degree of reliability and certainty of heading information.

This report focuses on the onboard system installed on a continuous mining machine testbed by the Bureau. A block diagram showing the computer and sensors is given in figure 3. The data output is via an RS-232 serial data link. The gyroscope provides heading information, fluxgate sensors (compass 1 and compass 2) give heading with respect to magnetic north, and clinometers give machine pitch and roll information depicted in figure 4.

Sensor control and signal conversion is done by an Intel 8052 microcontroller programmed in Intel BASIC 52. This 8-bit microcontroller is used by a controller board from Micromint (*2*). The microcontroller also executes control algorithms to manipulate the tramming (locomotion) of the machine. The onboard system is dedicated to *executing* tram control. The *determination* of which tram function is needed and when it is needed is not within the domain of the onboard system. The intelligence for this task resides in external computers communicating with the onboard system.

The microcontroller operates within a computer network known as BITBUS (fig. 5). BITBUS is a distributed control network used to connect multiple computer-based subsystems (*3*). A description of how the onboard heading system utilizes BITBUS is given in the "Closed-Loop Control" section of this report.

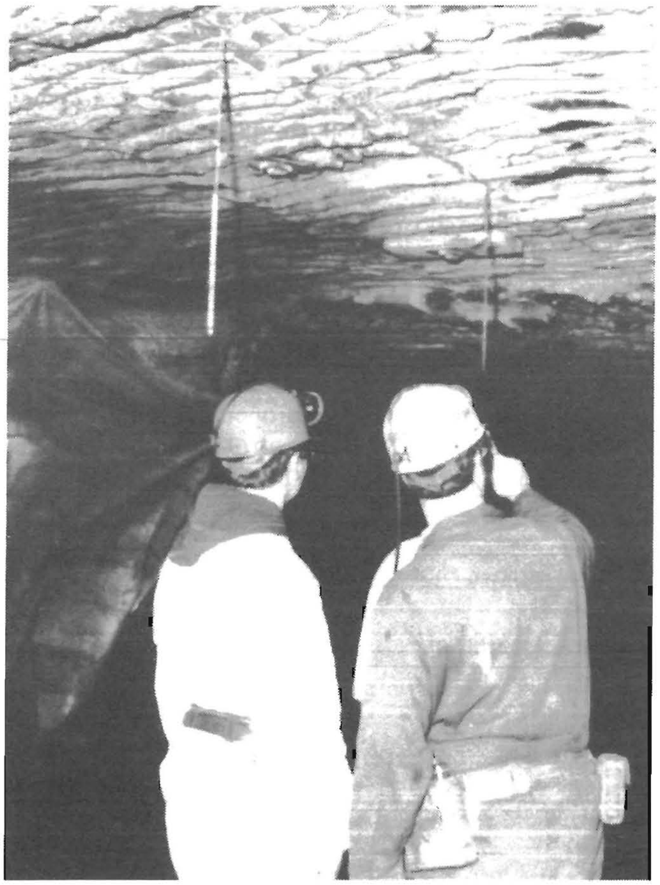

Figure 1.—Visual alignment.

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

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

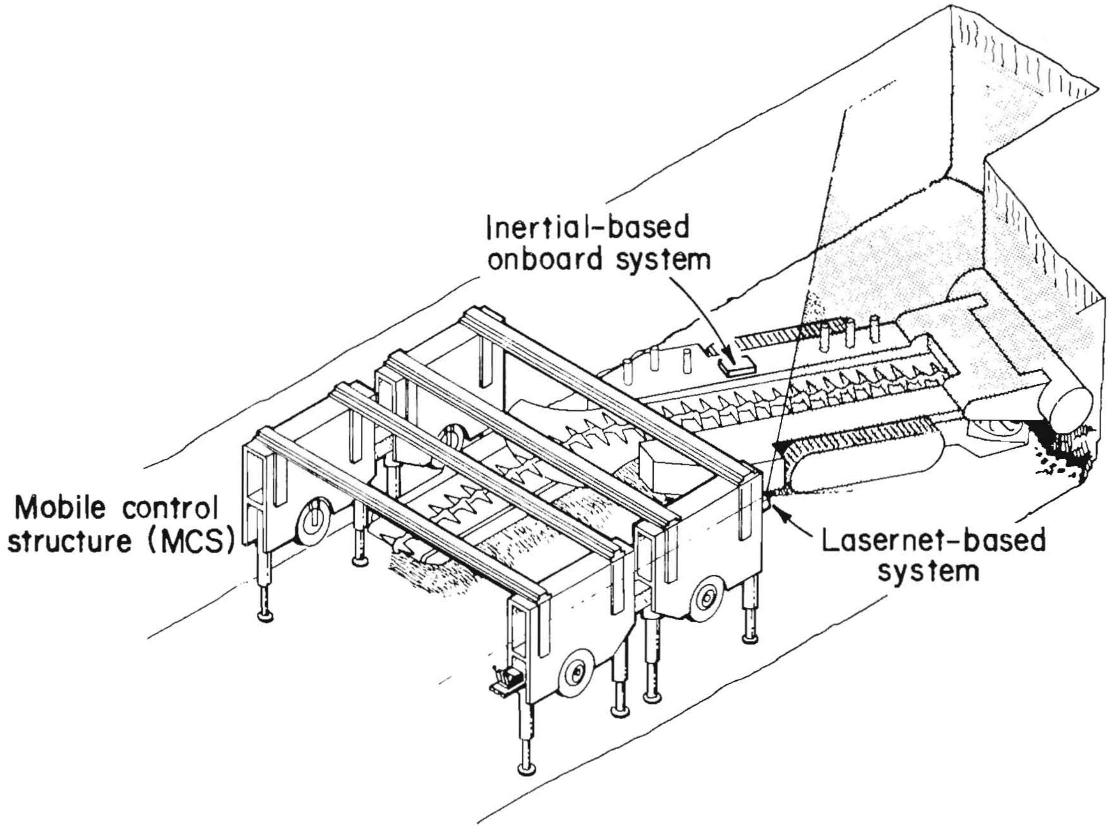

Figure 2.—Machine guidance system.

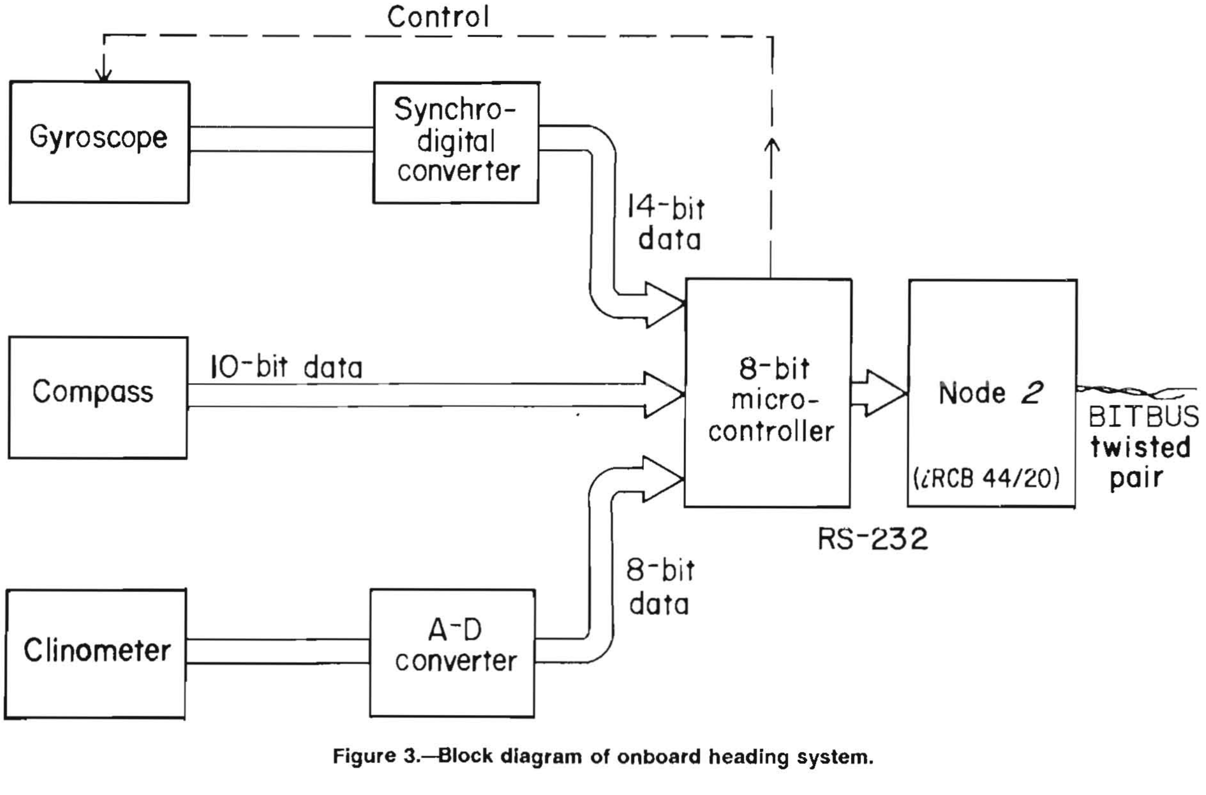

Figure 3.—Block diagram of onboard heading system.

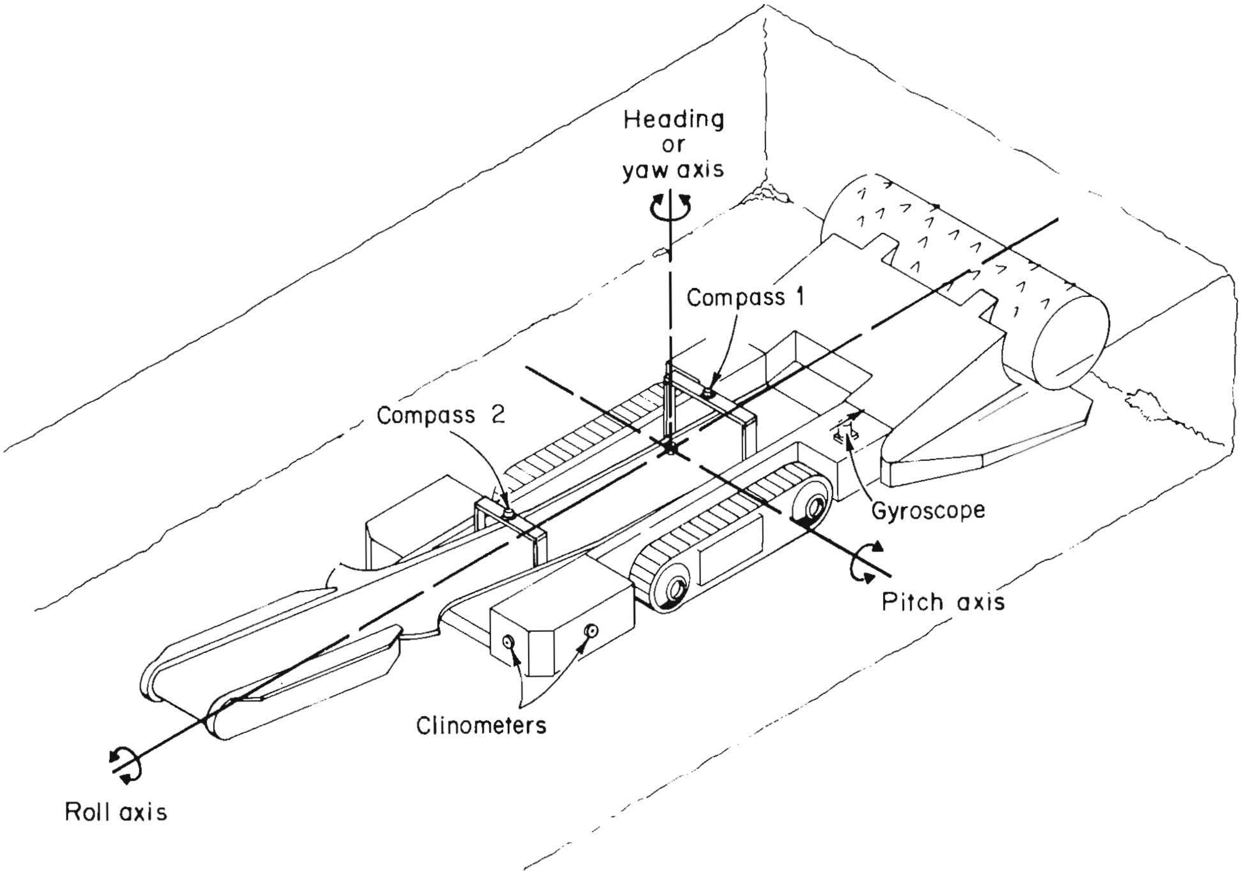

Figure 4.—Onboard sensors.

