

Information Circular 9293

Appendage Control of a Joy 14CM Continuous Miner

By John J. Sammarco

With an Appendix by Randall W. Casciola

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

A/V	ampere per volt	ms	millisecond
°C	degree Celsius	mV/V/°	millivolt per volt per degree
deg	degree	mV/°	millivolt per degree
deg/s	degree per second	pct	percent
deg/V	degree per volt	ppv	part per volume
°F	degree Fahrenheit	s	second
ft	foot	V	volt
Hz	hertz	V ac	volt, alternating current
in	inch	V dc	volt, direct current
kHz	kilohertz	V dc/deg	volt, direct current, per degree
lb/ft ³	pound per cubic foot	V/deg	volt per degree
lb/in ³	pound per cubic inch	°/s	degree per second
mA	milliampere	%/°C	percent per degree Celsius
MHz	megahertz	%/°F	percent per degree Fahrenheit
min	minute		

APPENDAGE CONTROL OF A JOY 14CM CONTINUOUS MINER

By John J. Sammarco¹

With an Appendix by Randall W. Casciola

ABSTRACT

This U.S. Bureau of Mines report describes the research effort and results for a computer-assisted appendage control system of a Joy 14CM continuous mining machine. The cutter head (shear), gathering head, conveyor, and stabilizer jack are the appendages. Positional control of each appendage is accomplished by specifying the desired position to the appendage control computer, which uses appendage position sensor data. Appendage movement is actuated until the desired position is attained as determined by control algorithms.

A description of the sensors, mechanical and electrical interfaces, data acquisition and control (DAC) system, experimental method to determine appendage response characteristics (range of motion, start and stop delay times, and movement rates), and their application to the position control loop algorithms are presented. Also, the test results for the shear in an unloaded (free space) and loaded (cutting) condition of the shear are presented.

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INTRODUCTION

The U.S. Bureau of Mines is conducting research to improve the health, safety, and efficiency of the underground coal mine worker. The general approach is to develop computer-assisted machines that allow machine operators to be relocated to less hazardous areas underground. The Bureau's comprehensive program explores many areas of computer applications for mining. Schnakenberg (1)² presents a research program overview of computer-assisted mining. A computer, along with proper sensors and software, can assist the mining operation by performing many operational functions for a continuous mining machine. Functions include navigation and positioning of the machine, electrical and hydraulic diagnostics, teleremote operation, and computer control of machine appendage positions.

Present research focuses on computer-assisted coal mining applications with continuous mining machines. These machines create longwall mining entries as well as room-and-pillar mining entries and crosscuts. The Bureau established computer control of a Joy 16CM³ continuous miner at its research facility at the Pittsburgh Research Center. One of the first areas of research involved

computer control of machine appendage position. Closed-loop computer control, employing position sensor data, manipulated the positions and sequences of movement for the shear, conveyor, stabilizer jack, and gathering head (2). Since the Joy 16CM continuous miner only serves as a surface research test bed, the Bureau is modifying a Joy 14CM continuous miner for underground field testing, based on the Bureau's Joy 16CM continuous miner research results and on U.S. Mine Safety and Health Administration standards.

There are a number of steps needed to realize an autonomous mining system. This report presents one of those steps—the characterization process of continuous miner appendages and closed-loop test results. The report also describes the sensors and the test setup, detailing data acquisition and analysis for each appendage. Finally, the report gives the values for appendage start and stop dead times, appendage position ranges, and appendage rates of movement. From these data, researchers implemented closed-loop control algorithms that used appendage position sensor feedback and tested control accuracy in free space and while cutting simulated coal.

ACKNOWLEDGMENTS

The author acknowledges Timothy J. Matty, electronics technician, Pittsburgh Research Center, for his assistance in testing and analyzing data.

MACHINE INSTRUMENTATION

Two types of sensors, rotary variable differential transmitters (RVDT) and clinometers, were installed on the Joy 14CM continuous miner to measure the machine's appendage positions. The resulting position data are used in the closed-loop control of the appendages. The sensor locations and sensor types for the shear, gathering head, conveyor, and stabilizer jack are depicted in figure 1.

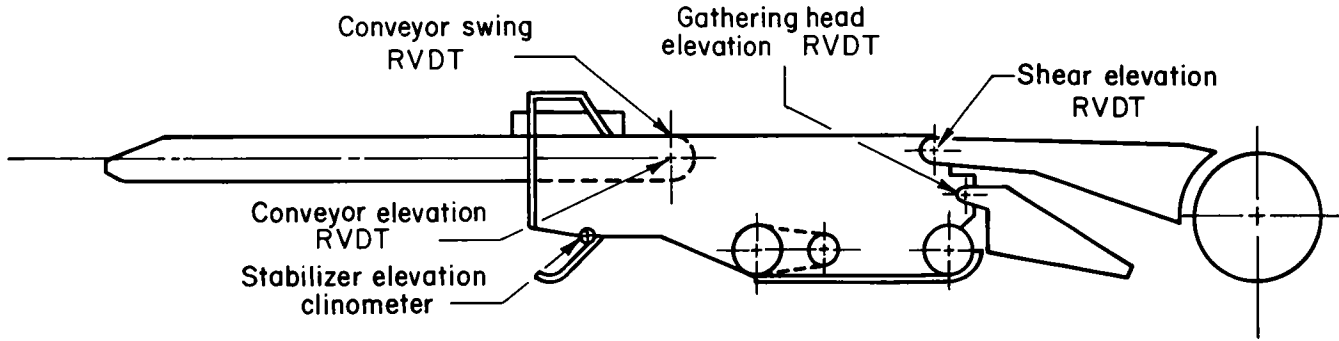
The Bureau selected RVDT's for appendage position measurements since they are rugged and accurate, offering infinite resolution. RVDT's measure angular displacement using the principle of magnetic induction. The sensor consists of a primary coil and two secondary coils. The primary coil is excited with 3 V ac at a frequency of 400 Hz to 20 kHz. The secondary coils produce a voltage directly

proportional to the angular position of a center shaft. The RVDT's used are model R30A manufactured by Schaevitz Sensing Systems Inc. They provide a linearity of better than $\pm 0.5\%$ of full-scale displacement in a $\pm 40^\circ$ range. A complete specification of the RVDT's is given in appendix A.

The stabilizer jack is instrumented with a clinometer to indicate its position. Basically, miners need to know whether the stabilizer jack is up or down. Intermediate position of the stabilizer jack is not important since its main function is stabilizing the continuous miner. The clinometer used for the stabilizer jack has a linearity of $\pm 1\%$. The clinometer is a gravity-referenced sensor that uses differences in capacitance for measuring angular position. It consists of a differential capacitance sensor and complimentary metal-oxide semiconductor electronics that convert signals into an analog voltage output (3). The sensor housing consists of a common capacitor plate between two zinc sensor plates. The internal housing is filled with

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

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



ELEVATION VIEW

Figure 1.—Appendage sensor locations of Joy 14CM continuous miner. (RVDT = rotary variable differential transmitter.)

a dielectric liquid and inert gas. As the sensor rotates about its sensitive axis, the dielectric fluid contacts the capacitor plate, thus changing the capacitance. Appendix A contains a complete specification for the clinometer.

The mounting of the sensors are as follows. The RVDT's and clinometer are mounted within explosion-proof housings. Mechanical linkages connect the RVDT's to the machine's appendages. A clinometer mounted within an explosion-proof housing is mounted directly onto the stabilizing jack for angle measurements. Both types of sensors electrically connect to the analog device's type 3B signal conditioning modules for signal conditioning and amplification, prior to analog-to-digital (AD) conversion. The type 3B module also provides excitation for the RVDT's.

Amplification, or gain, of each module is given in table 1. Variable potentiometers within the signal conditioning module adjusts the gain and zero offset for each module. For the RVDT's, the potentiometers provide secondary adjustment of transducer zero and span. Primarily, mechanical adjustments to the mechanical linkages provide coarse calibration of the sensor system. The transducer signal range and calibration factors for each appendage are listed in table 2.

