RI 9545

REPORT OF INVESTIGATIONS/1995

Teleoperation of a Compact Loader-Trammer

UNITED STATES DEPARTMENT OF THE INTERIOR

UNITED STATES BUREAU OF MINES

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Teleoperation of a Compact Loader-Trammer

By T. M. Ruff

UNITED STATES DEPARTMENT OF THE INTERIOR
Bruce Babbitt, Secretary

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

Metric Units

cm	centimeter	MHz	megahertz
kg	kilogram	s	second
m	meter	V	volt
m^3	cubic meter	W	watt
mA	millampere		

U.S. Customary Units

ft	foot	lb	pound
in	inch	yd^3	cubic yard

TELEOPERATION OF A COMPACT LOADER-TRAMMER

By T. M. Ruff[1]

ABSTRACT

The U.S. Bureau of Mines has developed a portable, inexpensive teleoperation system for mobile hard-rock mining equipment. The system was tested on a compact loader-trammer in a simulated stope. The teleoperation system includes radio remote control and computer-assisted navigation. A recent enhancement includes video cameras mounted on the machine to provide visual information to the operator. This system allows the operator to remain in a safe location while operating the machine from a distance, thus increasing both operator safety and mining productivity.

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INTRODUCTION

A miniature load-haul-dump unit (LHD) developed under a U.S. Bureau of Mines (USBM) contract was designed to muck narrow stopes more effectively than existing equipment. The machine, called a compact loader-trammer (also referred to as the "minimucker"), is radio remote controlled and uses a computer-assisted navigation system that allows the machine to follow stope walls automatically. This navigation system assists the remote operator when the machine is tramming through narrow stopes and has been shown in previous research to reduce operator fatigue and machine wear.

However, tests indicated the need to provide visual information to the operator when the machine is tramming long distances in dark, underground environments. If the machine operator remains stationary while controlling the machine, the distance between them may exceed 60 m (200 ft). Under these conditions, it is difficult for the operator to determine if obstacles are in the machine's path, if the machine is loading muck properly, or if it has reached its load capacity. It would be beneficial if visual information could be provided to the operator in this situation.

The goal of this current research was to incorporate video cameras into a portable, inexpensive teleoperation system that could be mounted on any mobile piece of mining equipment. This work is in support of the USBM mission to promote greater safety and productivity in the Nation's mines.

COMPACT LOADER-TRAMMER

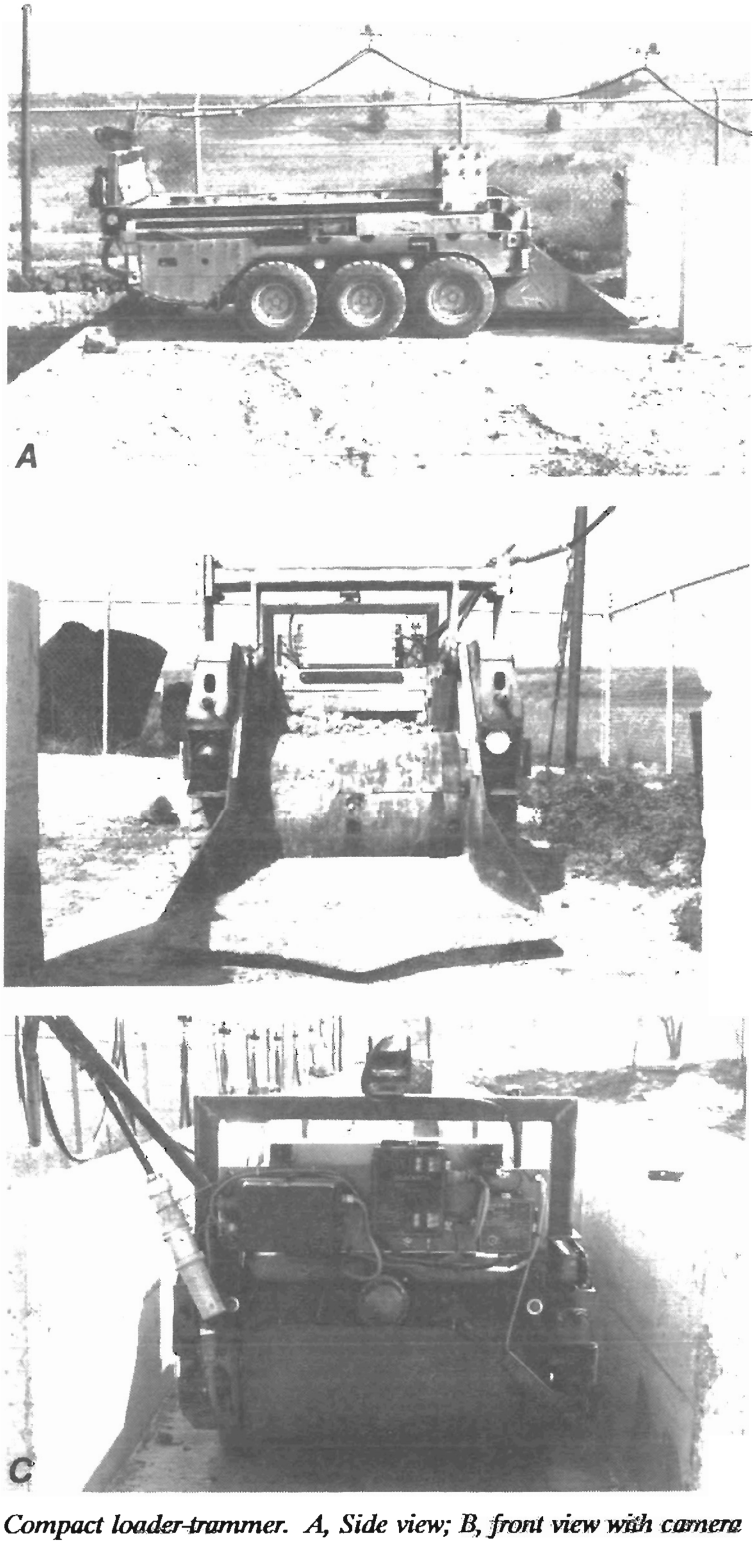
The original motivation for this work came from automation research using the compact loader-trammer, although the goal was to develop a teleoperation system that could be used with any hard-rock mining machine. A detailed description of the compact loader-trammer can be found in a contract report.[2] The compact loader-trammer is a prototype machine developed to replace the slushers, conventional LHD's, and overhead loaders used to muck narrow stopes. The machine, shown in figure 1, uses an innovative approach to loading and dumping that allows it to tram between a muck pile and an ore pass without turning around. The compact loader-trammer is approximately 4 m (13 ft) long by 1.4 m (4.5 ft) wide by 1.5 m (4.75 ft) tall.