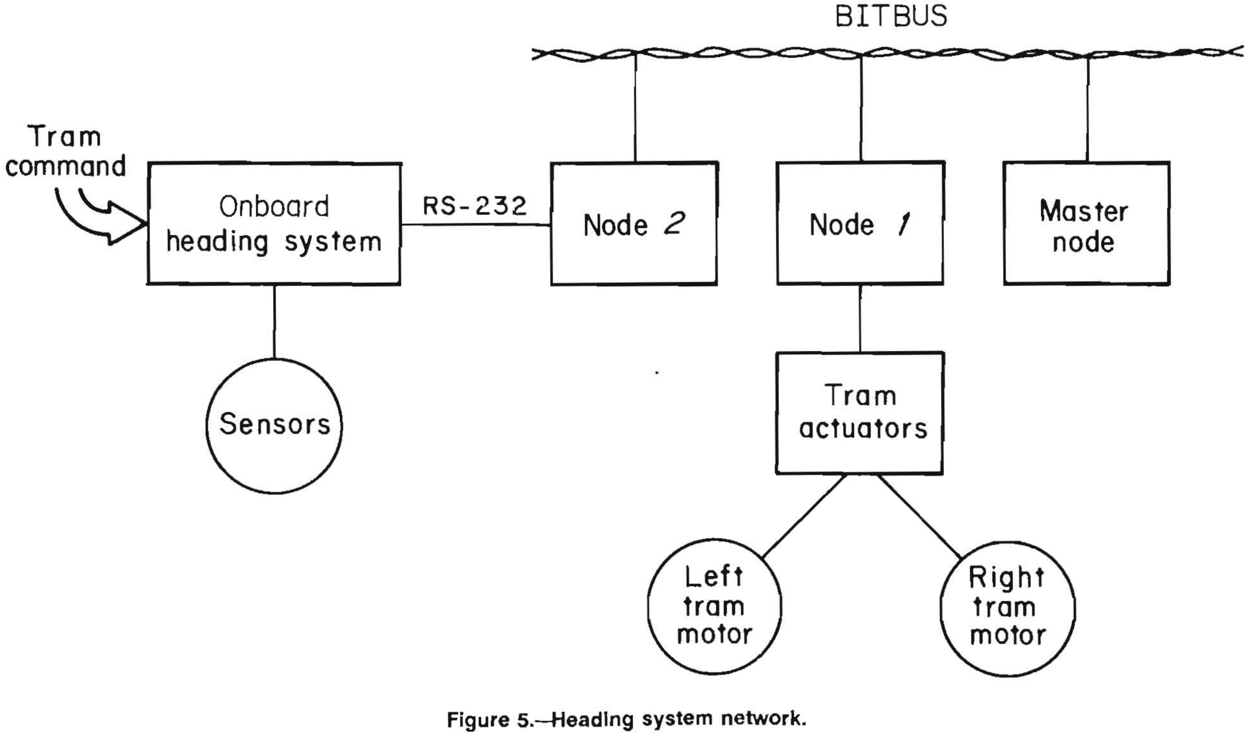

Figure 5.—Heading system network.

SENSORS

Various sensors were surveyed with respect to their suitability for the mining environment. Accelerometer-based systems for heading data did not appear to be suitable. Major difficulties were anticipated in discriminating system noise, caused by machine shock and vibration, from the low levels of acceleration generated by the gradual changes in machine movement. Therefore, efforts focused on gyroscopes and fluxgate sensors for heading information.

Various types of gyroscopes, such as the optical based devices, were investigated. Optical gyroscopes such as the ring laser gyroscope (RLG), the interferometric fiberoptic gyroscope (IFOG), and the resonant fiberoptic gyroscope (RFOG) are laser-based, solid-state devices (*4*).

Operation of all optical gyroscopes are based on the Sagnac effect. This occurs when two light beams travel in opposite directions of a closed light path. Physical rotation of the light path causes a proportionate change in path length difference for the two light beams. Measuring this path length difference can be very difficult and a significant source of error since this difference is extremely small for small rotational rates.

In general, optical gyroscopes offer the advantages of reliability, low weight, and low power consumption. Military applications of optical based gyroscopes seem to be most dominant; however, commercial applications are found in some Boeing jets. While commercialized, the relatively new optical gyroscopes are still quite expensive. For instance, a RLG-based navigation system can cost $150,000. For this reason, use of a conventional mechanical gyroscope was pursued. However, cost and performance improvements should continue for optical gyroscopes.

The fluxgate sensors are also solid-state devices. However, they do have limitations because the localized magnetic field they measure can be disturbed by ferrous objects and stray magnetic fields. Part of the research investigation was to determine if the limitations of the fluxgate sensor could be overcome. Detailed discussion of the mechanical gyroscope, fluxgate sensors, and clinometers is given in the following sections.

GYROSCOPE

The directional gyroscope gives heading (yaw) data with respect to a horizontal plane. It contains a motor, spinning at 20,000 rpm, coupled to a set of gimbals. It is used to measure various forces generated during a change in heading. The forces cause changes in the electrical signal generated by the gyroscope. The resultant gyroscope signals are converted to a 14-bit signal read by a microprocessor.

Gyroscopes drift because of mechanical limitations such as mass unbalance and friction. This drift is random and cannot be compensated. The directional gyroscope used in this system has a specified random drift of up to 0.1°/min. After 14 min, the gyroscope drift could be as high as 1.4°. This drift is significant when *absolute* readings of heading are needed. In this case, the gyroscope is reset and referenced using data from the Lasernet system on the MCS or from the compass. In this way, absolute heading can be obtained from the gyroscope through periodic resets and updates from other sensors.

The gyroscope can also be utilized for *relative* heading data, thus the periodic reset and update is not needed. For instance, if the gyroscope data were needed to implement pivots or turns, one would be interested in the heading data relative to the start of the pivot or turn. Typically the gyroscope will be used for relative heading data during pivots and turns of the mining machine.

When the gyroscope is used for relative heading, the amount of random drift accumulated previous to the start of a pivot or turn is not of concern. If, for example, the mining machine needed to pivot left 90°, and the heading at the start of the turn was 100°, then the gyroscope data of concern are from 100° to the destination of 190°. Random drift during the turn is not significant and can be ignored. With a pivot rate of 3.2°/s, it would take less than 30 s to pivot 90°. Random drift would be less than 0.05° for this 90° pivot.

In addition to random drift, gyroscopes are affected by the Earth's rotation, which induces a constant error in the gyroscope called apparent drift. This apparent drift can be factored out once latitude is known. The apparent hourly drift for Pittsburgh, PA, is 9.73°/h (see appendix A for calculation of apparent drift). Apparent drift is factored into the gyroscope heading data by the microcontroller.

Static friction in the gyroscope gimbals can be a source of erroneous readings of heading. The particular gyroscope tested in the Bureau's program gave erroneous readings if it remained stationary for an extended time. For example, the gyroscope was kept in a stationary position for 24 h and was then allowed to power up and stabilize. While it was still in a stationary position, the output drifted 8° in 10 min (fig. 6). The specified random drift of the gyroscope was 1° in 10 min. If the gyroscope was moved prior to the stationary test, the output was within the specified drift of 1° in 10 min (fig. 6). Note that once the machine's heading changes, the gyroscope will accurately provide data. The static drift exists only during the condition of the extended stationary position and not while the machine is moving.

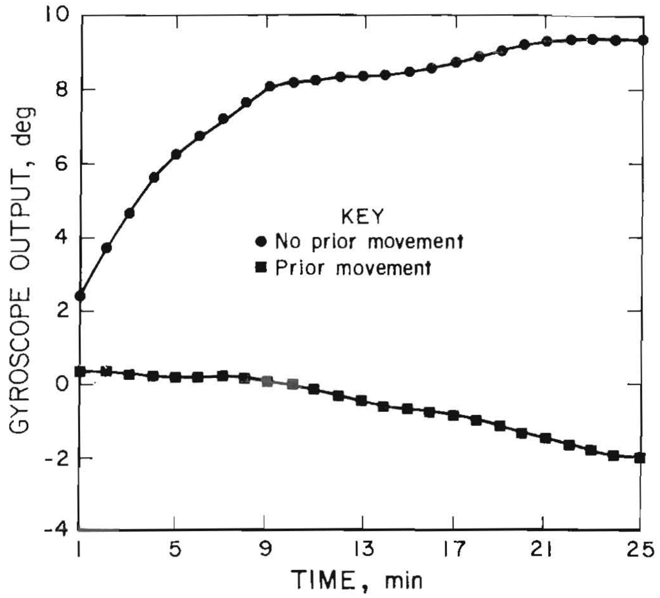

Figure 6.—Gyroscope drift with and without prior movement.

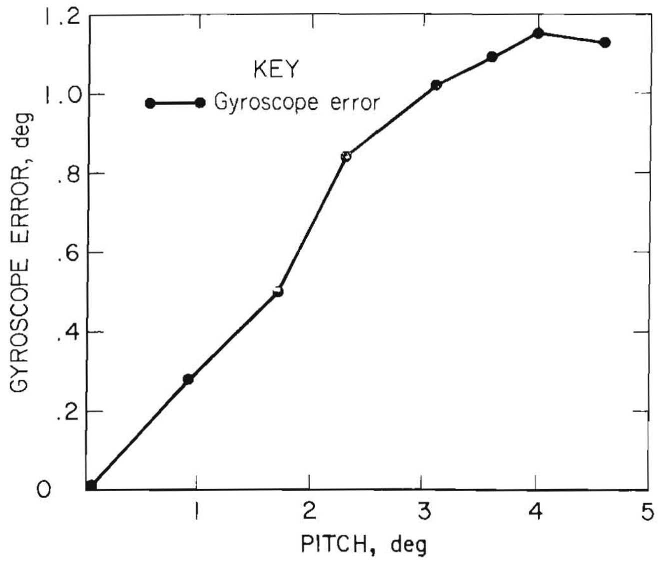

Figure 7.—Gyroscope errors for gradual changes in pitch.

This static friction error was also evident when the gyroscope experienced a change in pitch. Theoretically, a gyroscope with gimbals would be insensitive to changes in pitch and roll. Tests showed an error of about 1.1° when the gyroscope was gradually tilted to 3° in 4 min (fig. 7). However, when quickly tilted 3° and allowed to remain there for 4 min, the drift was only 0.25°. These gimbal errors are not expected in a mining situation. The various levels of shock, vibration, and movement encountered during tram and shear operations should eliminate these problems.

FLUXGATE SENSORS

The fluxgate sensors give heading information relative to magnetic north as a compass does. They are active sensors, requiring external excitation to sense the direction of the Earth's magnetic field. Internal coils generate a magnetic field to interact with the magnetic flux of the Earth. The sensor then processes data into an electronic signal that is easily interfaced to microprocessors. For the fluxgate sensor used, the resultant signal representing heading is processed into a 9-bit parallel data word.

The fluxgate sensor has limitations and error sources since it is affected by magnetic disturbances (natural and generated) that can cause reading deviations. However, through various techniques and proper application, the desirable aspects of this magnetic sensor are utilized in certain applications such as on ships and airplanes. Various arrangements of magnetic rings and bars are used to compensate for the localized magnetic fields of such transport vehicles. Other sensors, such as a turn-rate sensor, are used in land vehicles to help compensate for magnetic anomalies (*5*).