Figure 2 is a block diagram of the shear sensor system comprised of the mechanical linkage, RVDT sensor, type 3B signal modules, and computer system for signal conversion. The type 3B module provides proper signals to the transducer and conditions the signal as a dc analog voltage for the computer. Next, the microprocessor board reads the shear angle represented by an analog voltage by using an AD converter. The AD converter transforms analog signals in the 0-to-10-V dc range into digital words the microprocessor can use.

Table 1.—Signal conditioning module gains for Joy 14CM continuous miner appendage sensors

Sensor and function	Gain
RVDT:	
Shear elevation	18.78
Gathering head elevation	32.38
Conveyor elevation	128.57
Conveyor swing	140.63
Clinometer: Stabilizer jack elevation	4.24

RVDT Rotary variable differential transmitter.

Table 2.—Calibration data for Joy 14CM continuous miner appendage sensors

Function	Signal range, V dc	Physical movement, deg	Scale factor	
			deg/V	V/deg
Shear elevation	0.5-9.5	0-44	4.888	0.205
Conveyor swing	0.5-9.5	0-86.46	9.606	.1040
Gathering head elevation	0.5-9.5	0-15	1.666	.6000
Stabilizer jack elevation	0.5-9.5	0-35.4	3.933	.2542
Conveyor elevation	0.5-6	0- 6.1	1.090	.9166

The AD converter does not transform negative voltage signals; if the transducer and/or signal conditioner module drifts below 0 V dc, the negative drift goes undetected. To circumvent this, the zero position of the sensor system is set to indicate 0.5 V dc. For example, in the shear circuit, a negative drift of 0.5 V dc represents an apparent change of 2.45° in shear position. Significant changes in drift cause inaccurate control of appendage positions. Drift can occur from physical changes in mechanical linkage and from temperature variations that change the electrical outputs of the sensor and signal conditioning electronics.

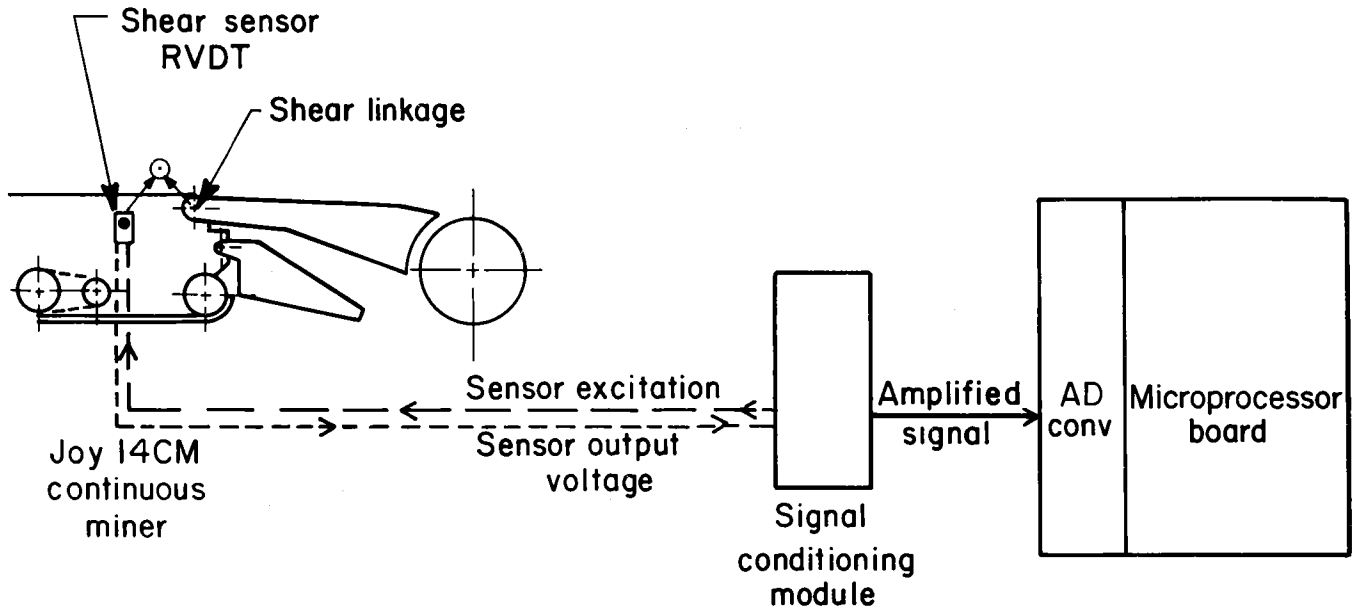


Figure 2.—Block diagram of shear sensor system. (RVDT = rotary variable differential transmitter; AD conv = analog-to-digital converter.)

TEST SETUP

The Bureau concentrated on two test areas: open-loop tests and closed-loop tests. Open-loop tests provided the characterization of the machine's appendages. These tests include measuring each appendage sensor output while monitoring the signals actuating each appendage on the machine. Researchers used the test data to formulate the closed-loop control algorithms needed to manipulate appendage positions as discussed in the "Control Methodology" section of this report.

The Bureau used a Keithley model 500 personal computer (PC) based DAC system to measure the analog output voltage of each appendage sensor and the actuation signals for each appendage. The test setup is depicted in figure 3. The three main components of the test setup are the Joy 14CM continuous miner instrumented with appendage sensors, the Joy System III radio remote control pendant for the machine, and the DAC system located in the control room of the Bureau's test facility. This basic test setup operated as follows for open-loop testing.

A Joy System III radio remote control pendant, transmitting at 318 MHz, provided the control signals for actuating the appendages. The DAC system recorded these control signals and the sensor outputs for each appendage, as seen in figure 3. The actuation and each appendage response signal was used to determine start and

stop dead times. A radio remote control receiver that is a duplicate of the one onboard the Joy 14CM continuous miner located in the control room and connected to the serial port of the DAC system's PC, monitored the radio control signals and sent them to the PC. The PC software, written in the computer language C, collected the control signals of the pendant with respect to time. A second program reformatted the data file containing time and pendant control signals into a format compatible for processing by spreadsheet software.

Once the pendant control data file is in a spreadsheet format, it can be combined with sensor data also in a spreadsheet format. Thus, the combined file contains time, actuation signal, and sensor signal for the appendage. Detailed information on the software for acquiring pendant data is given in appendix B.

The DAC system is PC-based and capable of acquiring and analyzing data. A PC-based system provides flexibility and uses commercially available acquisition and analysis software (4). With the proper software, DAC's reduce the time needed to collect data, reduce errors that occur through manual data input, and make high-speed data collection possible.

Three main types of DAC system architectures exist today. The first type consists of plug-in cards that fit

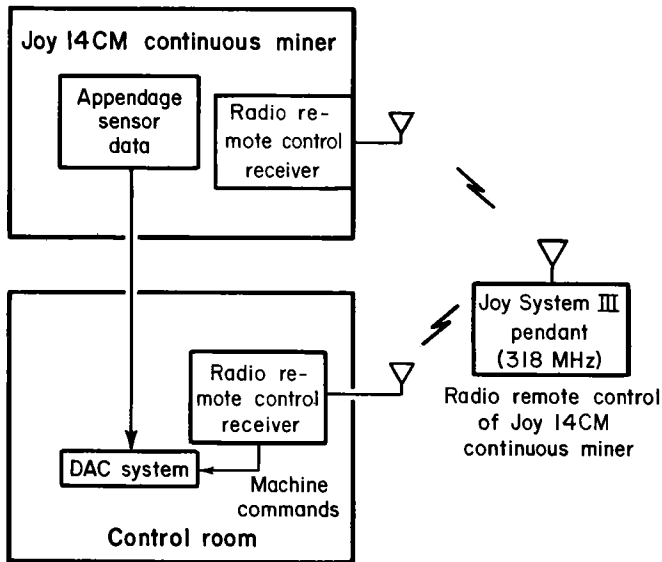


Figure 3.—Joy 14CM continuous miner appendage characterization test configuration. (DAC = data acquisition and control.)

directly into the bus of the PC. This system architecture is a low-cost method generally suited for small applications with limited functions due to the small number of spare slots in the backplane of the PC. A second architecture uses a separate chassis and backplane connected to the PC bus through a signal bus interface. One advantage of this system is the ability to use a greater variety of interface cards in the DAC system backplane, thus adding more flexibility and capabilities. Also, there is less potential for noise contaminating the measured input signals since the plug-in boards are not exposed to the noisy environment of the PC bus. The third type of DAC system is intelligent enough to run without an external PC. However, a user still needs an external PC for data analysis and display. For Joy 14CM continuous miner experiments, researchers used the DAC system architecture containing a separate chassis and backplane.