A slide bucket loads the muck onto the deck. The machine's capacity is approximately 1 m^3 (1.5 yd^3), and it takes approximately four bucket loads to fill the deck. The machine is then trammed, in reverse, to the ore pass, the tailgate is opened, and the bucket slides to the rear of the machine, ejecting the muck. Power is supplied by a 480-V, three-phase electric motor that transfers power to hydraulic pumps for the tramming drives and bucket-tailgate cylinders.

The compact loader-trammer can be controlled using either a tethered remote-control station or a computer-based radio remote control. When the radio remote control is used, tramming is assisted by an automatic guidance system that allows the compact loader-trammer to tram in the stope without assistance from the operator. An onboard computer monitors ultrasonic sensors mounted on the corners of the machine. Using distance information provided from the ultrasonic sensors, the compact loader-trammer's position is constantly adjusted so that it stays in the center of the stope. This system reduces the operator fatigue that results from steering the machine in the narrow confines of the stope and machine wear caused when the machine hits the stope walls.

[2]Tallone, T. Compact Loader/Trammer for Underground Metal/Nonmetal Mines. General Design and Review. (Contract JO205037, Foster-Miller, Inc.) USBM OFR 10A-86, v. I, 1985, 93 pp.; NTIS: PB 86-193414.

Figure 1



Compact loader-trammer. A, Side view; B, front view with camera on lower left and halogen floodlight on lower right; C, rear view with radio control enclosures and camera mounted at lower center and floodlight on the upper left.

CONTROL SYSTEM[3]

The preferred control system for the compact loader-trammer is a computer-based radio remote control. A tethered remote control can be used as an alternative; however, the tethered control requires that a control cable be attached to the power cable and the festoon system. A brief description of the radio control system follows. A detailed description of the design of the radio remote-control and guidance system is provided in Ruff (1992).

The system consists of a control pendant and transmitter (figure 2), receiver, microprocessor, and control electronics (shown on the rear of the machine in figure 1*C*). The control outputs are not connected directly to the servovalves and other machine functions; instead, the radio control system interfaces with the electronics originally used for tethered remote-control operation. This simplified the installation and allows the option of using either radio or tethered remote control.

TRANSMITTER

The system's transmitter is located within the control pendant. The modulation scheme uses narrow-band FM, pulse-width modulation at 450 to 470 MHz. The transmitter requires a 12-V, nickel-cadmium rechargeable battery. Control commands include turn motor on and off, open and close tailgate, raise and lower bucket, set and release brakes, turn rear and front lights on and off, learn-and-repeat, turn automatic guidance on and off, and tram forward, reverse, left, and right.

