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DEVELOPMENT OF SHOTCRETE ROBOT

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ABSTRACT

In recent years, concrete spraying or shotcrete work carried out at NATM method tunnel construction sites has become a social problem because the dust put into the air during work. Further, current shotcrete methods result in a large amount of rebounded concrete and dust, which raise both cost and safety concerns. Although some companies have developed shotcrete robots, all such robots must be controlled manually - and the above two problems remain. To solve these problems, we have developed a fully automatic shotcrete robot, the performance of which has been verified through actual construction work.

In efficient shotcrete work, there are two requirements: (1) the distance from the nozzle to the wall must be kept constant, and (2) the nozzle must be maintained perpendicular to the wall. To do these things, our robot determines its position in the tunnel and controls the nozzle movement by a hydraulic arm with five degrees of freedom through feedback loops.

This paper describes the robot's construction, the way it locates its own position, its control system, its operation, and experimental results at construction sites.

1. Introduction

Shotcreting is done to form a primary lining on newly excavated tunnel walls to prevent crumbling immediately after excavation. Concrete is sprayed under air pressure and adheres closely to the work surface. This eliminates any need for forms or other supports - a great advantage. On the other hand, about twice as much concrete rebounds as adheres so the materials cost is rather high and there is a safety problem. In addition, much dust is raised by shotcreting and presents a health hazard as well. Although shotcreting robots have been used to some extent at construction sites, all of them have these basic shortcomings. Conventional shotcrete robots operate a spray nozzle by simple repetitive operations consisting of manual operations and sequence control (even though they are called robots), so it is difficult to keep the distance from the nozzle to the wall constant and to maintain the nozzle at a right angle to the wall. These factors closely affect shotcrete quality and finishing accuracy, as does the operator's skill. In addition, it takes a quite long time to train an operator to use most of these machines.

2. Features

Our shotcrete robot is superior to conventional shotcrete robots in several ways. First, the robot determines its own position in the tunnel and, by computer, controls hydraulic booms to correct positional deviations of the robot, to keep the distance from the nozzle end to the tunnel design line constant, and to maintain the nozzle perpendicular to the wall. These functions enable the robot to do shotcreting accurately and efficiently. Other functions are described as follows.

(1) Locating its own position

The cross section of a tunnel has a horseshoe shape generally, and it is difficult to position the machine exactly at the center of a tunnel for shotcreting of the upper half of the tunnel. Because the robot is mobile and changes its for each job step (different from what general industrial robots do), it is necessary for the robot to know its position in the tunnel. Our robot's positioning system utilizes laser beams at the starting point of shotcreting; by setting the nozzle end to the right and left points of the tunnel, the robot can calculate the distance between each point and the robot. The robot can then calculate its vertical and transverse deviations from the center of the tunnel and its angle with respect to the direction of the tunnel - these data determine the robot's position. (Fig. 2-1)

(2) Free selection of shotcrete area division and sequence

Because the robot was developed as an experimental machine and there were indefinite factors (such as an unknown optimum shotcrete process), it is constructed so that the details of shotcreting can be changed easily. The robot is used to spray concrete on the upper half of road tunnels, automatic operation being controlled to move the nozzle in a semicircle with its center at the center of the tunnel. The range of the nozzle within the semicircle (i.e., the shotcreting area) can be set as required, and can be divided into as many as eight shotcreting areas. Further, shotcreting areas can be shotcreted any number of times and in any order. (Fig. 2-2)

The shotcreting conditions are entered into our robot interactively from a keyboard and can be changed by digital switches even during the work.

(3) Free shotcrete mode selection

There are three types of nozzle movement for shotcreting. The robot automatically selects the most suitable one for the specified conditions.

1) Depth mode: The nozzle is moved back and forth in the depth direction and raising it in the circumferential direction. This mode allows the nozzle to spray concrete as if it piles up concrete from the bottom.

2) Circular mode: The nozzle is moved back and forth in the circumferential direction within the shotcreting area. This mode is used near the crown of the tunnel.

3) Timbering mode: The nozzle is moved in the circumferential direction within the entire circular area, regardless of the designated shotcreting area. This is done to shotcrete within the timbering.

The robot allows you to select any of the modes to do shotcreting in a specified area. (Fig. 2-3)

(4) The nozzle speed is easily adjusted to compensate for changed shotcreting conditions.