The PC-based DAC system consists of a Keithley 500 DAC system and a Compaq portable 386 PC (fig. 4). The PC controls and acquires data through the physical interfaces provided by the Keithley 500 DAC system. In addition, the PC stores test data on hard or floppy disks. The PC also analyzes and presents data. The Bureau chose Labtech Notebook software, a simple, menu-driven software package requiring no programming skills, capable of acquiring, controlling, and analyzing data. Researchers used Quattro Pro spreadsheet software to analyze data and to generate graphs. Keithley gives a basic overview of commercially available PC-based DAC software (5).

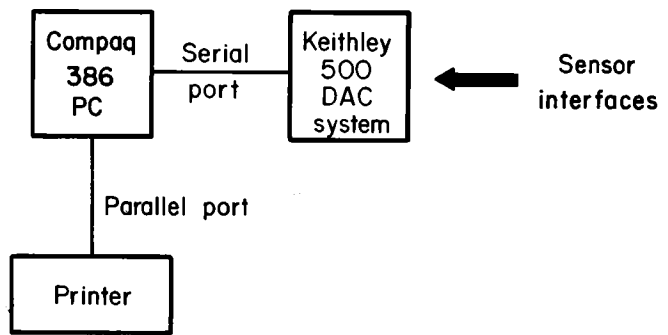


Figure 4.—PC-based DAC system. (PC = personal computer; DAC = data acquisition and control.)

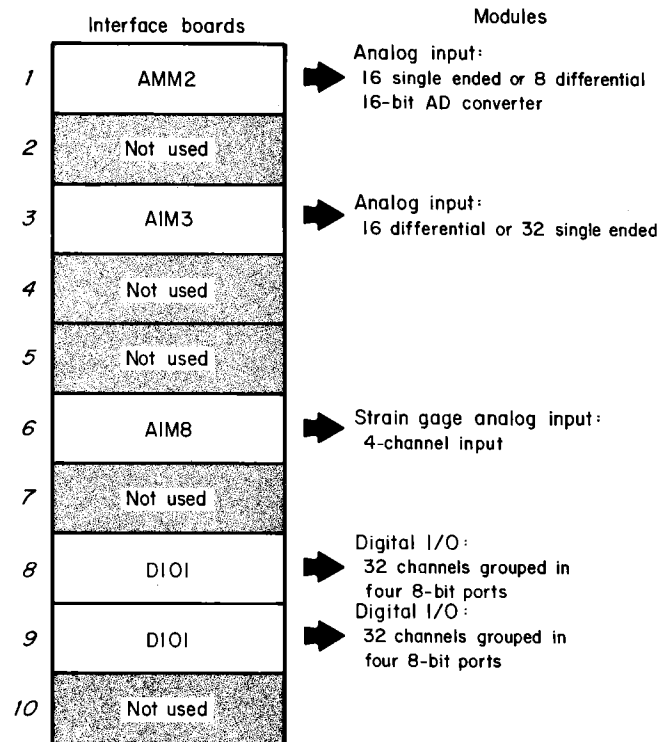


Figure 5.—Keithley 500 DAC system backplane. (AD = analog-to-digital.)

The Keithley 500 DAC system backplane supports 10 interface boards for signal acquisition and control. The Bureau's backplane configuration to support computer-assisted mining research is depicted in figure 5. The appendage sensors are connected to the Keithley AIM3 board for analog input. This particular interface board is configured for 32 single-ended analog inputs and provides signal conditioning as well as analog signal interfacing.

CONTROL METHODOLOGY

The Bureau uses a closed-loop control system for control of appendage positions. This type of control employs a sensor on each machine appendage to provide the feedback for the appendage control algorithm. A basic closed-loop system is depicted in figure 6. With this control, one can precisely monitor and manipulate the position of the machine's appendages by using sensor feedback. An on-off control scheme implements closed-loop control with sensor feedback (6). Operating a basic on-off control is quite simple. When sensor feedback signals reach various fixed set points, the appendage operation starts or stops depending on the set point reached. On-off control action bases itself on an error signal (E), which is the difference between the present value (PV) of the system output and the desired position or target value (T).

$$E = PV - T.$$

A positive error (POS) results when the system output is more than the target value; a negative error (NEG) results when the output is less than the target value.

For each sign of error there are two set points. One that starts (turns on) appendage motion and one that stops (turns off) an appendage already in motion. These four set points are named appropriately POS-ON and POS-OFF for positive errors and NEG-ON and NEG-OFF for negative system errors. The set points for a negative and positive error are depicted in figure 7.

If an error exceeds the absolute value of POS-ON or NEG-ON, the control system actuates (turns on) the appendage so that it reduces the error and thus moves to the desired position. Needless activation of the appendage is prevented by choosing the on set points to be larger than the sensor noise and the resolution of the actuation system for the appendage. The appendage directions for these set points are listed in table 3. Appendage actuation stops when set points reach the corresponding POS-OFF or NEG-OFF values. These values are also set differently from zero error to account for activation delay and appendage inertias.

Table 3.—Appendage directions for set points

Function	POS-ON	NEG-ON
Conveyor elevation	Down	Up.
Conveyor swing	Right	Left.
Shear elevation	Up	Down.
Stabilizer jack	Down	Up.
Gathering head elevation . .	Up	Down (float).

The calculation of set points for the shear elevation is given below as an example. Sammarco (2) gives a more detailed discussion of the same type of control implemented on the Joy 16CM continuous miner appendages. Set point levels for each appendage algorithm, calculated as shown in the following example, are given in table 4.

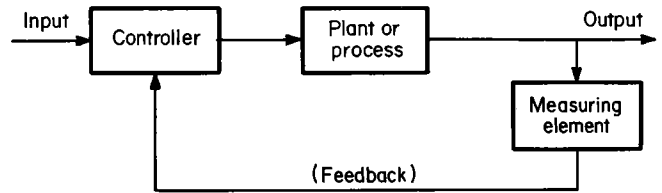


Figure 6.—Basic closed-loop control system.