RECEIVER

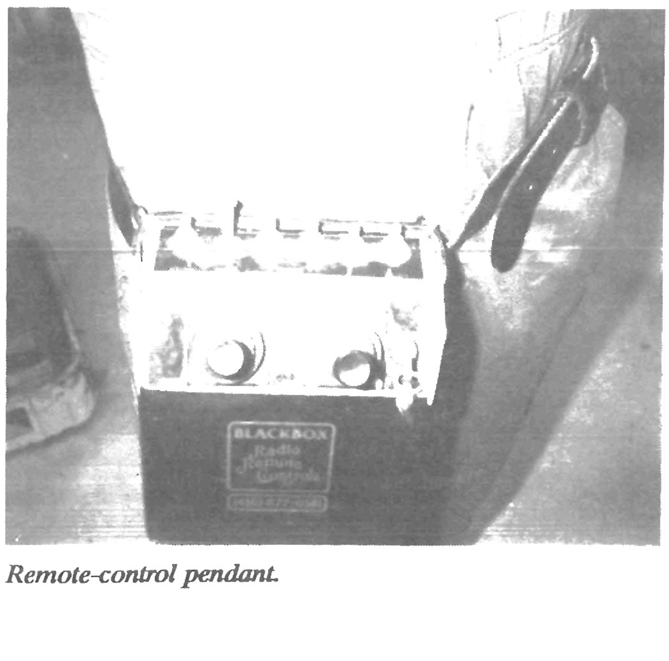
The receiver portion of the system is located on the exterior of the compact loader-trammer in a steel enclosure. A 15-cm (6-in) monopole, whip-type antenna is also mounted on the exterior of the machine. Commands received from the transmitter initiate software routines that execute the desired function. All functions are controlled by relay or on-off switches except the tramming controls, which are proportional. The tramming outputs from the radio receiver are intended to drive electrohydraulic controls directly. However, since the output is connected to the original control electronics, isolated proportional potentiometers (known as ISOPOTS) are required to convert the pulse-width modulated input from the radio transmitter to a signal that simulates the potentiometer system used in the original tramming controls. Thus, movements of the tramming joystick allow the operator to increase or decrease the speed of the compact loader-trammer in proportion to the deflection of the joystick.

COMPUTER SYSTEM

The computer portion of the remote-control system consists of an INTEL 8031 microprocessor and battery SRAM modules that contain the programs to operate the compact loader-trammer. This system is similar to a programmable controller and allows customized programs and sensor input to be used in the control of the machine. To enter customized programs or modify existing ones, a personal computer or dumb terminal can be connected using serial (RS232) communication.

Along with customized programs, a learn-and-repeat mode allows automation concepts to be tested. That is, the compact loader-trammer can be "taught" to execute a series of commands automatically by memorizing the commands in "learn" mode. Memorization is accomplished by going through the steps of the operation one at a time. After these commands have been stored by the microprocessor, depressing the repeat switch on the control pendant causes the compact loader-trammer to repeat the commands. This can be useful in decreasing the time required to execute a simple repetitive action that would normally take several separate commands to achieve—for instance, unloading the compact loader-trammer.

Figure 2



Remote-control pendant.

[3]Ruff, T. M. Development and Testing of a Computer-Assisted Remote-Control System for the Compact Loader-Trammer. USBM RI 9431, 1992, 10 pp.

AUTOMATIC GUIDANCE SYSTEM

One ultrasonic sensor is mounted on each of the four corners of the compact loader-trammer and provides a 0- to 5-V analog signal to the on-board computer. This signal is digitized and is proportional to the distance between the sensor and the stope wall. Figure 3 shows the layout of the sensors.

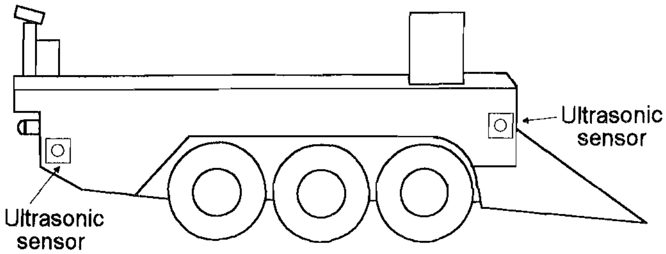
The computer scans each sensor 10 times a second. After the signals are digitized, the binary values are inverted so that small voltages relating to close distances to the wall result in large binary values. When the compact loader-trammer moves forward, the front sensors are monitored, and the computer program determines which wall is closest to the machine. This determines which rear sensor is used to set the amount that the compact loader-trammer should turn. For example, as seen in figure 4, if the compact loader-trammer were traveling forward and close to the left-hand wall, the guidance software would subtract the value of the right front sensor, V_{RF}, from the value of the left front sensor, V_{LF}. V_{LF} would then be subtracted from the value of the left rear sensor, V_{LR}, and this value would be multiplied by a software adjustable constant, K. These two values would then be subtracted, resulting in the correction factor that controls the amount the machine turns away from the wall. Thus,

$$G = (V_{LF} - V_{RF}) - K(V_{LR} - V_{LF}),$$

where G = path correction gain.

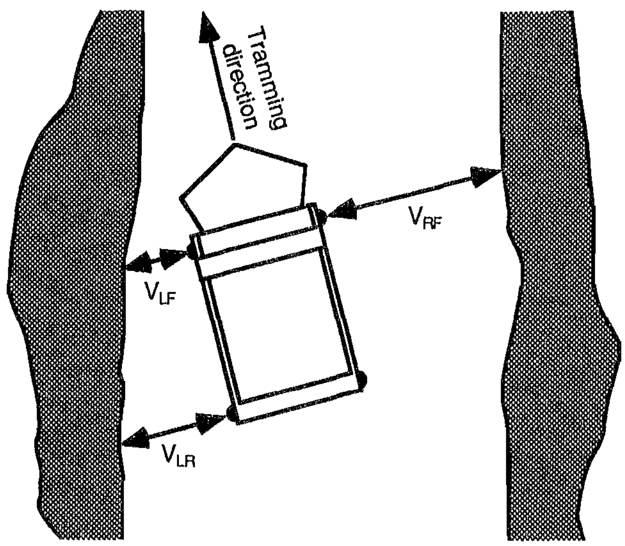
If the front of the machine were closer to the wall than the rear, $(V_{LR} - V_{LF}) < 0$, then the second term of the equation would be multiplied by K, and the steering correction would be increased. If the rear of the machine were closer to the wall, $(V_{LR} - V_{LF}) > 0$, then the machine would already be correcting its position and the second term would be ignored. Similar, but opposite, operations would take place when tramming in the reverse direction. Tests showed that setting K equal to 2 resulted in the required performance.