The main *source of error* lies with disturbances of the measured medium (the Earth's magnetic field) and not with the sensing device itself. Deviations or anomalies in the localized magnetic field can cause errors in heading. Magnetic anomalies can be static or dynamic in nature. Also, one must be aware that variations of the Earth's magnetic field can occur on a periodic basis, such as in daily fluctuations. Abrupt changes are possible during magnetic storms (*6*). Daily variation of magnetic north is typically 0.3°.

Static errors are due to magnetic influences from the vehicle and are not induced from external sources. Electrical systems and metal components are sources of magnetic influences that can cause deviations in magnetic fields and thus the indicated machine heading. Degaussing of the machine should reduce the deviations resulting from machine metal magnetization. In general, static errors can be reduced through the use of compensation techniques.

A static error was observed when compasses 1 and 2 were mounted to the mining machine. The proximity of the sensors to the metal machine resulted in a compass 1 reading of 119° and a compass 2 reading of 240°. The correct reading should have been 93° for both. The readings of compass 1 and compass 2 were corrected through adjustments to the sensor as described in appendix B; however, the compass 2 readings were too large to correct using adjustments available on the fluxgate sensor. Compensation using external magnetic rings and software algorithms would be needed for total correction.

Dynamic errors are not constant in time or space, making compensation somewhat difficult. Dynamic errors can occur if the sensor passes a ferrous object such as a mining machine or shuttle car. Errors can also result when operating in a geological formation capable of causing localized disturbances in the magnetic field.

Disturbances with the compasses under test were observed when passing within 4 ft of a ferrous object. The degree of disturbance depended on the content and quantity of ferrous material. In some cases, these disturbances can be detected using turn-rate sensors (*5*) and steps can be taken to obtain a correct reading. Also, by using multiple fluxgate sensors and machine data, a means for cross checking and confidence assessment exists.

Consider the machine's turning rate per second of 1.6°. Magnetic disturbances can cause swings in readings of as much as 20° in a few seconds; therefore, rate of heading change provides a means for assessment by comparison to the machine's physical capabilities.

Because multiple sensors are used, cross checking provides valuable information. Such can be the case when the mining machine passes a ferrous object. The first compass to pass the object will register a change, while the other sensor outputs remain stable. The machine's tramming state can also help in the assessment. A significant swing in heading is not probable when the tramming motors are in a forward tramming mode.

Random disturbances generated by signal noise, highly concentrated magnetic field anomalies, and random electrical noise can be reduced through time averaging of sensor readings. The accuracy of the reading tends to increase as the time average increases. This method can minimize random disturbance errors in some cases but will slow sensor response. Note that no random errors from potential error sources such as motors or trailing power cables were evident during tests.

Errors also occur when the fluxgate sensor is tilted. When it is tilted, the sensor does not sense the full vertical component of the Earth's magnetic field. Clinometers are placed on the mining machine to sense the pitch and roll, allowing compensation of the fluxgate sensors for tilt errors.

CLINOMETERS

These are gravity-based sensors capable of reading a tilt angle up to ±60° with an accuracy of ±1 pct. These devices have the advantage of offering an economical and accurate means of angle measurement (*7*).

The internal capacitance of a clinometer changes when the device is tilted about the reference axis. The sensor converts the capacitance change to an electrical signal representing the tilt angle. Electrical interfaces for the clinometer are available for analog output or for digital output.

CLOSED-LOOP CONTROL

A closed-loop control system will be used to control the machine heading through manipulation of the tram controls. This control scheme employs sensor feedback for machine heading. Figure 8 depicts a basic closed-loop system. With this control, the heading of the machine can be monitored and manipulated via the onboard heading system. Typically, the onboard system will be utilized for short-term control of the machine when Lasernet data are not available or when Lasernet data accuracy is compromised. The onboard system is the primary device when the Lasernet is approaching the extremes of its field-of-view. During this situation the Lasernet system heading accuracy will degrade. Changes in heading as a result of events such as machine jarring during cutting will be detected through sensor feedback so that the control system can maintain a desired machine heading.

An on-off control scheme is used to implement closed-loop control (*8*). Operation of a basic on-off control loop is quite simple. When the error signal (E) reaches various fixed set points, tram operation is started or stopped depending on the particular set point. Action of the on-off control is based on E, which is the difference between the present value (PV) of the system output and the desired value or target (T), or E = PV - T.

The control system algorithms using these set points are partly determined by the operating characteristics of the machine. Open-loop control tests have been conducted to determine these machine characteristics (*8*).

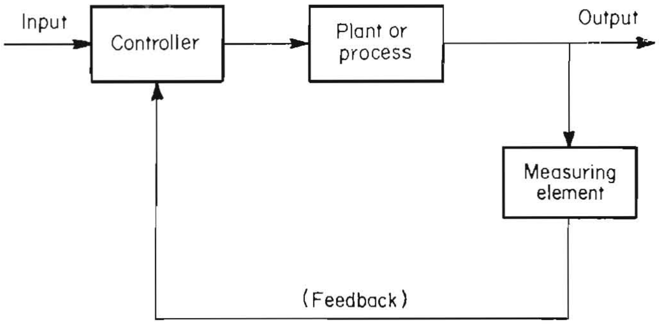

Figure 8.—Closed-loop block diagram

Open-loop control employs no feedback. The data from these tests give machine lag time and tramming rates. Lag time was measured for starting and stopping each primitive function. (Lag time is measured from the instant the computer sends an electrical signal to activate a primitive function to the instant the movement of that primitive function is detected.) Open-loop tests were also useful in finding any signal abnormalities that may affect closed-loop control. Table 1 summarizes the allowable tram states and their associated parameters determined in open-loop tests.

Table 1.—Open-loop test results for tramming functions

Tram function	Rate of change		Lag time, s	
	ft/s	deg/s	Start	Stop
Tram forward slow . .	0.27	NAp	0.32	0.40
Tram forward fast . . .	.54	NAp	.40	.80
Tram reverse slow . .	.27	NAp	.32	.34
Tram reverse fast . . .	.54	NAp	.38	.40
Pivot left	NAp	3.23	.34	.46
Pivot right	NAp	3.31	.32	.46
Tram reverse left . . .	NAp	1.67	.32	.54
Tram reverse right . .	NAp	1.64	.30	.50
Tram forward left . . .	NAp	1.67	.30	.52
Tram forward right . .	NAp	1.64	.34	.38

NAp Not applicable.

From these data, closed-loop control algorithms were written. These algorithms for control of machine pivots and turns are executed by the onboard system. A description of the system follows.

The onboard heading system is a part of a larger computer network that enables implementation of closed-loop tram control. This network, utilizing BITBUS, is shown in figure 5. Multiple computers can be networked together, communicating through a high-speed serial bus. BITBUS uses hardware and software to accomplish networking.

The hardware components are called nodes. Each node contains an INTEL 8044 microprocessor and is capable of running its own application software. Nodes can also serve as a gateway giving external computers access into the BITBUS network. The ability of multiple nodes networked together allows dedicated control of events that are physically separated.

BITBUS, as applied to the onboard heading system, utilizes two nodes. The first node (node 1) is responsible for actuation of the machine appendages, which are the shear, conveyor, gathering head, and stabilizer jack. Tram actuation is also the responsibility of this node designated as node 1. The second node (node 2) is a gateway, which allows the onboard heading system access to the BITBUS network. Both nodes are designated by INTEL as a "Remote Analog I/O Board" known as an iRCB 44/20. The node contains 16 analog inputs and 2 analog outputs. More information about this node can be found in the INTEL documentation (*9*).

Closed-loop control operates in the BITBUS network as follows. Tram commands are sent to the onboard heading system by transmitting the proper data over the BITBUS serial data bus to node 2. The tram command contains information on the type of tram function and its magnitude, such as pivot left 20°. The onboard system will read the data and send the proper data message to node 1, so that node can actuate the proper machine relays for a pivot left. Next, the onboard system will acquire machine heading data from the gyroscope. Closed-loop control algorithms are executed so that the machine can be precisely controlled to obtain a pivot left 20°. Once the machine obtains the goal, the onboard heading system will send a data message to node 1 that instructs the machine to stop.

DATA ACQUISITION

Test data for compass tests and for gyroscope heading control tests were acquired with a personal computer (PC) based data acquisition system. A PC-based data acquisition system provides flexibility and can use commercially available acquisition and analysis software (*10*).

The system is composed of a Compaq portable 386 PC and a Keithley model 500 data acquisition unit (fig. 9). The data acquisition system resides outside of the PC and utilizes a PC interface board placed in the PC. The data acquisition unit can be expanded to accommodate up to 10 data interface boards. These boards can provide signal conditioning, signal conversion, and control. The system as presently configured has 48 analog input channels, 8 frequency input channels, 32 general purpose digital input-output channels, 4 strain gauge interface modules, and 16 channels for power control of ac-dc devices such as relays and motors.

The Compaq PC contains a data acquisition and analysis program known as Labtech Notebook for the Keithley unit. The PC also has a 40-megabyte hard disk as the storage medium for the collected data. Additionally, the PC can download data to floppy disks. Data can be exported to a data analysis program such as RS/1 by BBN software. RS/1 provides data analysis, modeling, and graphics capabilities. Data files can also be exported to Lotus, a spreadsheet analysis program that enables data manipulation and graphing.

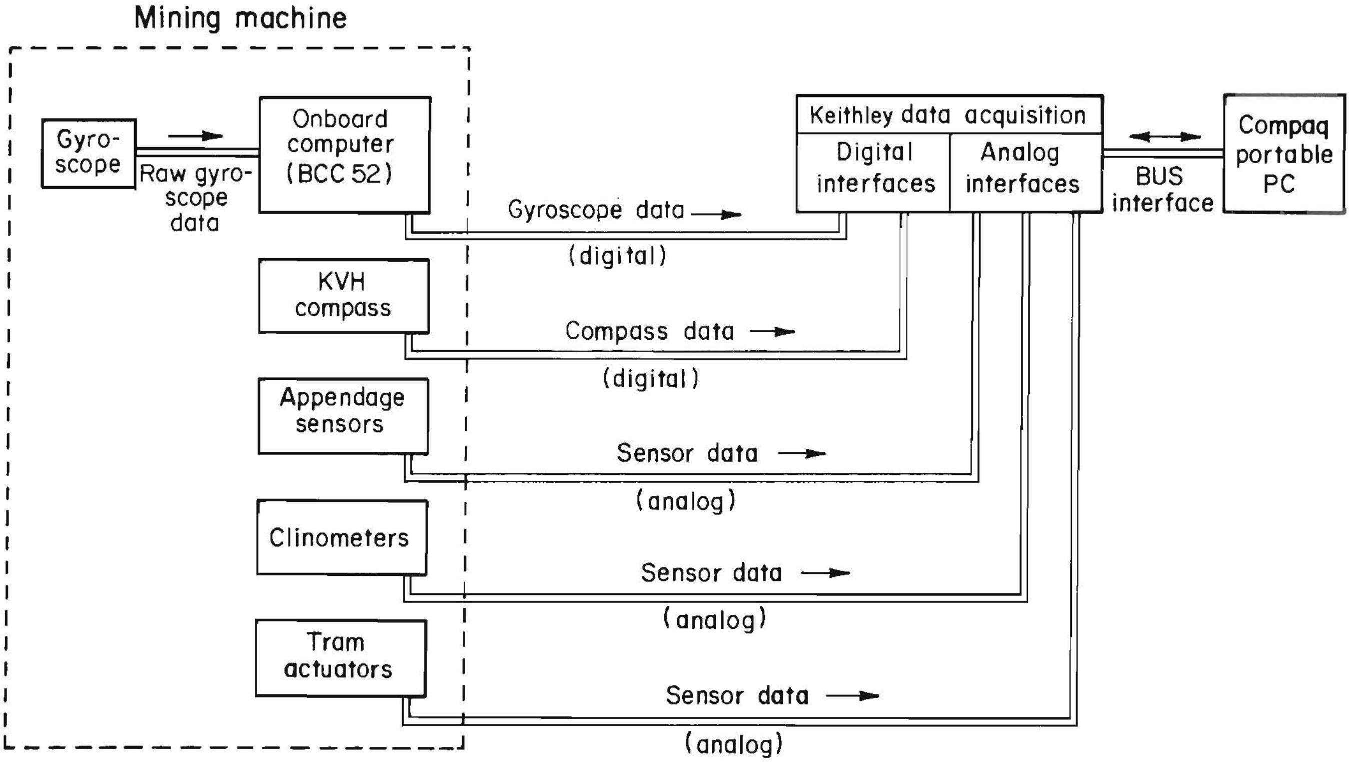

Figure 9.—Data acquisition.