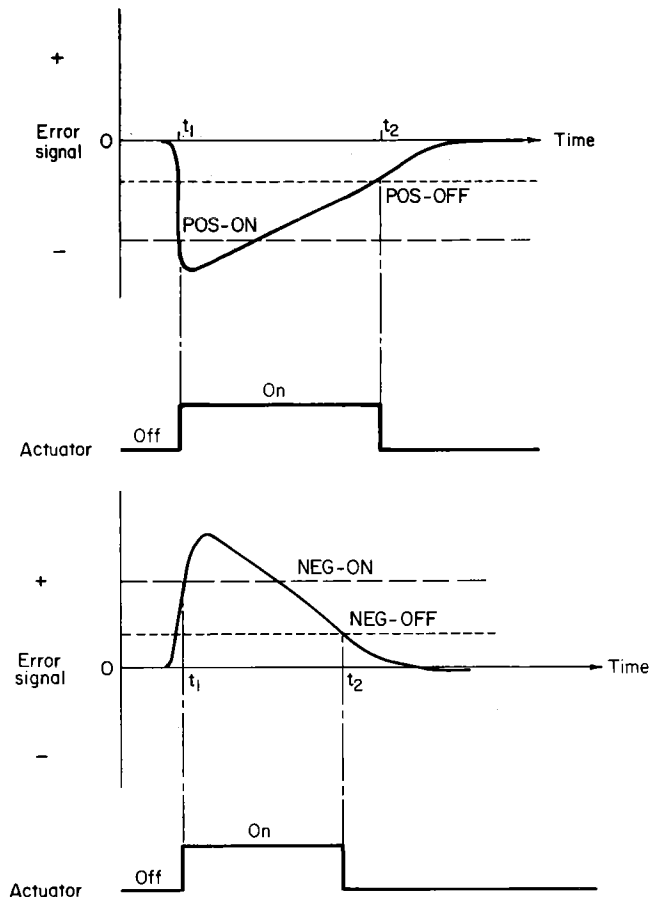


Figure 7.—On-off set points for negative (top) and positive (bottom) error. (t = time.)

Table 4.—Set point levels, degrees

Function	POS-ON	POS-OFF	NEG-ON	NEG-OFF
Conveyor elevation	0.7	0.5	0.5	0.4
Conveyor swing . .	2.2	2.0	2.1	2.3
Shear elevation . .	.2	.1	.9	.8
Gathering head elevation	2.0	1.8	NA	NA

NA Not available.

The NEG-ON is calculated for the shear movement down. The value of NEG-POS-ON is derived from considerations of sensor noise, appendage control system (actuation system) capabilities, and required resolution of motion, whichever is larger. In this example, minimum increment of position, or in other words the resolution of control, is about 1.8 in.

$$\text{NEG-ON} = \frac{\text{max shear arc}}{\text{desired steps of control}}$$

$$\text{NEG-ON} = \frac{44^\circ}{49^\circ}$$

$$\text{NEG-ON} = 0.9^\circ \text{ (1.8 in, vertical shear height).}$$

The NEG-OFF and POS-OFF set points, which instruct the appendage to stop movement, are calculated from measured activation delay times. The NEG-OFF is calculated for the shear:

$$\text{NEG-OFF} = t_d \, d\theta/dt,$$

where t_d = total delay time,

$$\begin{aligned} &= \text{lag time (off) + sample time}^4 + \text{program execution time (lag time (off))} \\ &= 110 \text{ ms; sample time + program execution time} = 147 \text{ ms),} \end{aligned}$$

and $d\theta/dt$ = rate of shear movement down
= 3.11°/s.

$$\text{NEG-OFF} = (100 + 147 \text{ ms}) \times 3.11^\circ/\text{s},$$

$$\text{NEG-OFF} = 0.8^\circ.$$

TESTS

Open-loop and closed-loop control tests were conducted to determine the dynamic operating characteristics of the machine. The open-loop test results were used to determine the parameters (set points) in the algorithms for closed-loop control. Once researchers designed the closed-loop control system, it was tested in free space and while cutting a simulated coal seam known as coalcrete. The coalcrete had an average compressive strength of 94.5 lb/ft³ (4,636.4 lb/in³). Its composition is 10 ppv of 1.5- to 2-in nominal coal, 8 ppv fly ash, 1 ppv cement, and 1.5 ppv water.

The coalcrete tests served two purposes with respect to appendage control. First, the tests showed the accuracy and stability of shear elevation control during load conditions. Second, coalcrete tests demonstrated the robustness of the system. The mechanical sensor linkages and the sensors were subjected to shock, vibration, and dust similar to that encountered during real mining procedures.

OPEN-LOOP TESTS AND RESULTS

Open-loop tests consist of activating the appendage for a fixed time period. In the open-loop tests, the sole purpose of the appendage sensor is to send back signals

representing the appendage position. When the timing of the signals that actuate appendage movement are compared with the time response of the appendage sensor, the start and stop lag times and the rates of appendage movement can be determined. Lag time is defined as the time between the instant an electrical signal for appendage actuation is sent and the instant appendage movement is detected.

Two types of open-loop tests are needed to determine these parameters: full-scale and step-function tests. The full-scale test data provide the maximum range of appendage movement and the rate of movement. All full-scale tests were repeated three times. The rate of movement was determined from the slope of a linear regression of the signal in the range of 10% to 90% of the maximum signal. The maximum range and movement ratio for each appendage are presented in table 5. Figure 8 is a plot of full-scale tests for shear elevation as an example of full-scale response data. No disturbances are evident in the signal, and the rate of change is very constant. An r^2 value of 0.99 was calculated for this curve. This r^2 value is a statistical measure of how well the data represent the fitted line; a perfect linear fit would have an r^2 value of 1.00.

⁴Sample time is the rate that appendage sensor data are read.

Table 5.—Full-scale open-loop test results for Joy 14CM continuous miner appendages

Primitive function	Average measured maximum range, deg	Rate of change, deg/s
Conveyor up	6.56	1.95
Conveyor down	6.68	3.33
Conveyor swing left	87.65	11.81
Conveyor swing right	88.98	14.39
Shear up	44.52	2.18
Shear down	44.57	3.11
Stabilizer jack up	41.20	10.28
Stabilizer jack down	41.21	16.79
Gathering head up	15.21	2.64
Gathering head down	15.12	12.03

Next, researchers conducted step-function open-loop tests where each appendage was on for a short time. The step-function response analysis yielded start and stop lag times. Both the start and stop lag times, along with the appendage rates, assist in determining closed-loop control algorithm parameters described in the previous section. The lag times at which each appendage will change, as determined by the open-loop tests, are given in table 6. The step-function response of the shear, as an example of step-function response, is depicted in figure 9.

Table 6.—Step-function open-loop test results for lag time in free space, seconds

Primitive function	Start lag time	Std dev	Stop lag time	Std dev
Conveyor up	0.14	0.04	0.06	0.04
Conveyor down	.11	.02	.08	.02
Conveyor swing left	.21	.04	.15	.02
Conveyor swing right	.17	.02	.14	.03
Shear up	.14	.01	.06	.01
Shear down	.11	.02	.11	.01
Stabilizer jack up	.19	.03	.55	.14
Stabilizer jack down	.22	.05	.38	.12
Gathering head up	.20	.06	.11	.02
Gathering head down	.08	.04	NA	NA

NA Not available.

CLOSED-LOOP TESTS AND RESULTS

Researchers conducted closed-loop appendage position tests once they calculated the set points. The control algorithms reside in an onboard computer consisting of an Intel IRCB40/20 remote analog I/O board. This computer, designated as node 1, contains 16 analog inputs and 2 analog outputs and operates within a distributed control network known as BITBUS (7). Additional information on this computer is in Intel documentation (8). Adding a CDX-P48 parallel I/O port from Computer Dynamics

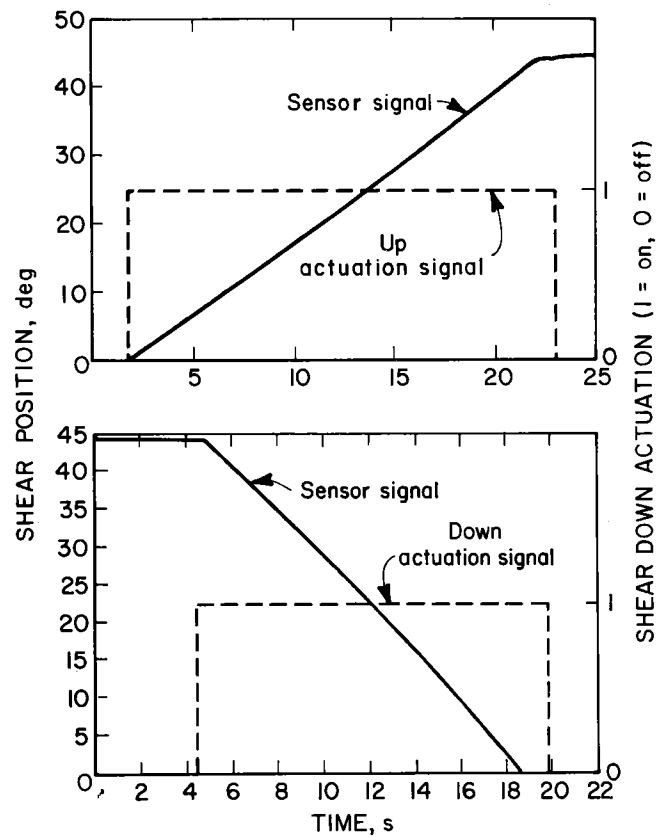


Figure 8.—Full-scale test response, shear up (top) and shear down (bottom).