Figure 3



Placement of ultrasonic sensors.

Figure 4



Operation of guidance algorithm.

Operation of the guidance system is controlled with the existing pendant. A switch turns the automatic guidance system on or off. When the system is on, pushing the tramming control full forward or full reverse causes the compact loader-trammer to move forward or reverse at full speed while the guidance system automatically corrects the machine's path to keep it away from the walls. The automatic guidance system can be turned off when muck is being cleaned up next to the walls; otherwise, the system can be left on, and loading and dumping can continue as usual.

CLOSED-CIRCUIT TELEVISION (CCTV) SYSTEM

Surface tests of the compact loader-trammer in a simulated concrete stope revealed the difficulty of trying to see the loading operation at distances of 15 m (50 ft) or more. In a dark environment where tramming distances may be as great as 60 m (200 ft), the remote-control operator would have even more difficulty monitoring the presence of obstacles in the tramming path or oversized pieces of ore in the muck pile and watching loading of the machine. It was obvious that additional visual information was needed if the operator was to remain stationary in a relatively safe location.

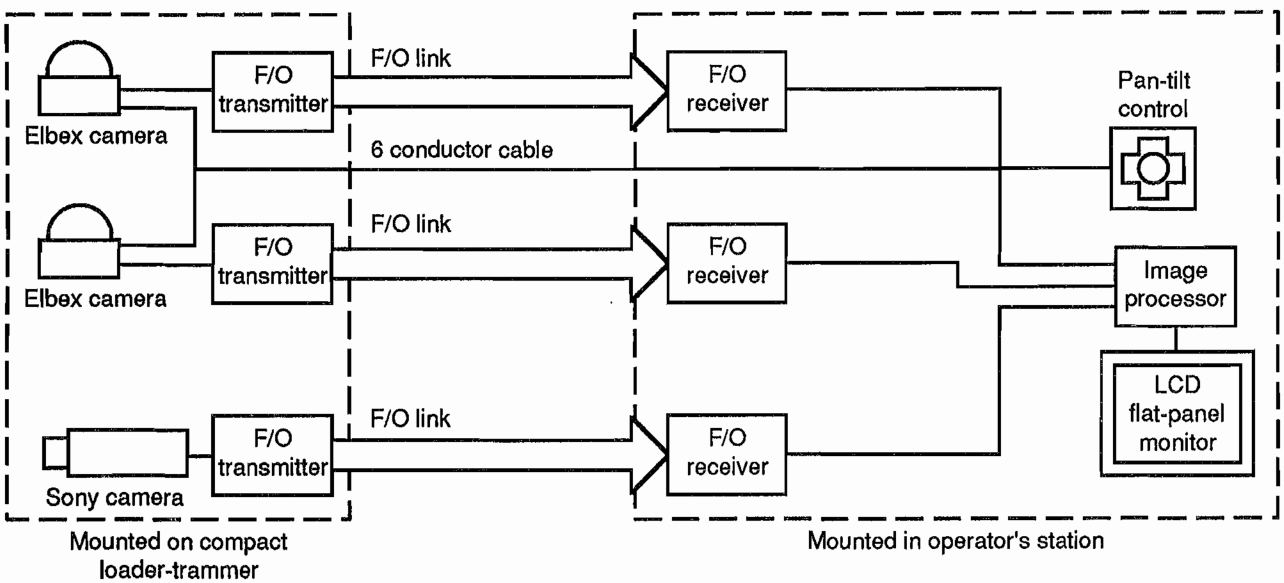
A CCTV system was designed that provides the remote-control operator with views of the compact loader-trammer and stope from three cameras. The video cameras are mounted in hardened enclosures on the machine. Video information is transmitted via fiber-optic (F/O) cable that also has been protected against the harsh mine environment. The camera pan-tilt controls are hardwired to the machine. The portable operator's station is placed near the operator so that the functions of the compact loader-trammer can be seen on a video monitor. Figure 5 shows a simplified block diagram of the total system layout.

VIDEO CAMERAS AND ENCLOSURES

Three color video cameras are mounted on the compact loader-trammer, as shown in figure 6. One camera monitors the bucket and load deck (figure 7*A*), one camera views the stope for forward tramming (figure 7*B*), and one views the stope for reverse tramming (figure 7*C*). Note that the views shown in figure 7 are not actual outputs from the video cameras but are photographs of their approximate views.