TEST SETUP AND RESULTS[4]

Testing was concentrated into two areas. The first area focused on the operational characteristics of the fluxgate sensors and the second concerned closed-loop control of machine heading. Testing of the operational characteristics and accuracies of the gyroscope and compass was limited because of the availability of manufacturer's test data on the gyroscope and the simplicity of the clinometer.

The gyroscope manufacturer supplied a calibration sheet that contained test data for angular accuracy. The accuracy of the gyroscope met the manufacturers specifications of ±0.5°; therefore, testing of the gyroscope's accuracy by the Bureau was not necessary. As seen in table 2, the average angular error was 0.3° in the clockwise direction and 0.27° in the counterclockwise direction.

Testing of the clinometers consisted of verifying sensor angular accuracy through comparison to an angular resolver of known accuracy. The clinometers are simple devices and did not require extensive testing.

Testing of the compass, however, was quite extensive since heading data were very important for control of the machines heading. Also, it was known prior to testing that ferrous material of the mining machine could present a situation of improper compass operation. Tests were conducted to determine the extent of compass inaccuracies and to identify various factors contributing to errors.

Table 2.—Gyroscope angular accuracy as determined by manufacturer testing, degrees

Angle	Measured clockwise	Measured counterclockwise
0	0.2	0.2
20	.4	.1
40	.2	.0
60	.3	.2
80	.3	.0
100	.1	.4
120	.3	.4
140	.3	.5
160	.4	.5
180	.4	.3
Average error	.3	.27

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[4] Timothy J. Matty, electronics technician, Pittsburgh Research Center, assisted in the testing program and data analysis.

SENSOR MOUNTING

The fluxgate sensors were mounted on a wooden platform about 32 in above the Joy 16CM. A survey of possible mounting positions revealed that the present location (fig. 10) above the conveyor exhibited the least amount of induced error. Next, the compass alignment error was checked as described in appendix B. The mounting position was adjusted so that the fluxgate sensors were parallel to the centerline of the machine.

The gyroscope, microcontroller, and some miscellaneous support hardware were mounted on a vibration-isolated chassis. The chassis was mounted in an enclosure attached directly to the mining machine frame. The chassis was aligned such that the gyroscope centerline was parallel to the centerline of the machine. Unlike the experience with fluxgate sensors, the mounting location of the enclosure and chassis did not adversely affect the gyroscope operation.

The clinometers were mounted to the platform used to mount the fluxgate sensors. During initial testing, the clinometers were directly mounted to the machine frame. Unusually high levels of electrical noise were noted with this mounting; therefore, the sensor bodies were electrically isolated from the machine frame by mounting them to the wooden compass platform. The presence of the clinometers near the compass had no detectable effect on the compass readings.

COMPASS TEST SEQUENCE

Testing was conducted to determine compass operation as the machine is subjected to operation. The test sequence started with initialization tests to determine any differences in compass readings when the machine is in an off state or when energized on with the hydraulic pump in operation. Next, compass operation was evaluated during movement of the machine's appendages and during tramming. During tests involving appendage movements data collected represented the movement of the appendages, the outputs of the fluxgate sensors, and machine pitch and roll. Tramming test data consisted of fluxgate sensor outputs, machine heading as supplied by the gyroscope, and machine pitch and roll as measured by the clinometers. The test sequence details follows.

Initialization

Without moving the position of the machine or the trailing cable, fluxgate sensor readings were observed with the machine initialized as follows.

Control safety latch	off
Pump run control	off
Cutting motor control	off
Conveyor elevation	down
Conveyor swing	center
Gathering head	float
Stab jack	up
Drum extension	in
Shearer	center
Gathering extension	in

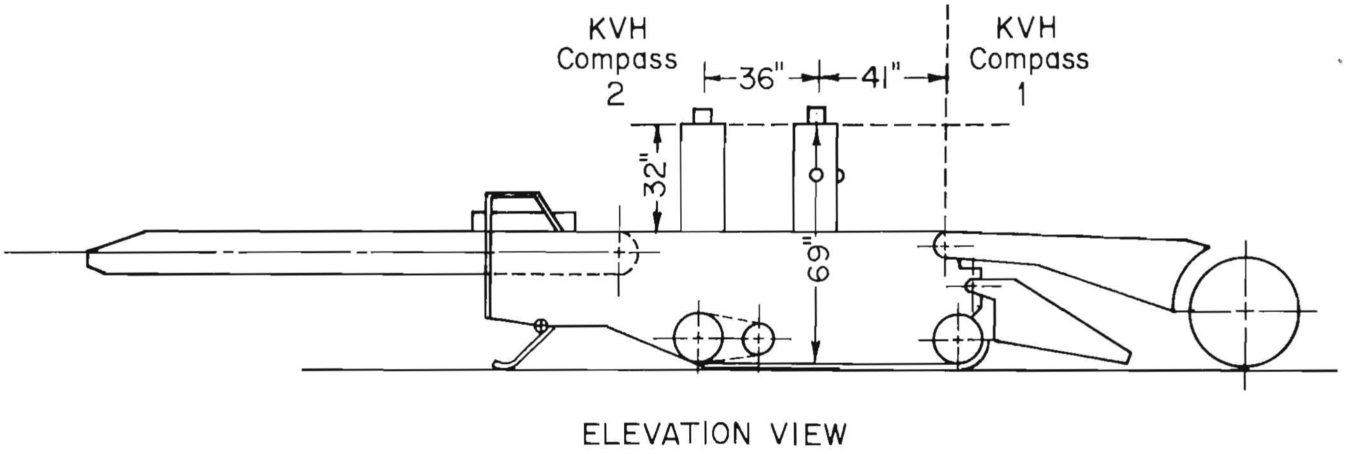

Figure 10.—Compass mounting locations.

Electrical power was then applied to the machine and the hydraulic pump run control was switched on. The 135-hp hydraulic pump motor is the motor nearest the fluxgate sensor. The intent was to determine the effects on the compass from the machines electrical system. No change in compass reading was observed for this condition. It is evident that the presence of electrical power and the running of the pump has no affect on the compass output.

While electrical power was supplied to the machine, the position of the trailing cable was continuously moved from the left to the right side of the machine. The intent of this test was to evaluate compass stability during changes in the proximity of the energized trailing cable to the compass. No changes in compass readings were observed during movement of the trailing cable.

Appendage Tests

The objective of the appendage tests was to determine the effects of conveyor, shear, gathering head, and stabilizer jack position on the output of the fluxgate sensors. It was felt that changing orientation of these appendages would result in changes of the localized magnetic field. As an example, raising the shear would place a significant amount of metal closer to the fluxgate sensor, thus disrupting the reading. During appendage tests, fluxgate sensor readings were recorded for each appendage as it was moved throughout its total range of movement.

Appendage test results show that movement of any appendage will cause erroneous readings in both compass 1 and compass 2. It is felt that the conveyor, shear, and gathering head induce these errors by disturbing the magnetic field localized about the machine. These appendages represent a significant amount of ferrous material such that a position change can alter the localized magnetic field.

Typically, the output from each compass varied 1°. Compass output for changes in conveyor elevation are shown in figure 11, and figure 12 shows the effect of conveyor swing. Shear elevation appears to have the most significant change in compass output as seen in figure 13. Shear elevation began at 42° and decreased to 0°. Note the change in compass output during movement of the shear. Compass 1 varied from a high of 170° to a low of about 168.2°, while compass 2 varied from 168° to about 166.2°.

A closer examination of test data revealed that shear position movements were not unique in the changing of compass readings. It appears that the compass output is changed by two factors, the position of the shear and a change in machine pitch. Figure 14 shows the positioning of the shear does cause a slight change in machine pitch. Further testing in machine pitch and compass output confirms this.

Testing machine pitch effects on compass output testing was conducted as follows: Cribbing was placed on the floor and the machine was trammed forward over the cribbing. The output of machine pitch, roll, compass heading, and gyroscope heading were recorded. Figure 15 depicts the test data (during the test, machine roll was constant; therefore, it was deleted from figure 15 for graphic clarity). As the figure shows, machine pitch will cause inaccurate readings of heading by the compass (note that actual machine heading, as determined by the gyroscope, remained relatively constant).

Machine tilt affects the compass because of the orientation of the Earth's magnetic field. The field is horizontal near the Earth's equator but curves considerably at each of the Earth's poles. The more the field curvature, the more critical tilt becomes since a fraction of the field will be picked up as the sensor is tilted. This tilt, as measured by the clinometer, can be factored into the compass reading to obtain a corrected value of heading. Tilt errors, in general, can be calculated with an equation described by Foster (*11*): Tilt error = arctan [(sin A)(tan D)], where A is tilt and D is magnetic dip angle.

For a 1° tilt and a dip angle of 69° 44', as supplied by the U.S. Geological Survey, the tilt error in the Pittsburgh, PA, area is about 2.7°. (Dip angle is the angle of the magnetic field with respect to the horizontal plane. At the magnetic equator of the Earth, the dip angle is 0° and the angle increases as one moves away toward the Earth's magnetic poles.) If the test data of figure 15 are evaluated with the equation for tilt error, one finds that the calculated tilt error does not correlate well with the measured values. This results from distortions of the localized field about the mining machine thus rendering the tilt error equation inaccurate in this situation.

Compass output changes due to machine pitch are also confirmed in tests conducted involving the stabilizer jack (fig. 16). The compass output will change during various positions of the stabilizer jack. Figure 17 reveals that these changes are induced by changes in machine pitch variation. Compass variations were detected when testing the gathering head elevation (fig. 18). Note that pitch remained stable (fig. 19); therefore, pitch was not a factor in gathering head tests.

The act of running the conveyor, seen in figure 20, induced significant changes of output for compass 2. Note that compass 1 data were not available during this test; however, similar results would be expected.

The ferromagnetic material of the conveyor chain is felt to be the major cause of compass error. The chain is about 1.5 ft wide and has a total linear length of about 80 ft. Additionally, the chain moves virtually across the entire length of the machine.

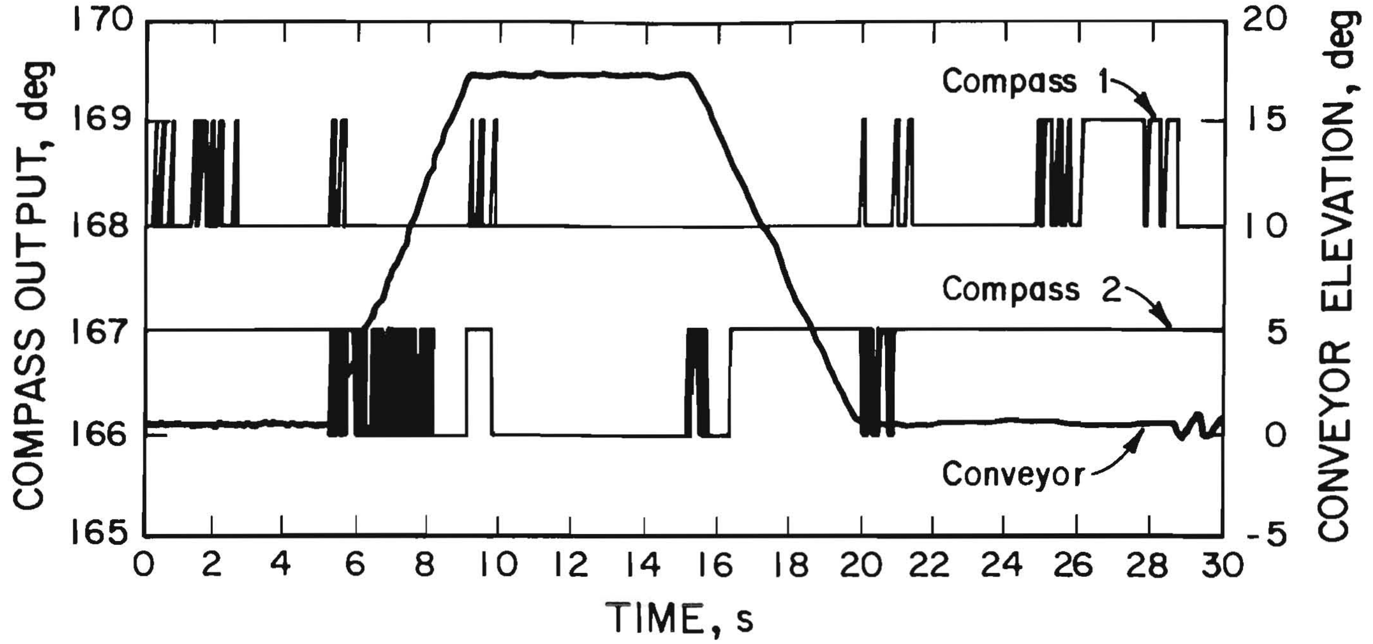

Figure 11.—Effects of conveyor elevation on compass readings.