Corp. enhanced the computer's interface to 48 digital I/O lines. The digital I/O lines enabled actuation of various machine appendages. The analog inputs of the IRCB40/20 interfaced to the outputs of the appendage sensors. Researchers implemented closed-loop control tests using the test setup shown in figure 10. The Bureau designed a remote operator and diagnostic node (RODNE) to input commands to node 1. RODNE consists of a liquid crystal display (LCD) and keypad for data entry. Menu-driven software for RODNE enables a user to manually input closed-loop control commands to node 1. As node 1 executes closed-loop control of the Joy 14CM continuous miner appendages, the DAC system records sensor data.

Researchers tested closed-loop control in two situations. The first involved machine control in free space to verify the basic operation of closed-loop appendage control. In the second, the machine cut coalcrete so researchers could observe both the accuracy and the stability of control while the machine was under load. This also helped evaluate the robustness of the appendage system.

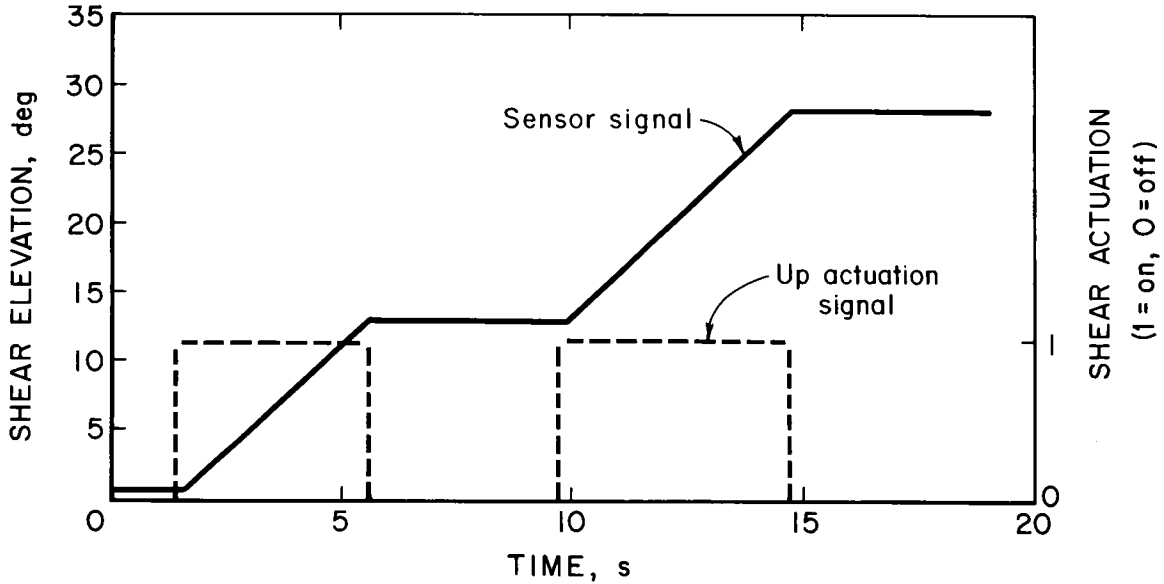


Figure 9.—Shear step-function response.

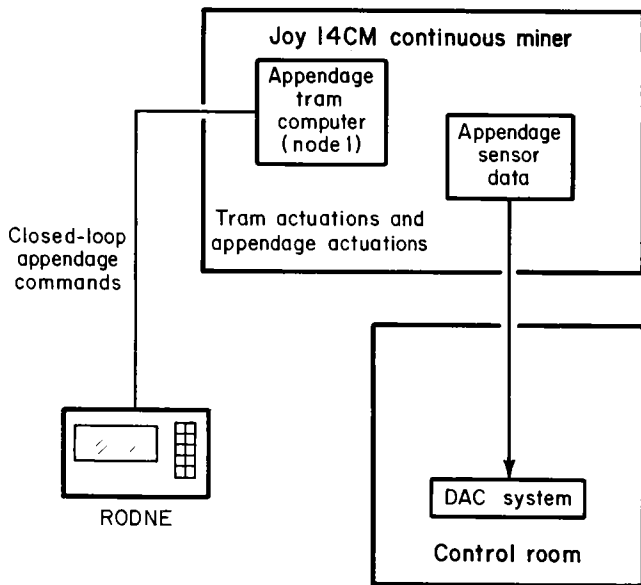


Figure 10.—Test setup of closed-loop appendage control of Joy 14CM continuous miner. (RODNE = remote operator and diagnostic node; DAC = data acquisition and control.)

FREE SPACE TESTS AND RESULTS

For free space testing, researchers gave each appendage a target value. Each appendage was tested for targets near each end of the range of movement. The first target was a small step in the up or left direction. This tested

the ability of the control to achieve a request for a small excursion. The next target was a much larger excursion in the same direction. This verified the accuracy of control starting from a point other than zero and meeting the request for a large excursion in movement. Next, researchers tested each appendage for its ability to return to the first target. They repeated each test sequence three times. The appendage position was taken as the data position supplied by the appendage sensor.

Control accuracy in free space is presented in table 7. The average value presented is an average of three tests for a particular appendage. The closed-loop test results in free space for the shear elevation are graphically depicted in figure 11. In this test, the shear was instructed to go from floor level (5°) to 30°, which is approximately 68% of total shear range. The resulting position error for this test was 0.3°.

Table 7.—Closed-loop test results in free space for fixed target, degrees

Function	Target	Average	Error
Conveyor elevation	2.0	1.79	-0.21
	4.0	4.14	.14
Conveyor swing	20.0	20.06	.06
	60.0	61.34	1.34
Shear elevation	5.0	4.74	-.26
	30.0	30.22	.22
Gathering head elevation . .	14.0	13.97	-.03