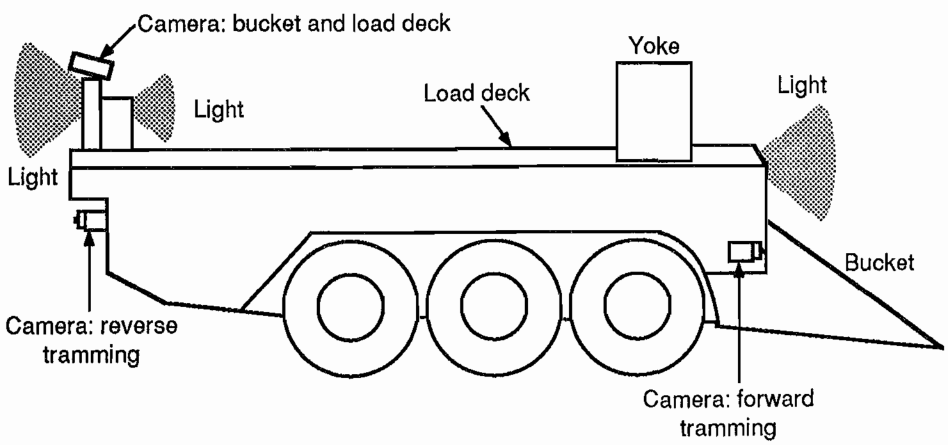
The two cameras that view the stope are miniature Elbex color video cameras with integrated pan-tilt motors. Their small size and pan-tilt features make them ideal for the limited space available. Figure 8 shows an Elbex dome-style camera beside its protective case, and figure 9 shows the camera mounted on the compact loader-trammer. The camera is enclosed in a steel case and mounted on a vibration isolator. A custom-made transparent polycarbonate dome allows the camera to protrude slightly from the steel case, which eliminates obstruction

Figure 5



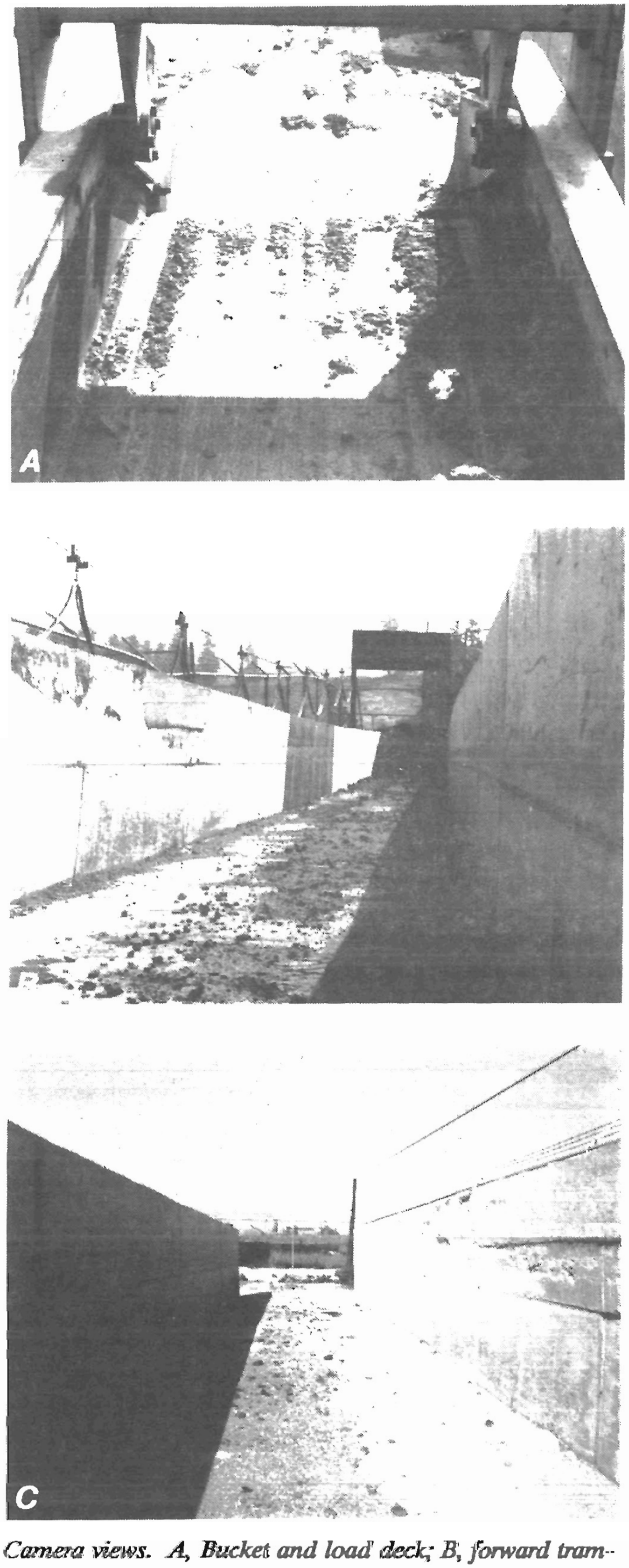
Block diagram of CCTV system.

Figure 6



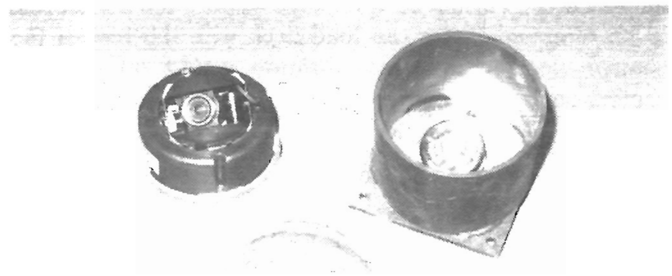
Camera placement.