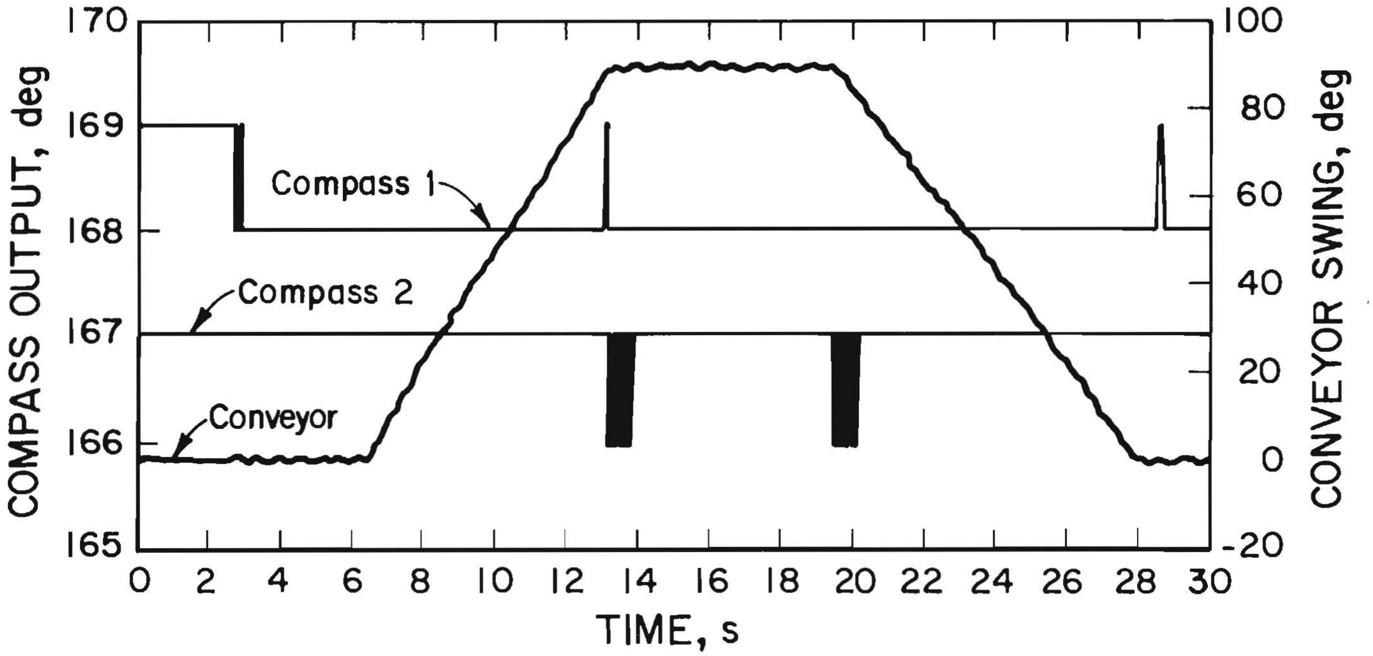

Figure 12.—Effects of conveyor swing on compass readings.

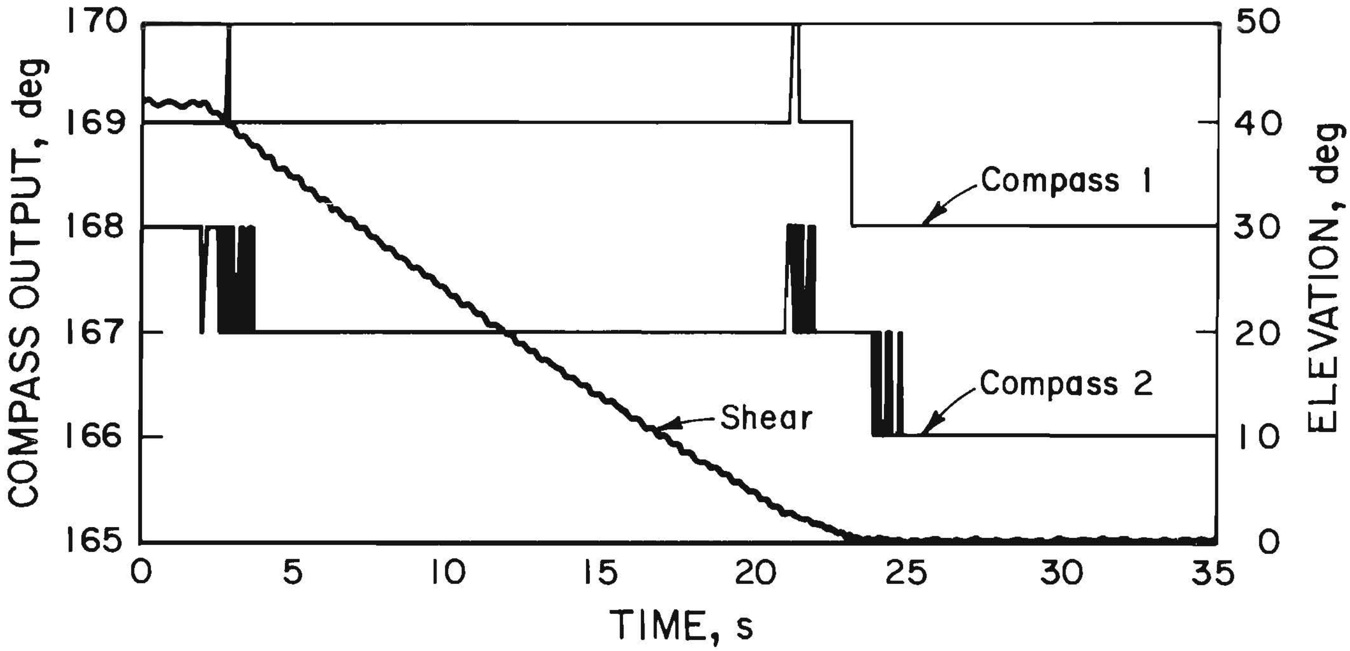

Figure 13.—Effects of shear elevation on compass readings.

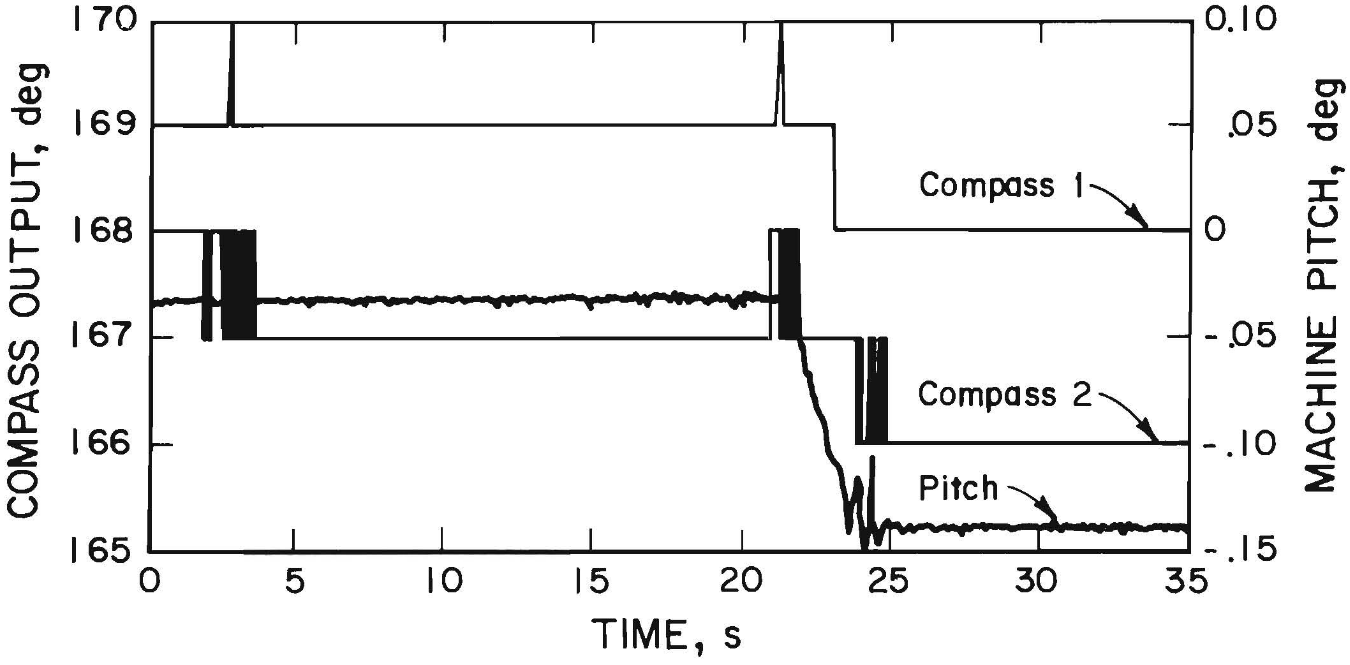

Figure 14.—Effects of machine pitch, as a result of shear operations, on compass readings.

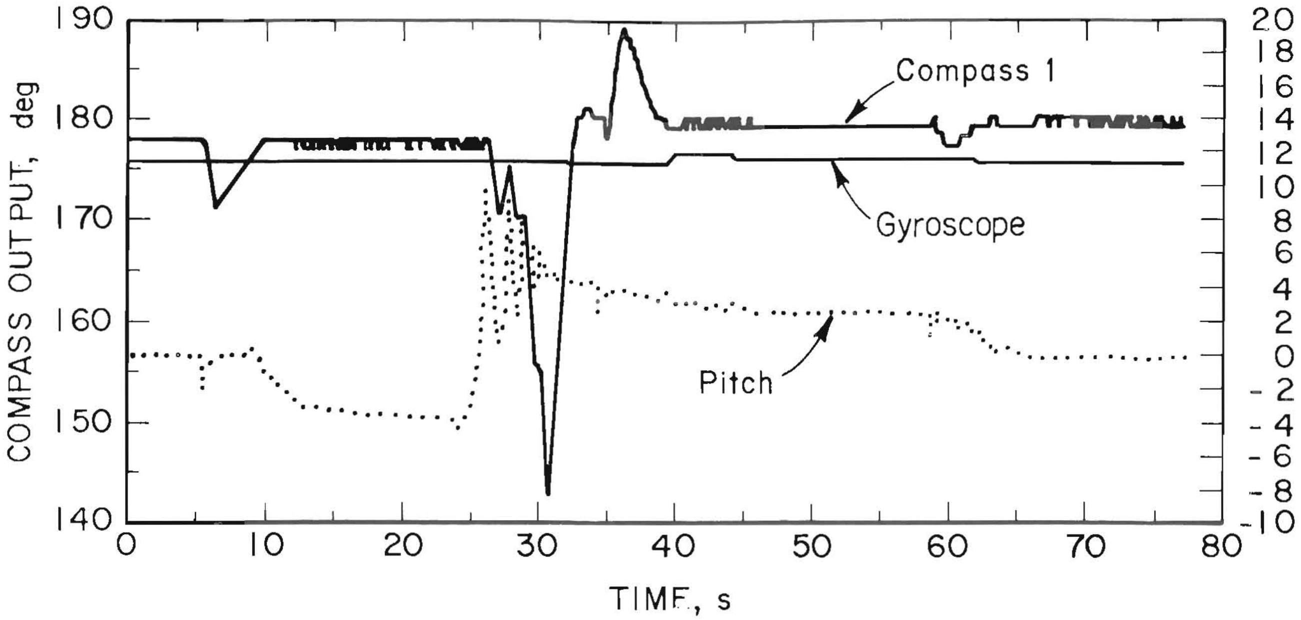

Figure 15.—Effects of machine pitch on compass and gyroscope readings. Pitch was induced by tramming over cribbing. Machine roll was constant.