A computer program changes the nozzle speed in four steps in the circumferential direction and in three steps in the depth direction.

The constants for the above conditions ((1) through (4)) are stored in computer S-RAM and can be changed to suit new conditions. When the optimum shotcrete process is established, the set constants become fixed, so there is no need for resetting the conditions every time.

(5) Three operation modes are available.

There are three operation modes: automatic, semiautomatic, and manual (switch-selectable). In the automatic mode, the computer controls five shafts so the robot can fully and automatically do shotcreting with the nozzle perpendicular to a wall and moving at a constant distance from the wall. The automatic mode allows the operator to set various operating conditions.

In the semiautomatic mode, the computer controls three shafts and allows the nozzle to move at a constant distance from the tunnel wall by the use of one lever. This makes it easy for the operator to control the robot. The semiautomatic mode is used to repair or finish a tunnel wall after shotcreting has been done in the automatic mode.

The manual mode allows the operator to control each shaft individually with a lever.

3. Description of the robot

(1) Construction

Figure 3-1 shows the entire robot and important specifications. The robot uses a hydraulic shovel with a capacity of 0.4 m^3, and hydraulic pump that is driven by an engine when the robot is moving or doing shotcreting.

The robot consists of the base machine (man unit), a hydraulic unit, a control panel, an operator's cab, and a robot arm. The robot arm has five shafts for turning, lifting/lowering, and extending the boom, for turning the manipulator and for changing the angle of the nozzle. There are also horizontal and vertical manipulators and the nozzle inclination, so there are eight degrees of freedom altogether. The first five shafts are controlled by the computer (8 to 12 in Fig. 3-1). The horizontal manipulator (item 7) operates in concert with the lifting/lowering of the boom to always maintain a horizontal nozzle position. Furthermore, the boom is equipped with a working stand with a 300 kg loading capacity so that the robot can also be used as an elevated work support car.

(2) Control system

Figure 3-2 shows the block diagram of the control system. A 16-bit computer with a keyboard and display unit is used because the robot is still an experimental machine and using the computer helps shorten the development period and facilitate program development. Each shaft is equipped with multi-rotating absolute encoder to feedback signals. The robot arm is operated by controlling the hydraulic flow rate using digital valves which control the flow in proportion to the current angle of the stepping motor.

1) Operation flow

Figure 3-3 shows the operation flow for the shotcrete robot. The basic machine is installed then the robot position is taught. Next the spatial coordinates are calculated so that the end of the nozzle moves in a circular path (the "moving locus"), keeping at a constant distance from the tunnel design line.

The moving locus is a semicircle circumference. With its center at the center of the tunnel, which is defined by 1800 points that are used to calculate the turning angle, lifting/lowering angle, boom extension, manipulator turning angle, and nozzle angle at each point (the five shafts for these movements are called the control shafts). The five shaft values for each point are regarded as target positions.

Operation preparation is complete when the above calculations have been completed.

In automatic operation, the robot operates as specified for shotcreting conditions (sequence, mode, and area).

In control shafts compare the current positions (obtained by reading data from each encoder and pulse counter in realtime) with the target positions, then calculate deviations, and output to a digital controller signals corresponding to these deviations (the number of pulses needed to drive the stepping motor to the desired positions) controller drives hydraulic motors and cylinders through too digital valves of the shafts.

Digital valves with a built-in stepping motors are used for hydraulic control to achieve a valve opening that corresponds to the desired displacement. The target positions are updated every second and control is done to follow the updated target positions automatically.

2) Control program configuration

Figure 3-4 shows the configuration diagram for the program.

The program has two main parts: a BASIC program that determines the base machine position and calculates the moving locus; and a main control program for high-speed processing. The following description explains each part of the program in detail.

The BASIC program first reads the angle and length of the five control shafts through the encoders and pulse counters when the end of the nozzle is positioned at the laser beams at the right and left points of the tunnel; this is used to determine the position of the base machine. At the same time, signals from inclinometer installed on the base machine to measure inclination of front, back, left and right of the machine are read so the base machine's vertical and transverse deviations from the center of the tunnel can be calculated along with its angle to the tunnel axis (this uses the parameters stored in the computer, (such as the tunnel radius and the height of the laser beams).