Figure 7



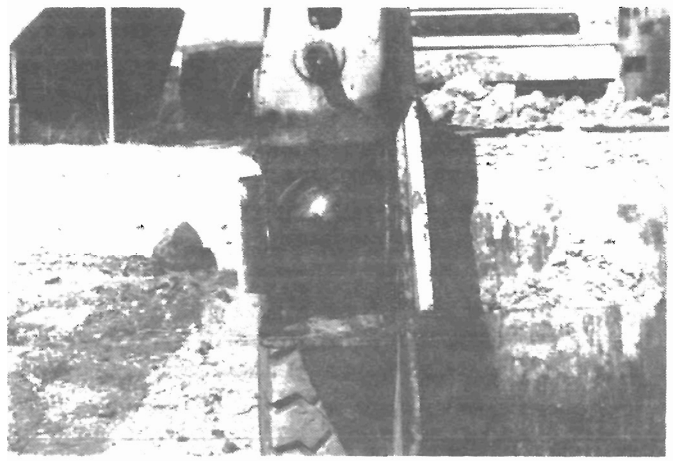
Camera views. A, Bucket and load deck; B, forward tramming; C, reverse tramming.

Figure 8



Elbex dome camera with case components.

Figure 9



Elbex camera mounted on front of compact loader-trammer.

of the view when the pan-tilt controls are used. Each of these cameras requires 12-V dc at 200 mA and two 0- to 12-V dc control signals for pan and tilt. The dimensions of the camera when it is mounted in the custom case are 15 cm (6 in) in diameter by 15 cm (6 in) high.

A third camera is mounted at the back of the machine to monitor the bucket and load deck. This camera is a Sony color camera without pan-tilt features. It is also enclosed in a custom steel case with a polycarbonate window (figure 10). It requires 24-V ac at 4 W.

All the cameras require power, video, and control wiring that consists of a coaxial cable with integrated twisted-wire pairs. An electronic enclosure mounted on the compact loader-trammer contains the equipment required to power the cameras and transmit the video signals (figure 10). The enclosure houses several power supplies for the system and three fiber-optic transmitters. The electronic equipment in this enclosure is mounted on elastomer material that isolates it from vibration and shock.

This enclosure is temporarily mounted on the exterior of the machine. A final design would require the electronics to be mounted under the load deck with the rest of the control electronics. This location would offer better protection.

LIGHTING

Halogen floodlights made by Ocenco are mounted on the front and rear of the machine. They require 12-V dc, 50-W lamps. Figures 1 and 6 show the light placement. A third light was added later to illuminate the load deck.

OPERATOR'S STATION

The operator's station consists of a liquid-crystal display (LCD), flat-screen video monitor, three fiber-optic receivers, 12-V dc power supplies, an image processor, and pan-tilt controls. The entire station is packaged in a briefcase-style enclosure that can easily be picked up and moved. The operator's station weighs approximately 55 kg (25 lb) with dimensions of 46 by 53 by 20 cm (18 by 21 by 8 in) (figure 11). It requires 120-V ac for power.

The flat-screen video monitor provides a sharp color image of the camera view on a 21.6-cm (8.5-in) screen. It is powered with 12-V dc and requires 28 W. There are several different options for presenting the cameras views: (1) All camera views can be seen at once by splitting the screen into four parts, (2) each single image can be viewed on the full screen, or (3) the full-screen views can automatically sequence through the cameras and remain on the screen for approximately 5 s. This is accomplished using a Robot MV85 color digital image processor mounted in the operator's station. The three inputs from the cameras are connected to the image processor, which then provides a single output for the video screen.

Camera pan-tilt control is also mounted at the station; the cameras are controlled with a joystick and a camera selection switch, as shown in figure 11. Pan-tilt control is possible with the cameras mounted on the front and rear of the machine. Once the cameras are positioned, however, it is seldom necessary to use the pan-tilt controls. If an obstacle is encountered in the tramming path, or if oversize muck is present, the pan-tilt option would be useful in locating and viewing the obstruction.

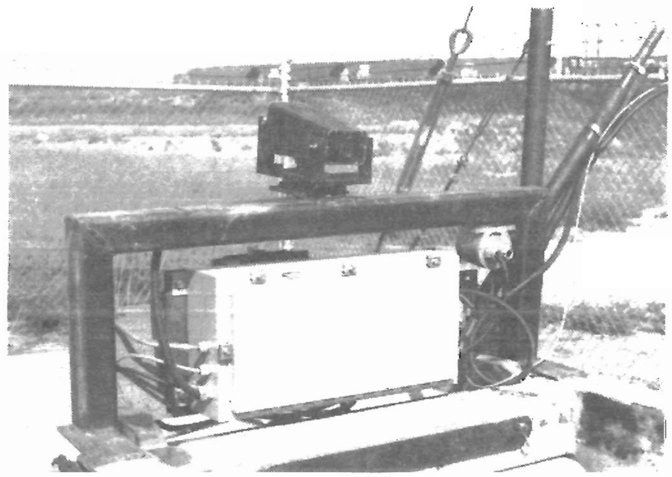
FIBER-OPTIC SYSTEM

Video signals are transmitted in multimode over three fiber-optic lines, 60 m (200 ft) long, to the remote operator's station. Fiber-optic cables were used to avoid electromagnetic interference from the power cable. The fiber-optic cable is protected in a reinforced rubber tube and is fastened to the 480-V ac, three-phase power cable.