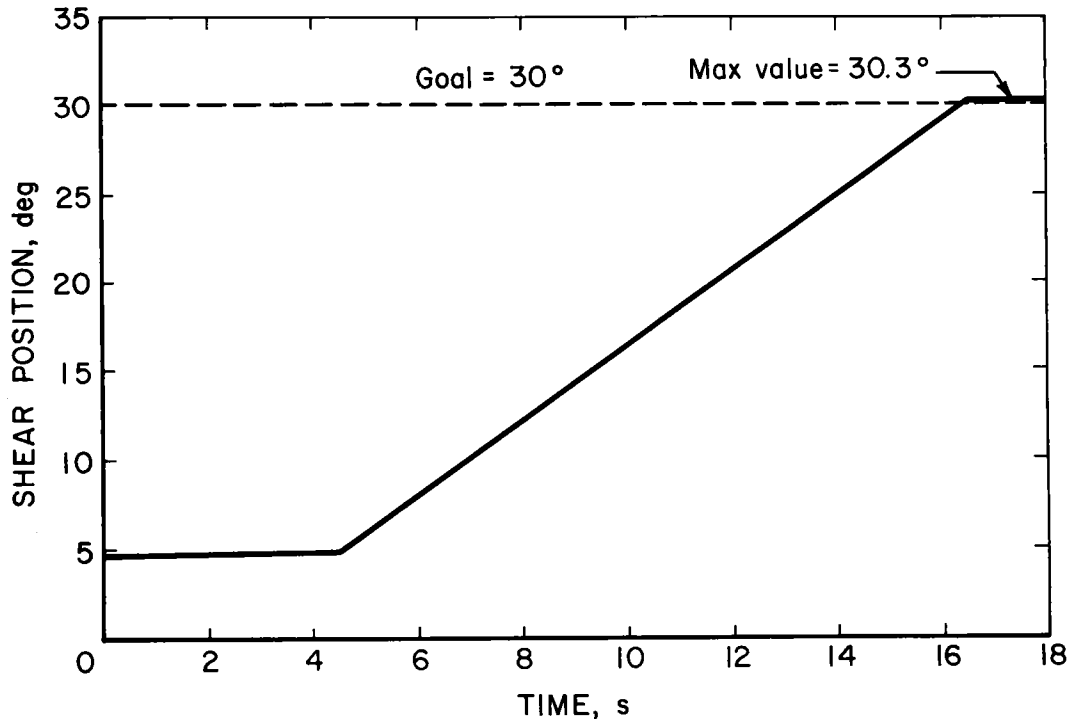


Figure 11.—Shear elevation under closed-loop control.

COALCRETE TESTS AND RESULTS

Researchers conducted coalcrete tests at the Bureau's Pittsburgh test facility. They instructed the Joy 14CM continuous miner to cut coalcrete under computer control of the machine's shear appendage. In this test situation, a research and development tool, Autonomous Mining Research and Development Systems (AMREDS), gave the commands for appendage and tram control.

AMREDS is a window-based computer program developed by the Bureau of Mines and Carnegie Mellon University (9). AMREDS provides a script mode, allowing the user to generate sequences of machine actions such as scripts of sump and shear cutting cycles. AMREDS interfaces with node 1 and sends it appendage and tram commands.

An AMREDS script for cutting coalcrete was generated. The appendage control algorithms placed in the node 1 software implemented closed-loop control of the shear position during script execution. The primary intent of the coalcrete test is to determine shear control accuracy and stability under a dynamic situation of machine loading and vibration.

In the AMREDS script used for cutting coalcrete, the cutting drum sumped into the face approximately 39 in (full diameter) at the top of the coalcrete block (about 6 ft

high) and sheared to the bottom of the block. The script steps are the following:

1. Raise shear to 20° (top of coalcrete block).
2. Tram forward slow to the front of the coalcrete face.
3. Turn the conveyor on to the forward position.
4. Turn the cutting motors on.
5. Lower the stabilizing jack.
6. Sump in a full diameter of the shear drum by tramping forward slowly, for about 40 s. (Because the tram tracks slip on the concrete floor, it tramped forward approximately 40 s to achieve the proper sump depth.)
7. Shear down to 5.0° (floor level).
8. Raise the stabilizer jack.
9. Turn the conveyor off.
10. Turn the cutting motors off.
11. Tram low-speed reverse for 40 s.

CLOSED-LOOP TEST RESULTS IN COALCRETE

Shear position for the described script while cutting coalcrete is depicted in figure 12. As evident in figure 12, no control instability was observed while cutting the coalcrete. Shear position was 5.72° for the time intervals between 40 and 110 s. The shear was instructed to obtain a target of 5°, but was unable to owing to interference with

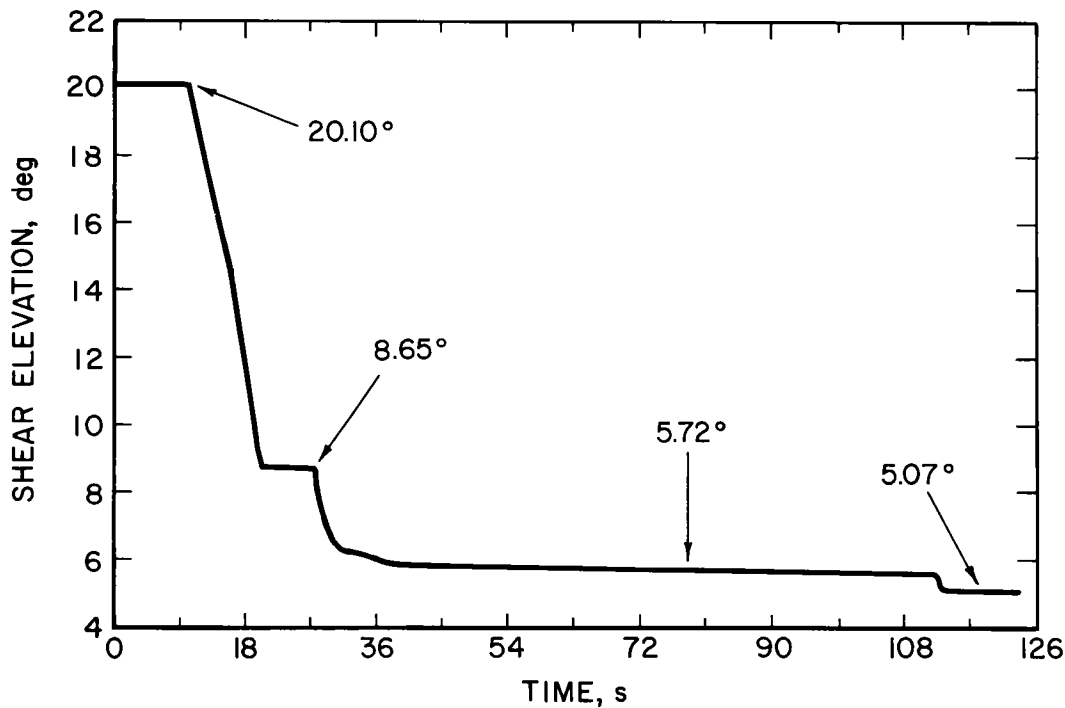


Figure 12.—Closed-loop coalcrete test sequence 1. Values shown are piecewise linear averages.

the gathering head, which was floating on rubble and not resting directly on the floor. Therefore, the machine was trammed in reverse in order to let the gathering head rest on the floor, as seen in figure 13. Once the gathering head rested on the floor at about 112 s, the shear control obtained a measured shear position of 5.07°. The measured and the target values of shear control for this test are presented in table 8.

Table 8.—Sequence 1 test results for closed-loop shear elevation control while cutting coalcrete, degrees

Target value	Measured value	Error
20.00	20.10	0.10
9.00	8.65	-.35
5.00	5.07	.07

SENSOR SYSTEM STABILITY

The sensor system contains sensors, mechanical linkages, and signal conditioning modules. Initial calibrations set the zero and span for each appendage sensor system. The system should stay in calibration over time and environmental changes and after repeated activations and

vibrations. Errors in sensor system calibration cause errors in appendage positions.

Researchers conducted two tests to measure the stability of the sensor system: static and dynamic.

Static tests measure the drift of zero and span when the machine and its appendages are in a nonmoving position. The DAC system records and reads the zero and span for each appendage. Researchers gathered data every 5 min for a total of 900 min. Temperature was recorded at the signal condition modules. Over the 900-min period, the temperature range was 76° to 87° F. During this time, the machine and appendages were not moved. The minimum and maximum changes for a given appendage position during static tests are presented in table 9.

Table 9.—Zero offset drifts for sensor system appendages

Function	Zero drift, V dc/deg	Zero drift, deg	Zero drift, pct of full-scale span
Conveyor elevation . .	0.089	0.121	1.978
Conveyor swing . . . .	.018	.18	.200
Shear elevation . . . .	.021	.11	.467
Stabilizer jack . . . . .	.012	.05	.133
Gathering head elevation . . . . .	.045	.150	.500

NOTE.—Static tests conducted over a duration of 900 min. Measured temperature ranged from 76° to 87° F during tests.