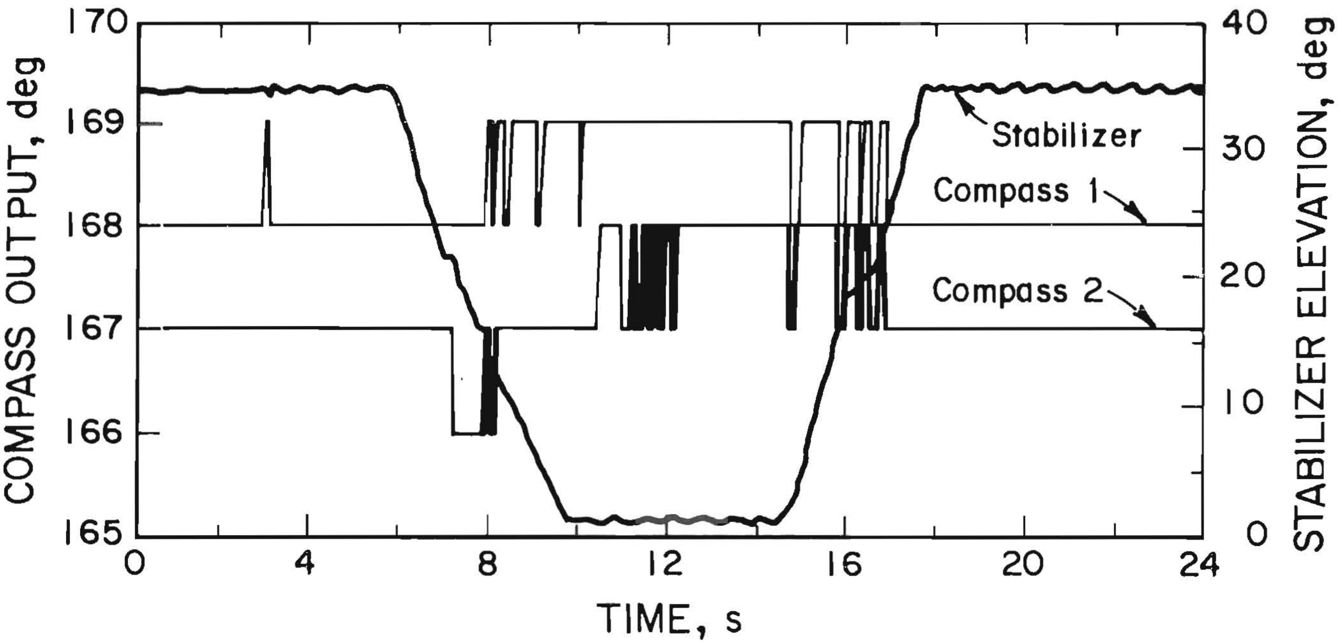

Figure 16.—Effects of stabilizer jack elevation on compass readings.

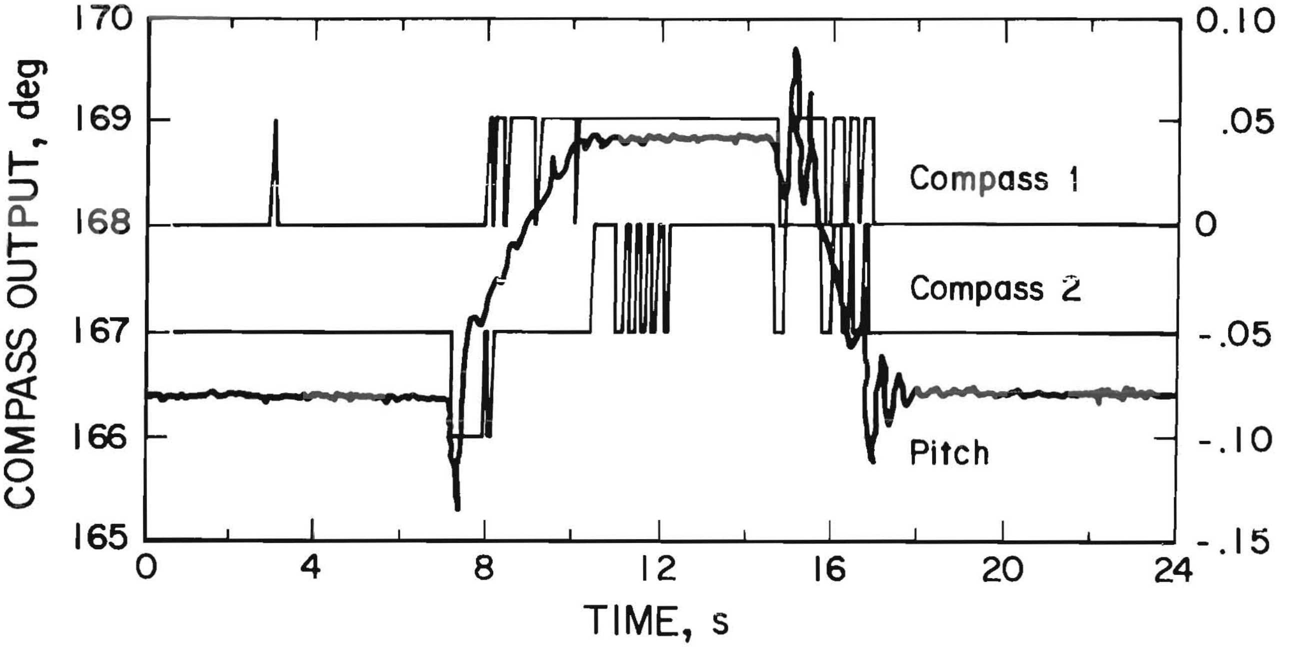

Figure 17.—Effects of machine pitch, as a result of stabilizer jack movement, on compass readings.

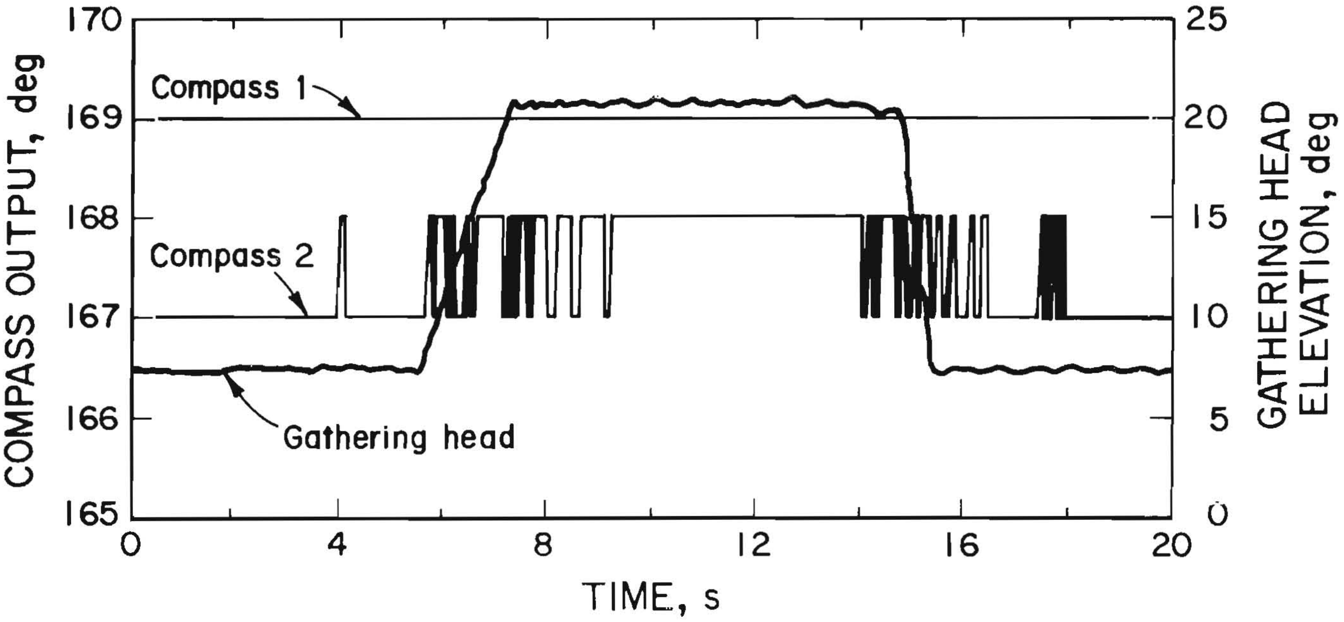

Figure 18.—Effects of gathering head elevation on compass readings.

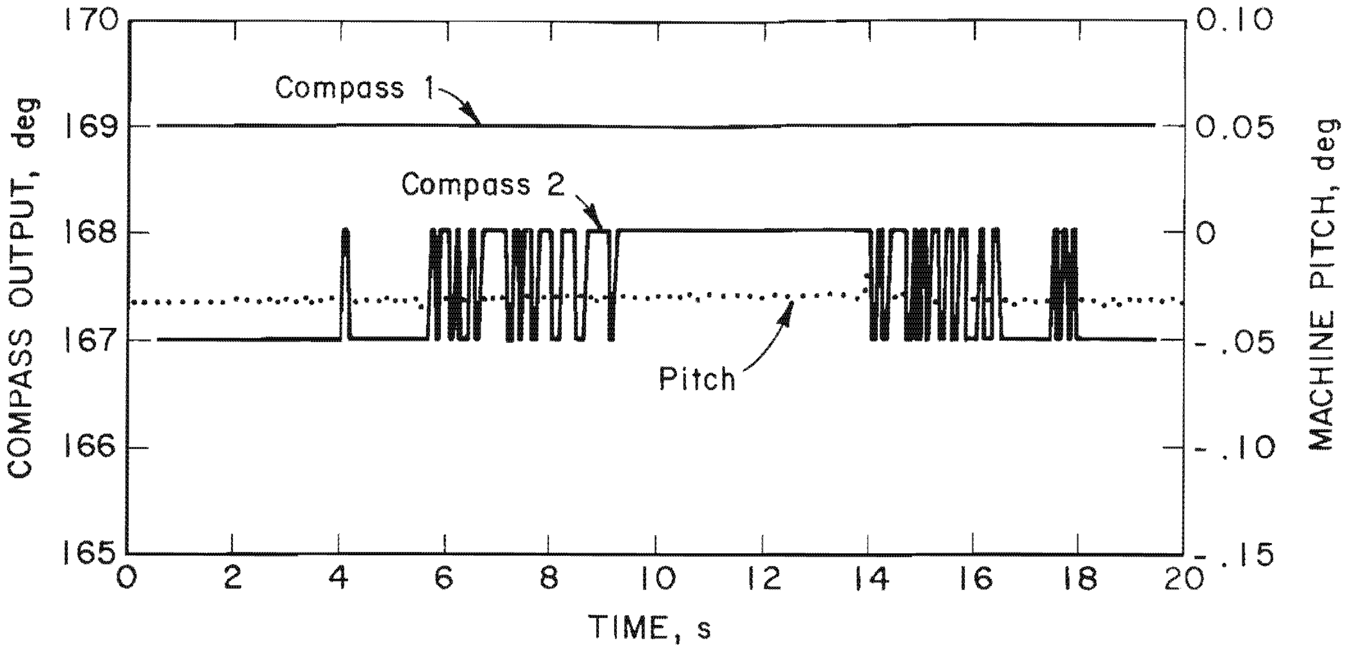

Figure 19.—Effects of machine pitch, as a result of gathering head movement, on compass output.