After this position has been calculated, the moving locus is calculated from the position and the parameters. In this calculation, the nozzle angle from -90° though 90° is divided into 0.1° increment - 1800 steps altogether, and five shaft positions are obtained for each point. The data (one byte) for each shaft is stored in S-RAM.

The main program moves the robot arm according to the data calculated by the BASIC program. The main program has three subroutines: an input/output program that reads signals from each setting switch and encoder, and outputs signals to the valves; a program that displays errors and system status on the display unit; and a control program that calculates signals corresponding to the current and target positions. The main program updates the target values every second to meet the value defined by the speed setting switch; the control program does control operations every 0.1 second in response to the updated target values. In addition, the main program checks each limit, direction of motion, and moving distance to execute self-diagnosis during every control cycle, and stops the control system if an abnormality occurs.

4. Verification experiment in construction site

The shotcrete robot did experimental shotcreting on the upper-half wall of the tunnel in our Hokuriku Expressway tunnel for about half a year (starting Dec. 1986). There are two types of shotcreting: one is a wet process in which concrete is mixed with water from the beginning; the other is a dry process in which water is added to dry concrete while it is fed. The dry process was adopted for the experiment, which needed an operator to control the water mixing rate. It was found that simply maintaining the nozzle perpendicular to the design line did not decrease the concrete rebound rate much because the shotcreted surfaces were considerably uneven and the rebounding rate varied significantly with the capacity of the concrete feeding machine, pulsation effects, the volume of water, nozzle shape, etc.

Because the robot was prototype and its capability, from the viewpoints of both function and construction, were large, it was particularly large. This was a disadvantage in actual work where space was insufficient. The smaller the robot can be made, the better. Moreover, there were special functional and constructional problems, that prevented the robot from spraying concrete on the back of timbering, and the nozzle had to be finely adjusted by the operator. However, it operated fully automatically at natural excavated areas, and the robot's shotcreting capacity and performance were verified. The robot's concrete adherence was better than that of manually-operated shotcrete robots.

5. Future plans

We have already completed version 2 of the shotcreting robot, which solves the problems discovered during the verification experiment of the first prototype. This robot is now being used at an underground power plant construction site. It is a manually operated type, but is smaller and simpler to operate than the previous robot. The main improvements are as follows.

1) The robot arm has been designed for easy mounting and removal. This allows it to be used on the base machine or on a truck.

2) The base machine was reduced from 0.4 m^3 to 0.25 m^3, and it now weighs about half what the previous one did.

3) The horizontal manipulator operates interlocked with an turning movement hydraulically the vertical manipulator is no large used - the nozzle rocking has been added instead.

4) Boom turning is independent of base machine turning to allow the machine to remain stationary during shotcreting.

5) A radio control system is now used.

We will develop another automatic shotcrete robot during 1988. While the experimental shotcrete robot controlled nozzle movement along a semicircular locus, the new robot will adopt a multi-point teaching system, which will allow the robot to be taught its position at each point and control the nozzle movement by interpolating positions between points. Therefore, the new robot will be able to cope with various uneven surfaces to be shotcreted.

Although the experimental shotcrete robot is still in the early stages of development (its operation checks have been completed, though), we plan to finish the robot's development by emphasizing the following to achieve integrated, unattended robotized shotcreting.

1) To systematize the shotcrete robot with a concrete pump and to check for concrete clogging, to adjust the water feed rate, etc. (all unattended).

2) To urge development of lining thickness sensors to prevent excess shotcreting (a large part of shotcrete work cost).