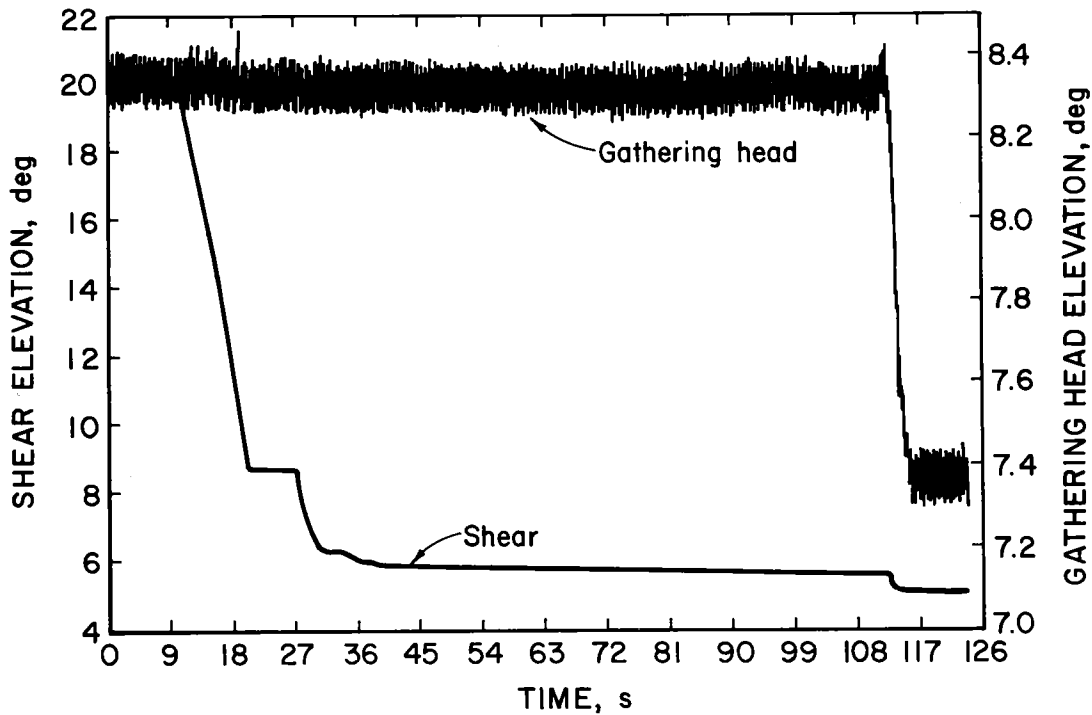


Figure 13.—Gathering head position for coalcrete test sequence 1.

For dynamic tests, the DAC system first records zero and span of each appendage before the machine cuts coalcrete. The machine cut approximately 50 in of coalcrete as described in the coalcrete tests for closed-loop control, then researchers measured the zero and span again. The resulting data are presented in table 10.

Both static and dynamic tests showed adequate stability. Studies will continue concerning the stability of appendage sensors. Field testing in an underground coal mine began in January 1991.

Table 10.—Calibration stability results for sensor system after dynamic tests, degrees

Function	Before cutting coalcrete		After cutting coalcrete	
	Zero offset	Full-scale span	Zero offset	Full-scale span
Conveyor elevation	0.07	6.1	0.35	6.33
Conveyor swing . . . . .	.58	87.03	.29	86.46
Shear elevation	-.05	43.89	-.15	43.84
Gathering head elevation . . .	.37	15.25	.27	15.18

SUMMARY

The Bureau designed and tested closed-loop position control systems for computer-manipulation of the appendages of a Joy 14CM continuous mining machine. The system consists of position sensors and an Intel iRCB 44/20 computer board. Researchers used an RVDT position sensor on the shear, gathering head, and conveyor. A clinometer was used on the stabilizer jack. Each sensor was mounted within its own explosion-proof housing.

Initial tests of the system included open-loop tests to characterize the movements of each appendage and to determine closed-loop control parameters. Next, researchers wrote closed-loop control algorithms based on open-loop test data. They tested closed-loop control in free space and while cutting coalcrete. Tests demonstrated the appendage control's acceptable accuracy and stability during free space and coalcrete tests.

REFERENCES

1. Schnakenberg, Jr., G. H. Computer-Assisted Continuous Coal Mining System—Research Program Overview. BuMines IC 9227, 1989, 15 pp.
2. Sammarco, J. J. Closed Loop Control for a Continuous Mining Machine. BuMines RI 9209, 1988, 17 pp.
3. McCarty, L. H. Capacitance Difference Reveals Angular Position. Design News, June 1986, pp. 110-113.
4. House, R. PC-Based Data Acquisition Systems. Sensors, Feb. 1989, pp. 5-12.
5. Keithley Instruments Inc. (Taunton, MA). Keithley Catalog and Reference Guide 1989-1990, v. 22, 1989, pp. 199-201.
6. Ogata, K. Modern Control Engineering. Prentice-Hall, 1970, pp. 1-14.
7. Schiffbauer, W. H. A Microcomputer Network for Autonomous Mining Research. Paper in 21st Application of Computers and Operations Research in the Mineral Industry. Soc. Min. Eng. AIME, 1989, pp. 928-935.
8. Intel Corp. (Santa Clara, CA). iRCB 44/20 Analog Remote Controller Board User's Guide 1986. 1986, No. 148816-001, pp. 1-4.
9. Ausefski, D. B. Researchers Interface Software for Computer Based Mining System Development and Testing. Paper in Tenth WVU International Mining Electrotechnology Conference. WV Univ., Morgantown, WV, 1990, pp. 130-133.

APPENDIX A.—SENSOR SPECIFICATIONS

ROTARY VARIABLE DIFFERENTIAL TRANSMITTER (RVDT)

Model	R30A.
Manufacturer	Schaevitz.
Locations	Shear elevation, conveyor elevation and swing, gathering head elevation.
General Specifications:	
Input voltage	3 V root-mean-square (nominal).
Input frequency	400 Hz to 20 kHz.
Operating temperature	-55° to 150° C (-65° to 300° F).
Temperature coefficient of sensitivity	0.04%/°C (0.02%/°F) over the temperature range -5° to 75° C (20° to 160° F).
Electrical Specifications:	
Linearity:	
At 2.5 kHz:	
±30°	25% of range.
±40°	0.5% of range.
±60°	1.5% of range.
At 10 kHz:	
±30°	0.25% of range.
±40°	0.5% of range.
±60°	1.5% of range.
Sensitivity:	
At 2.5 kHz	2.2 mV/V/°.
At 10 kHz	1.7 mV/V/°.
Primary impedance:	
At 2.5 kHz	125 ohms.
At 10 kHz	370 ohms.
Secondary impedance:	
At 2.5 kHz	500 ohms.
At 10 kHz	1,300 ohms.
Phase angle at 2.5 kHz	35°.

CLINOMETER

Model	Acustar PN 02383-01.
Manufacturer	Schaevitz.
Location	Stabilizer jack.
General Specifications:	
Linear range	±45°.
Total range	±60°.
Threshold and resolution	0.001°.
Linearity:	
Null to 10°	±0.1°.
10° to 45°	±1% of angle.
Null repeatability	±0.05°.
Sensor frequency response	0.5 Hz.
Electrical Specifications:	
Input voltage range	±8 to ±20 V dc.
Input current (each supply)	5 mA.
Output voltage	60 mV/°.

APPENDIX B.—JOY SYSTEM III PENDANT DATA ACQUISITION SOFTWARE

By Randall W. Casciola¹

The purpose of the software is to collect and manipulate control signal data from the Joy System III remote-control pendant. The software is comprised of two individual programs: (1) "Retrieve" is designed to collect the control signals from the pendant and write them verbatim to a disk file with only a time and date stamp at the beginning; (2) "Reformat" will take the file containing the pendant's control signals and create another file suitable for importing into a spreadsheet or graphing program. This second file can be customized by the user to contain switch activation information for any or all of the pendant's functions spaced at any time interval desired.