Fiber-optic signal convertors are used to convert the National Television System Committee (NTSC) signal from the camera to an optical signal. For this direction of conversion, the convertor is called the transmitter. When the signal reaches the operator's station, the signal is converted back to NTSC by the fiber-optic receiver. The convertors are manufactured by International Fiber Systems, Inc., Brookfield, CT. The transmitters require 24-V ac at 3 W (12-V dc optional). The receivers require 12-V dc at 100 mA.

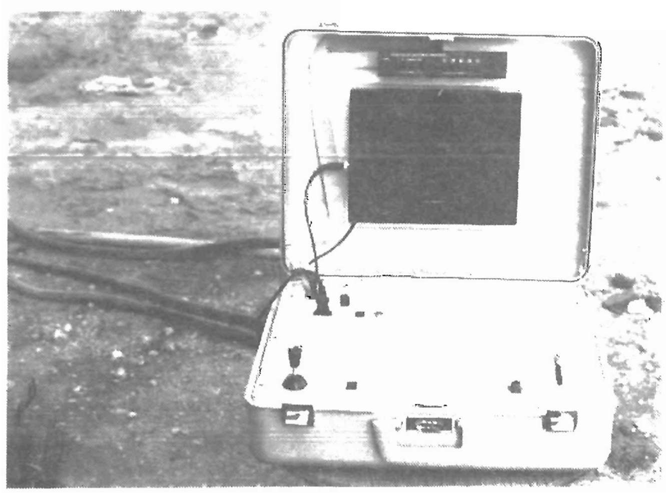
Pan-tilt control is currently hardwired to the compact loader-trammer; noise generated from the power cable is not sufficient to cause errors in the control signal. Pan-tilt control could also be transmitted over fiber-optic lines; however, custom convertors would be needed to accommodate the control voltage scheme used by the pan-tilt motors.

Figure 10



Sony camera mounted to monitor load deck and bucket. Electronics enclosure is mounted below.

Figure 11



Portable operator's station.

Original plans required that a camera be mounted on the yoke of the compact loader-trammer to monitor the bucket and load deck. This would have required a special cable reel system for the video and power cable because the yoke moves with the bucket (figure 6). A cable reel with Rotocon mercury contacts was to be used instead of a conventional slip ring assembly so that the video signal quality would be preserved. This system would allow the video camera to move a distance of 3.7 m (12 ft) with the bucket yoke and would provide a closeup view of both the bucket and the muck pile during loading. However, the cost and complexity of the proposed reel system outweighed the benefits, and the final, stationary position, as shown in figure 6, was adopted. It was discovered during testing that this final position of the camera was adequate and the closeup view offered by the proposed position was not a necessity.

SURFACE TESTS

The teleoperated compact loader-trammer was tested at a surface facility at the USBM's Spokane Research Center. This test facility, called the simulated stope, consists of 20-cm (8-in) thick concrete walls 33.5 m (110 ft) long and 1.8 m (6 ft) (inside dimension) apart. A muck pile is at one end of the stope and a recessed ore pass is at the other. A festoon system is used to carry the power, control, and fiber-optic cables. This festoon system can be seen above the compact loader-trammer in figure 1.

Figure 12 shows tests in progress at the simulated stope. The tests were conducted at night to duplicate actual mining conditions as closely as possible.

One of the first difficulties found was in the fiber-optic connectors. Standard industrial SMA-type connectors were used, but they were not robust enough for mining equipment. (Connectors that meet military specifications are recommended.) Also, the quality of the connection was low, and picture quality was affected by the looseness or tightness of the connectors.

Lighting proved adequate for the cameras that monitored the stope in forward and reverse tramming. However, ambient light was not sufficient to monitor the amount of muck in the load deck, and a third light was added to illuminate the load deck directly.

The polycarbonate windows on each of the cameras had to be wiped off periodically to clear dust and mud from the lenses. A teleoperation system tested on coal mining equipment at the USBM's Pittsburgh Research Center uses pressurized air to keep the lenses clear.[4] The surface tests did not show this to be necessary in the test stope; however, underground operations may require that the lenses be wiped clean every few hours.

The LCD flat-screen monitor provided an adequate picture for viewing and operating the machine. It was necessary to switch between camera views so that the view of interest filled the whole screen. Leaving the screen split into four sections made each camera view too small to be helpful during detailed operations, such as loading; however, the split-screen views could be used during tramming operations when fine detail is not required.

During surface tests, it was necessary for the machine operator to back the compact loader-trammer to the ore pass visually because the ore pass in the simulated stope is open and a slight mistake in tramming could result in the compact loader-trammer's falling into the hole. However, the rear camera view provides enough information to allow teleoperated positioning to the ore pass if it is covered by a grizzly, as it is in most cases. A marker placed on the grizzly would also be helpful, so that the machine could be positioned using the marker in the camera view.