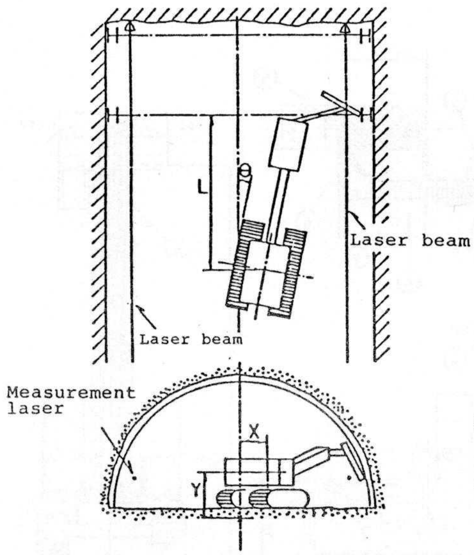

Fig. 2-1

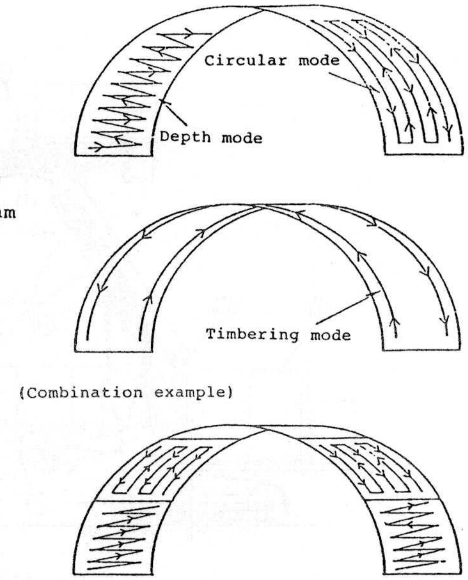

Fig. 2-3

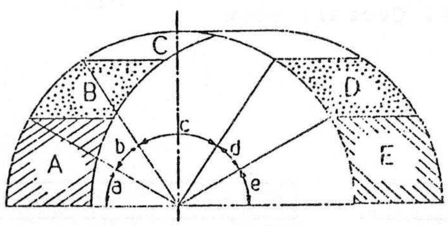

Fig. 2-2

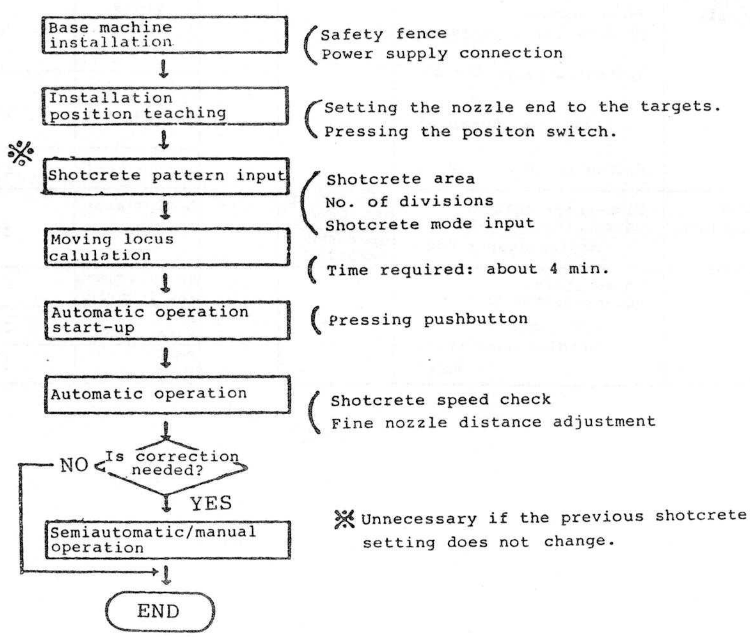

Fig. 3-3

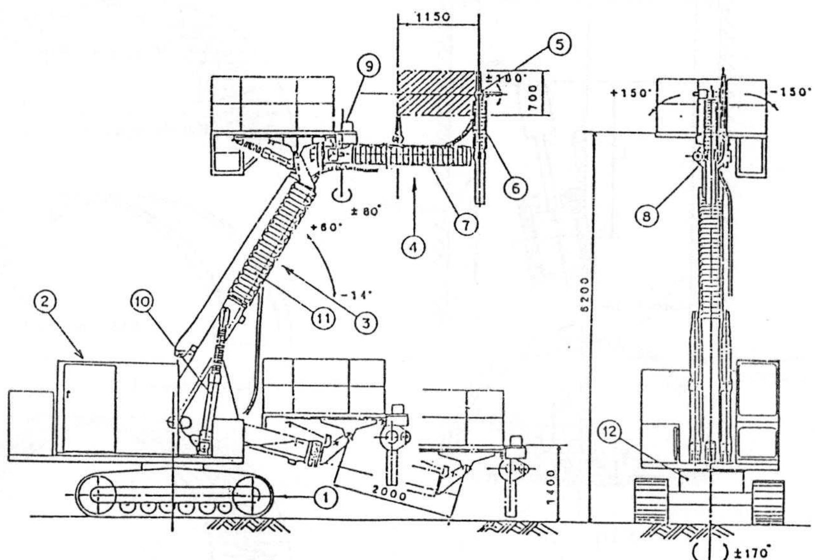

Fig. 3-1. Overall view

Table 3. Mechanical Specifications

Item	Specification	Remarks
Crawler	Hydraulic shovel S-40	
Hydraulic unit	Power engine Isuzu b 120 82ps/1800rpm Hydraulic pump: double 113ℓ/mn x 150kg/cm^2: Hydraulic tank 800ℓ	
Nozzle manipulator	Five-shaft column coordinates system manipulator robot	Two out of the five shafts are operated manually.
Boom	Three-shaft polar-coordinate arm robot Loading capacity: 300kg	