The programs require specific hardware for proper operation. The most critical hardware is the Joy System III remote-control pendant. Use of the software with

other Joy control pendant systems is not guaranteed to work. An IBM PC-compatible computer with an available serial port is also required. Although a hard disk drive is optional, it is highly recommended that the user copy the two programs (retrieve.exe and reformat.exe) to a hard disk under a separate subdirectory. Further, a link between the pendant and the computer is needed. This link can be accomplished in two ways: The pendant can be connected to the computer by a direct cable link, or by the Joy radio receiver-transmitter pair. Figure B-1 is a diagram showing connections and pinouts of various components.

The acquisition process consists of first collecting the control signals from the pendant and storing them to a disk file using the "Retrieve" program. The reformatting of the data is done with "Reformat" and can be performed at any time. To use "Retrieve," connect the hardware as

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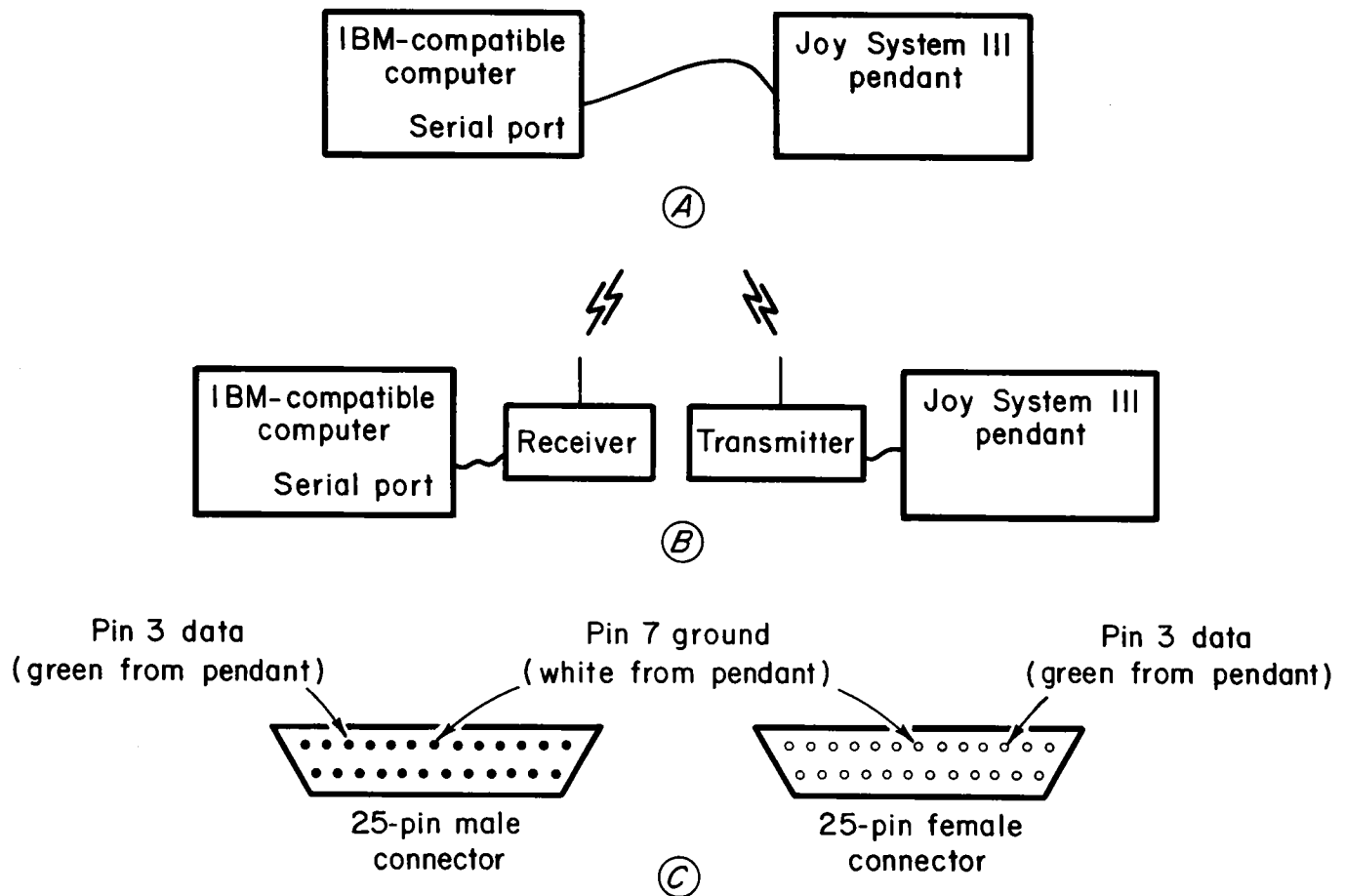


Figure B-1.—Joy System III pendant connections.

shown in figure B-14 or B-1B, depending on the hardware the user has. Pin connections for the serial port are shown in figure B-1C. Second, the user must either be in the same directory as, or have a path to the directory that contains, "Retrieve." An explanation of DOS terms can be found in the user's MS-DOS reference manual. Type

```
retrieve [pathname]filename.[ext]
```

at the DOS prompt. The first part of the command line, "retrieve," starts the program. The second part, "[pathname]," is optional. It is used only if the file that the program creates is to be placed on a drive or in a subdirectory other than the one the user is in presently. Examples of legitimate commands are shown below:

Example 1: retrieve c:\myfiles\data.1

This starts the program and creates the file "data.1", placing it in the subdirectory "myfiles" in the root of drive C. If the path is not valid, the program will alert the user to this and end, dropping the user back to the DOS command line.

Example 2: retrieve cut1

This will start the program and create the file "cut1" and place it in the present working directory.

Example 3: retrieve d:cut2

This will start the program and create the file "cut2" and place it in the active subdirectory of drive D. Once the program is running, it will display a "Taking Data" message on the screen along with the current data packet count. To stop taking data, the user should press the Esc key.

The program will then display some statistics about that session. The program has some error checking ability, and if it detects a possible error, the program will display a message warning the user to use the data with caution. If the program finds that an error is nearly certain, it will

warn the user not to use the data at all. The software has two modes of error checking. One mode is time dependent. Owing to a lack of resolution of the PC's time clock, this time-dependent mode may cause the program to caution the user against using data that are good, or fail to warn the user if the data are slightly tainted. The former will usually happen if the sample time is short, <1 to 2 min, and the latter if the sample time is long, ≥ 35 min. The researchers mention this so that the user will consider these error messages, especially the first one, not as absolute truth, but as warnings to possible trouble. The other mode of error checking is, however, absolute and will immediately end the session. If this happens, the data are good up until the instant that the program was aborted.

As soon as the first program has ended, the second can be started. To run "Reformat," simply type "reformat" from its directory or from any directory if there is a path set to "Reformat's" directory. The user will be presented with a menu of functions from which to choose. The user can select any number of functions to monitor and then select "0" when finished. Next, type in the sampling rate. Although in reality the output rate of the pendant is fixed at ~ 9.1 Hz, the program can appropriately skip or fill in data to fit the user's sampling rate. The user will next be asked for the filename from which to reformat the data. This would be the file just created with "Retrieve." The same protocol to pathnames described above also applies here. At the next prompt, the user will be asked to specify a file for the formatted output. Just type in an optional pathname and filename. If the file specified is already in use, the user will be warned and given the option of specifying a different name or writing over the file. Next, the user will be asked if all the information entered is correct. If it is, type "y." If not, type "n" and the program restarts. Since the program does not modify the original file created with "Retrieve," the user may use it as the source file as often as desired to try many combinations of functions and sampling rates. The "Reformat" program creates a file that can be imported into a spreadsheet program or graphing program that will accept comma-and-quote delimited files.