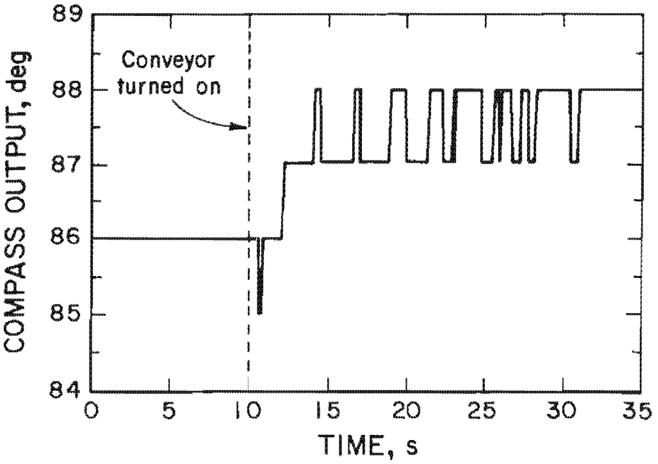

Figure 20.—Effects of conveyor actuation on compass readings.

Stray magnetic fields from the motor are not felt to be a significant error source. Earlier tests with the 135-hp pump motor and electrified trailing cable had no effect on compass readings. In contrast, the motor driving the conveyor chain is only 65 hp and is the farthest motor from the fluxgate sensors.

The appendage test results show that manipulation of any appendage function can have an adverse effect on compass accuracy. At least six factors have been identified. These include changes in appendage position, machine pitch and roll, and conveyor actuation and operation.

Compensation techniques exist to reduce the effects of magnetic interference from ferromagnetic material used in vehicle construction. Ships and airplanes have used such techniques; however, compensation becomes difficult for articulated vehicles such as the continuous mining machine (*11*). It appears to be impractical to compensate the compass because of the number of factors identified to cause erroneous readings.

Miscellaneous Compass Tests

Two tests were conducted within the miscellaneous compass test section: drift tests and compass operation during shearing. Drift testing was conducted to determine if the fluxgate sensor readings are consistent over an extended time period. Sensor readings were recorded over an 11-day period without disturbing the mining machine. Test results for compass 1 and 2 show no detectable change in reading during the 11-day drift tests. Therefore, it is concluded that the localized magnetic field about the mining machine and the operation of the compass presents a stable situation while the machine is in a static state. Next, testing involved the dynamic situation of shear operations.

Changes in appendage position, changes in machine pitch, and movement of the conveyor chain occur during shear cycles. Previous tests show that any one of these factors will cause incorrect heading indications from the compass. The shear test shows the net effect of these factors on compass operation during the shearing of simulated coal known as coalcrete. Compass heading reading ranged from 170° to 185° during shear tests as shown in figure 21. The combination of factors causing compass errors appears to be synergistic. A much wider range of compass error is present during shear tests than any of the single appendage tests. Note that the machine heading remained relatively constant as evident in the gyroscope output during a shear operation.

Tramming Tests

The tramming test objective is to observe the machine heading as determined by the fluxgate sensors during pivots, turns, and straight translations. The onboard gyroscope was used as a reference for actual machine heading.

Signals recorded during tramming tests include fluxgate sensor signals, machine pitch and roll, and gyroscope output. Testing was conducted as follows:

Tram Forward Slow.—Tram forward at least 10 ft at low speed while recording data.

Tram Reverse Slow.—Tram reverse at least 10 ft at low speed while recording data.

Pivot Left.—Pivot left continuously for at least 100° while recording data.

Pivot Right.—Pivot right continuously for at least 100° while recording data.

Tram Forward Left.—Tram a left turn forward at least 45° while recording data.

Tram Forward Right.—Tram a right turn forward at least 45° while recording data.

Tram Reverse Left.—Tram a left turn reverse at least 45° while recording data.

Tram Reverse Right.—Tram a right turn reverse at least 45° while recording data.

Test results for pivots and turn yielded similar results. In general, the compass did not accurately track pivots and turns. In all cases, the compass indicated headings that were not proportional to data as referenced by the gyroscope. The test results for a pivot right are discussed as an example.

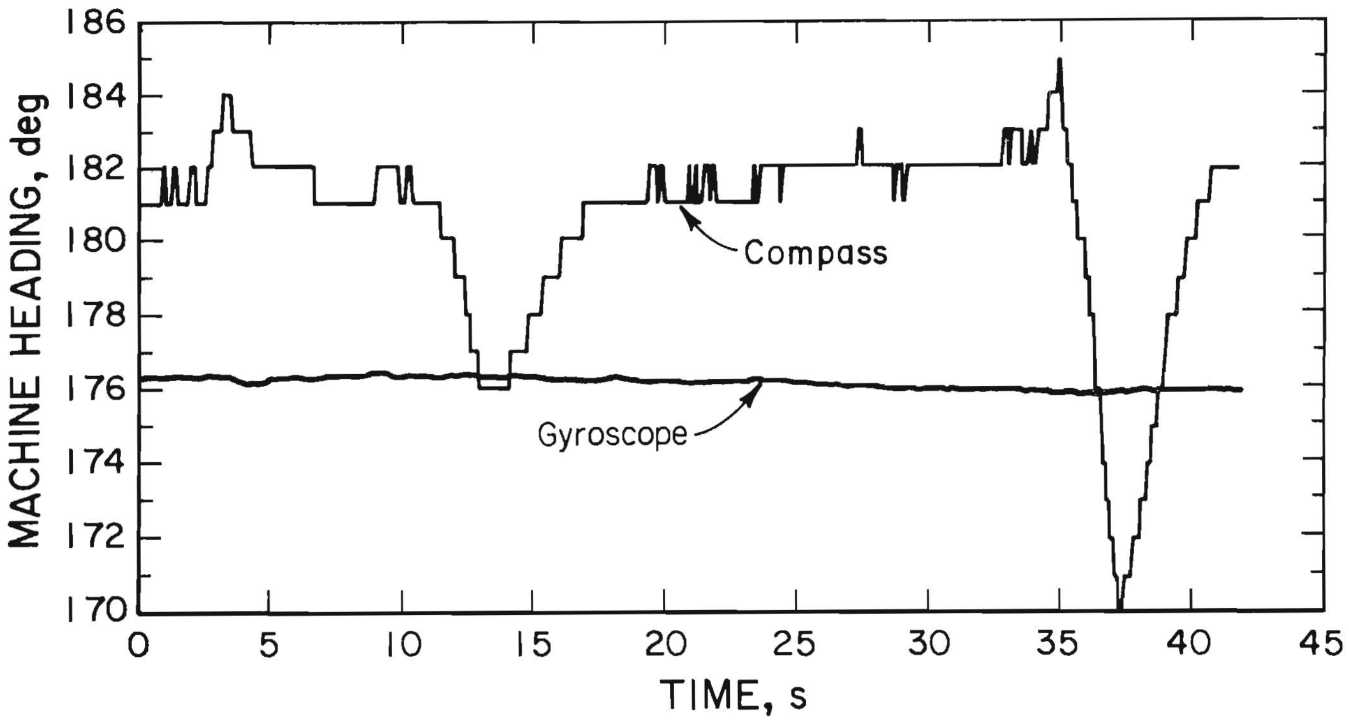

Figure 21.—Compass and gyroscope readings during shear operations in coalcrete. The gyroscope output is used as a reference for the machine heading. Erroneous readings of machine heading are shown.

Figure 22 depicts the compass and gyroscope output while the machine pivots right. The initial machine heading is about 90° with a final machine heading of about 340°. From this figure, the compass output generally follows the machine heading determined by the gyroscope. Figure 23 reveals the significant difference in readings between the compass and gyroscope. This figure plots the difference between the two sensors and shows that the relationship is nonlinear.

Noteworthy are the test results involving translations. Figure 24 depicts the output of the gyroscope and compass during a low-speed tram forward. During this test, the machine traveled about 14 ft in 55 s. Note that the gyroscope indicates a change in heading of about 1.5°. However, actuation of the tram circuits (at approximately 2.5 s) caused a significant change in compass output. Note that the compass shows a general increasing heading ranging from 52° to as high as 55°, while the machine actually translated 1.5° to the left. This test shows that it would be difficult to use the compass for detecting deviations from a straight line. In this situation, one would hope to monitor the output of the compass such that a change in compass readings would indicate a deviation from a straight line. But this test shows the compass to be incorrect in the direction of the deviation. Also, note that during the time period between 7 and 20 s, the heading changed only a few tenths of a degree, while the compass erratically indicates 1° changes.

CLOSED-LOOP HEADING CONTROL

Closed-loop computer control of tram pivots and turns was tested utilizing gyroscope data for machine heading. (The compass was not used to provide machine heading data since prior tests showed it to give erroneous heading data during appendage and tram tests. Therefore, only the gyroscope was used during closed-loop heading control tests. Since the compass was not used, tilt correction, based on clinometer data, was not investigated.) The on-off closed-loop control algorithms were written for tram pivots and tram left and right turns in the forward and reverse direction. For this group of tests, each tram pivot and turn function was given a desired translation of 5°. Each test was conducted three times to check the repeatability and accuracy of control.

Testing was conducted in the Bureau's mine equipment test facility (METF) in Pittsburgh, PA. The general configuration of the onboard heading system network under test is shown in figure 5. Test data were obtained using the data acquisition system described previously and as shown in figure 9. During each test the following signals were recorded: gyroscope pitch, machine pitch, left tram actuation, compass output, machine roll, and right tram actuation.

Table 3 summarizes the *initial* test results of closed-loop control of machine pivots and turns. The tests demonstrate the ability of closed-loop heading control. Hence, the original control algorithms were not modified to increase control accuracy at this time.

For each test a target of 5° was given. This target does not represent an *absolute value* of machine heading but rather a *relative* rotation. The last column of table 3 gives the difference between minimum and maximum relative rotations for three test runs. This gives an indication of control repeatability. Retuning of the control algorithms can increase the control accuracy.

Table 3.—Test results for closed-loop heading control, degrees

Function	Test run			Difference[1]
	1	2	3	
Pivot left	5.77	5.55	5.59	0.22
Pivot right	5.92	6.33	5.99	.41
Tram forward left	NA	5.13	5.08	.05
Tram forward right	5.22	5.30	4.89	.41
Tram reverse left	NA	5.21	5.21	.00
Tram reverse right	4.56	4.51	4.40	.16

NA Not available.

[1] Difference between minimum and maximum relative rotations for 3 test runs.

NOTE.—A target value of 5° was used for each function tested.

As a test example, figure 25 depicts data for test run 2 of a forward right turn. The signals of primary interest are the gyroscope output and the tram actuation signal. Only the tram left actuation signal is shown to maintain clarity of the figure. The original machine heading was 30.7° at a test time of 4.2 s. For a displacement of 5°, a final test value of 35.7° is required. The actual value of machine heading at the completion of the test was 36°, giving a *total relative* tram left of 5.3°.

Also, note that the gyroscope output remains stable once the final value is obtained and that actuation of the tram circuit to stop the machine occurred at 7.8 s. No further actuation of the tram circuits were needed to adjust for an undershoot or overshoot of the desired target. The control appears to be quite stable as the machine trams across the test floor.

Further evaluations of the tram control stability and accuracy will be conducted in field tests in an actual underground mine. The tests conducted at the METF were

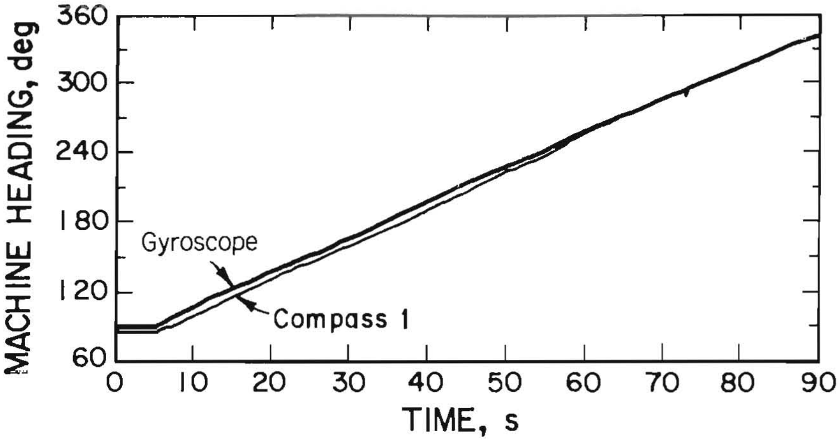

Figure 22.—Compass and gyroscope outputs for a machine pivot right.