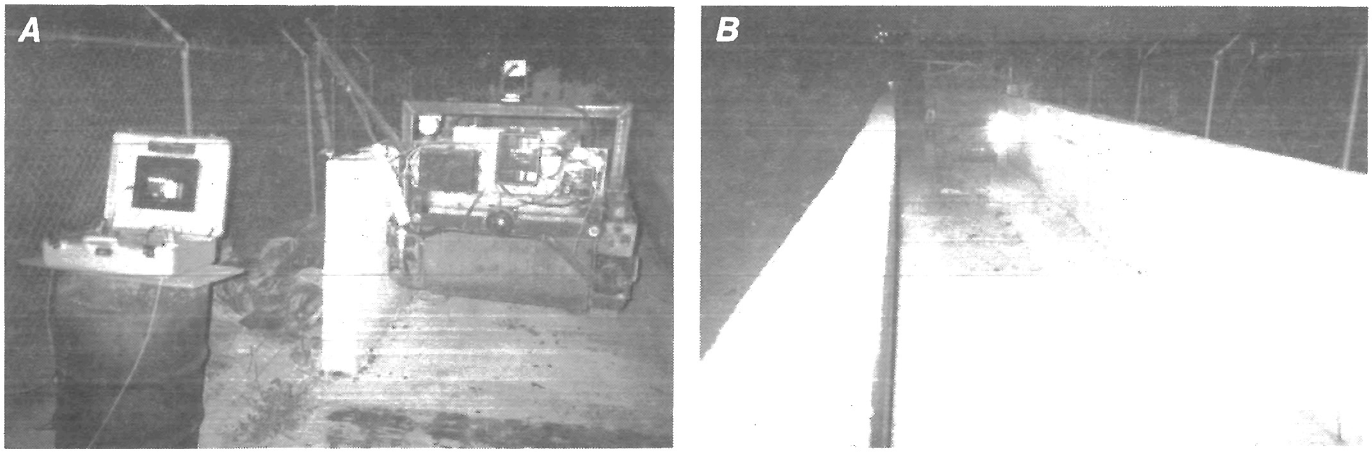
In cases where the operator cannot hear the machine, auditory information would be helpful. A microphone and amplifier mounted on the compact loader-trammer and a speaker mounted at the operator's station could easily be added to this system. Auditory clues are provided by the motors and the bucket and are used in loading to determine if the bucket is stuck or loading properly. The operator could also hear the machine strike the stope walls.

The portable operator's station is convenient and is easily positioned wherever the operator needs it. A table or stand is required to set the station at a position where the pan-tilt controls are easily accessible and the LCD monitor can be seen. The clarity of the LCD monitor is affected by the view angle so it is important to position the station at the correct level for the operator.

The information contained in a camera scene is an important consideration when placing the cameras on the machine and choosing their lenses. The resulting field-of-view must contain enough of the machine itself and its surroundings so that relative distances and locations can be easily determined. For example, it was found that tramming the machine in the stope using the front camera by itself made it difficult to determine where the machine was in relation to the stope walls. This camera view showed

[4]Kwitowski, A. J., A. L. Brautigam, and W. D. Monoghan. Telecontrol of a Continuous Mining Machine in Thin Coal Seams. Paper in IAS'93, Part III (conf. record, IEEE Ind. Appl. Soc., Toronto, ON, Oct. 2-8, 1993). IEEE Ind. Appl. Soc., 1993, pp. 2463-2469.

Figure 12



Surface tests in simulated stope. A, Operator's station positioned near ore pass; B, compact loader-trammer in simulated stope.

only the stope, as seen in figure *7B*. No part of the machine can be seen in this view, and the view from the top of the machine (figure *7A*) had to be used in conjuction with the front tramming camera to determine the exact location of the compact loader-trammer.

SYSTEM COSTS

The total cost of the off-the-shelf hardware for the video system was approximately $15,500 (table 1). Almost every component was readily available; the only components that were custom made were the camera enclosures. After the system was designed and built, installation of the cameras and the electronics enclosures required approximately 24 person-hours. The total cost for the radio remote-control system was $23,000, including installation. Assistance was required from the vendor for initial custom programming.

Table 1.—Approximate component costs for CCTV system (1993 U.S. dollars)

Item	Quantity	Amount
Elbex camera	2	$4,000
Sony camera	1	1,400
Fiber-optic transmitter	3	750
Fiber-optic receiver	3	750
Image processor	1	1,600
Fiber-optic cable and connectors, m	60	900
LCD flat-screen monitor	1	4,800
Power supplies	5	450
Lights	3	250
Portable case	1	250
Enclosures	1	350
Total		$15,500

SUMMARY

Previous research showed that the computer-assisted control system had a significant impact on the control of the compact loader-trammer. It required less setup than the tethered remote control, which had to be attached to the power cable festoon. Difficulties in maneuvering the machine in a narrow stope were alleviated by the automatic guidance system, which reduced operator fatigue. Also, machine wear from hitting the stope walls was minimized.

The current study showed the video system to be an essential addition to the teleoperated control of the compact loader-trammer. The productivity and safety of the machine were enhanced by increasing the amount of visual information to the remote operator. Typical tramming distances require remote visual information if the operator is to remain in a stationary, safe location.

This video system could be used on other pieces of mobile equipment that require miniature cameras and a portable operator's station. For diesel equipment that does not have a convenient method of attaching tethered cables for video communications, a radio-frequency system could be installed as the communications link (at an additional cost). Also, a system for extended use in an underground mine would require additional environmental hardening.

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