Item	Specificaiton
Nozzle inclination	± 180°
Vertical manipulator	700 mm
Horizontal manipulator	1150 mm
Nozzle angle	±150°
Manipulator turning	±80
Boom lifitng and lowering	-14°- 60°
Boom extension	2000 mm
Boom turning	±170

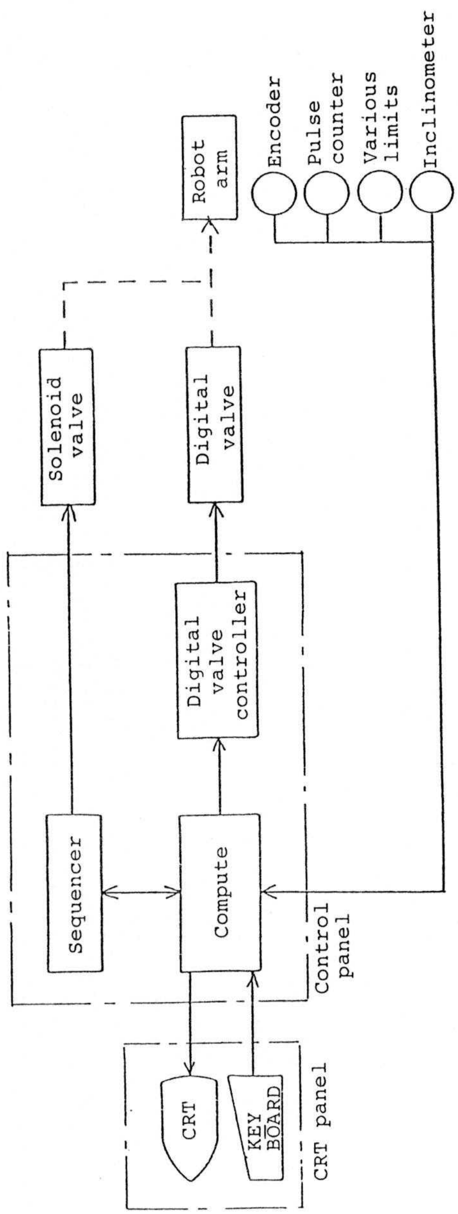

Fig. 3-2. Block Diagram of Control System

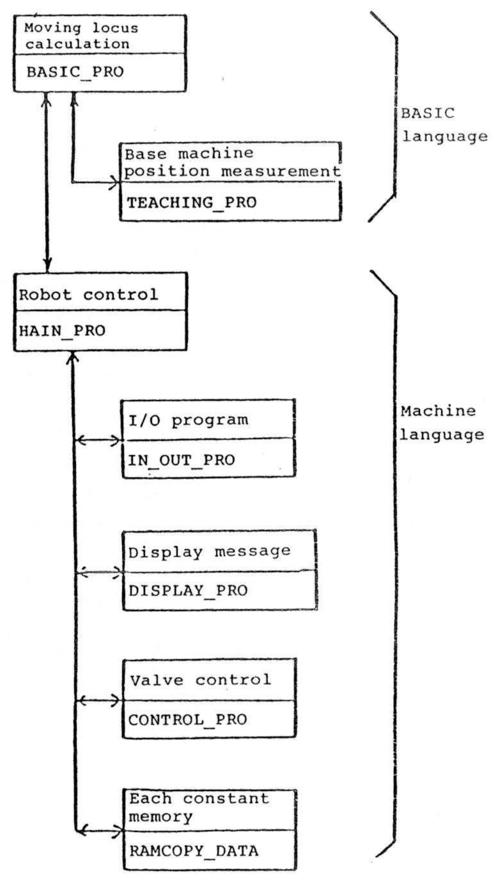

Fig. 3-4