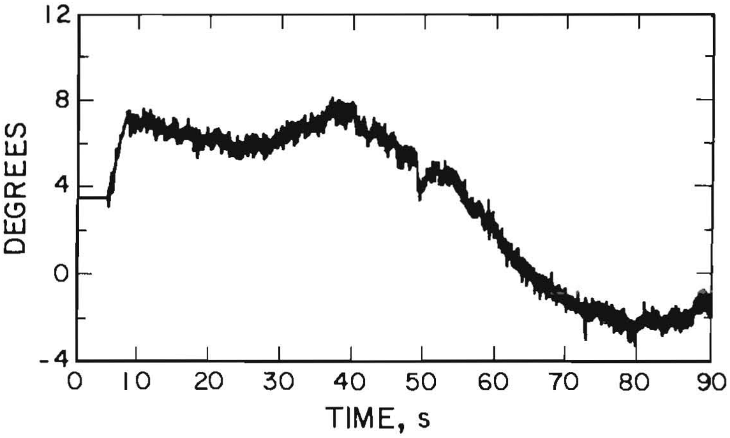

Figure 23.—Compass and gyroscope differential for a machine pivot right. Difference between gyroscope and compass data presented in figure 20 is highlighted.

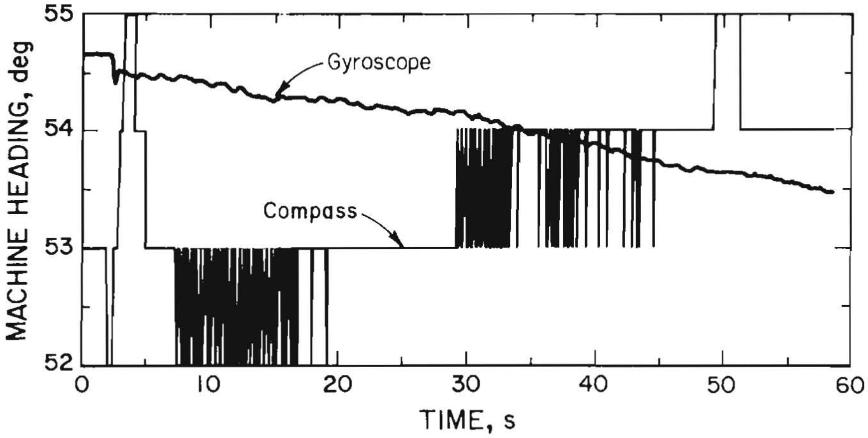

Figure 24.—Gyroscope and compass output for low speed tram forward. Gyroscope output is used as a reference for the machine heading. Erroneous compass reading of machine heading during a low speed tram forward is shown.

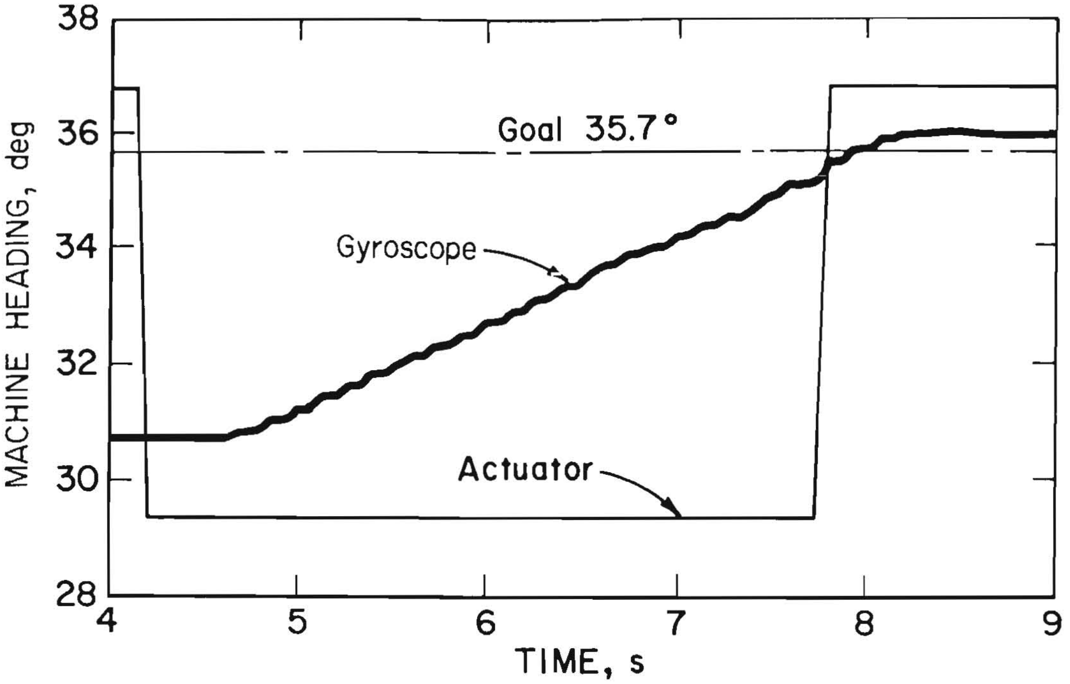

Figure 25.—Machine turn right under closed-loop control.

on a concrete floor where no detectable track slippage was observed. In field tests, it is expected that considerable track slippage can occur for the various floor conditions of a mine. It is anticipated that floor conditions conducive for track slippage might cause inaccuracies in heading control. For example, at the termination of a machine pivot, the tracks may stop but the machine may slide, causing it to exceed the desired heading.

FUTURE WORK

The onboard system will be tested in an actual underground mine. Of particular interest is the accuracy of heading control for varying floor conditions. To take the laboratory version of this system to a field prototype will require modifications in hardware to meet Mine Safety and Health Administration permissibility requirements. Hardware will also be simplified to promote reliability and to accommodate packaging of the system.

The most significant hardware change will be the elimination of the 8-bit microcontroller. The functions of this board will be implemented within node 2 hardware as shown in figure 26. Changes in software will also result. The 8-bit microcontroller board software was written in assembly and INTEL BASIC. This software will be written in C. Expected benefits of this hardware-software conversion include reduced hardware, faster network operation, and faster control program operation.

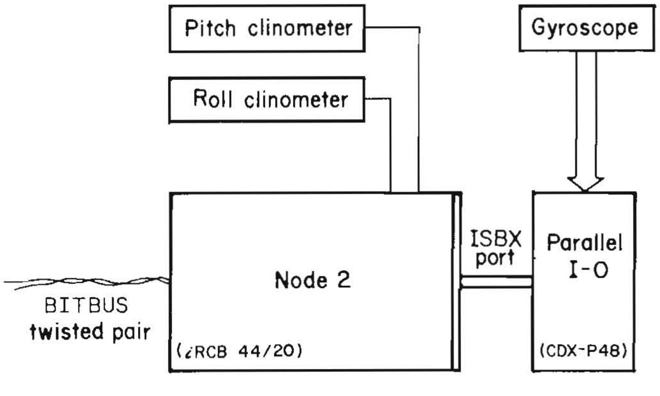

Figure 26.—Block diagram of second-generation onboard heading system.

In addition to these system refinements, other new technologies such as optical gyroscopes will continue to be monitored, in particular systems with proven capabilities in military and commercial applications. One such device is a RLG-based instrument developed by Honeywell (*12*). This system is capable of providing azimuth reference from true north, elevation, pitch, roll, and x,y position.

New areas of development include interfacing between the onboard system and the laser-based MCS system. Areas of investigation include testing the communication network between the systems and fusion of the sensor data from the onboard system and the Lasernet system located on the MCS. The main objective is for parallel operation of the onboard heading system and the Lasernet system. This work will be conducted in the laboratory. Once operational, field testing in an underground mine will take place.

SUMMARY

An onboard heading system composed of a gyroscope, two fluxgate sensors, and two clinometers was developed to primarily provide heading information and control for computer-assisted mining machines. Information concerning advantages, disadvantages, and error sources for each sensor is presented. Testing of the gyroscope revealed angle drift errors introduced during gradual changes in pitch and roll. Theoretically, the gyroscope output should be constant for these changes. The source of these angle drift errors is felt to be mainly due to mechanical limitation of the gyroscope gimbal network. Although these angle drift errors exist during laboratory tests, they are not anticipated to be encountered during normal operation of the mining machine.

Testing of the fluxgate sensors revealed errors induced by the proximity of the sensors to ferrous material of the mining machine. It does not appear feasible to correct these errors through recalibration and correction algorithms because of the large number of variables that could cause errors.

Testing of the gyroscope for providing sensor feedback for closed-loop heading control provided good results and should be sufficient for heading control of the mining machine. Initial test results were typically less than 1° in error for turn and pivot control of the machine.

The onboard heading system is only one part of a navigation-positioning system. The onboard system is responsible for determining and controlling the mining machine heading as well as providing pitch and roll information. This information will be used by the navigation-positioning system to aid in the manipulation of a mining machine through various positions and headings during mining functions.

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APPENDIX A.—APPARENT DRIFT CALCULATION

Apparent drift is a change in the output of the gyroscope as a result of the Earth's rotation. This change in output is at a constant rate; however, this rate depends on the location of the gyroscope on the Earth. At the North Pole, a gyroscope encounters a rotation of 360° per 24-h period or 15°/h. The apparent drift will vary as a sine function of the latitude as a directional gyroscope moves southward. The direction of the apparent drift will change once in the southern hemisphere. The equations for Northern and Southern Hemisphere apparent drift follow. Counterclockwise (CCW) drifts are considered positive and clockwise (CW) drifts are considered negative.

Northern Hemisphere: 15°/h [sin (latitude)] CCW.

Southern Hemisphere: 15°/h [sin (latitude)] CW.

The apparent drift for Pittsburgh, PA (40.443° latitude) is calculated as follows: 15°/h [sin (40.443)] = 9.73°/h CCW or apparent drift = 0.162°/min. Therefore, a gyroscope reading of 52° at time period of 1 min would be corrected for apparent drift where corrected reading = 52° - (0.162°/min)(1 min) = 51.838°.

Minute changes in latitude generally do not require changes in the correction factor. Once a correction factor is determined for a given mine location, it would then be used throughout the mine. For example, a 0.2° change in latitude (7 miles) gives an additional apparent drift of only 0.00067°/min.

APPENDIX B.—COMPASS COMPENSATION

Compensation of the fluxgate sensor is very similar to the compensation techniques for a conventional compass. The objective of compensation is to "realign" the magnetic field measured by the compass with the Earth's magnetic field. Compensation of alignment errors may be implemented through proper physical placement of the sensor. Internal magnetic compensation is another technique to counterbalance localized magnetic influences. This is accomplished by adjusting the internal coils or magnets of the compass. The basic compensation procedures used are described in reference 11 of the main text.

Compensation for local magnetic fields involves determining north-south and east-west deviations. The north-south deviation is the average deviation from north and south. To determine the deviation, align the compass (as mounted on the machine) to north and record the reading. Next, align the compass to south and record the reading. The coefficient of north-south deviation is determined as in the following example:

Initial north reading	5.00°
North deviation	0.00 - 5.00 = -5.00°
Initial south reading	177.00°
South deviation	180.00 - 177.00 = 3.00°
North-south deviation coefficient	[(-5.00) - 3.00]/2 = -4°

The north-south adjustment would be -4°; thus, the north reading is now 1.00° and the south reading is now 181.00°. Calculation of the east-west deviation is done with the same technique.

Alignment errors exist when the compass is not physically mounted such that it is parallel to the longitudinal axis of the machine. To compensate, the compass must be rotated by the average compass deviation for all four headings.

North deviation	-2.00°
South deviation	4.00°
East deviation	-3.00°
West deviation	0.00°
Alignment coefficient	[-4.00 + 3.00 + (-3.00) + 0.00]/4 = -1.00°

Therefore, the compass must be rotated clockwise 1.00° for proper mounting alignment.

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