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The Three-dimensional Marking Robot for Tunnel Driving

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ABSTRACT

This robot has been designed to support marking of the designed section and surveying operations, which take place daily at the tunneling cut face. When using NATM, a peripheral line marking the designed section of the tunnel is drawn after appropriate survey work in order to allow accurate excavation. This new robot constitutes a unique technology in which the tunnel section and drilling pattern are plotted using a residual image projected accurately and continuously by a laser beam under computer control.

Using this method, the accuracy of excavations is improved, rock overbreak and labor are reduced, and the conventional, uneconomical characteristics of tunneling work are overcome. This robot has been used in a number of tunneling tasks, including some for "Shinkansen" bullet trains.

1. INTRODUCTION

While construction sites have been prosperous and busy in recent years, changes in the social environment have added to a growing shortage of laborers and skilled workers. As one means of solving the resulting problems, there was an urgent need to develop a technology for improving the labor environment and upgrading productivity. There has been a particularly strong desire to reduce manpower and labor in tunneling work.

A robot has been developed which supports the marking of the cut face with the design section and surveying operations in the tunnel; tasks that have to be carried out daily during tunneling work. The proposed hardware combines laser technology and surveying equipment with computers and software technology to give a three-dimensional position-finding system that determines plane and height simultaneously.

As NATM has grown to be the main means of tunneling work, increased accuracy in tunnel excavations and improvements in workability have been demanded more strongly than before. Thus, a three-dimensional marking robot is ideal as labor saving technology to meet such demands.

2. OBJECTIVE OF DEVELOPMENT

In tunneling work, advances are made by repeating the processes of drilling, blasting, and mucking. It is necessary to continuously and accurately direct the driving direction and depth. The method of marking the appropriate points with paint through surveying is called "marking of the cut face." In this method, surveying is done to determine the tunnel cut face center point using one of the following methods: 1) A laser aligner is installed either on the tunnel side wall or at the top of the arch some distance away from the tunnel cut face. The laser beam is aligned with a control point farther down the tunnel. 2) The center line point at the top of tunnel arch is determined by survey at 2 points along the tunnel. Plumb bobs are hung from these points. By visually aligning the 2 plumb bobs, the center line of the tunnel face can be determined. Based on these points, in conventional tunnelling methods, a steel support is erected. In NATM, this method is used to determine the center of the tunnel and the peripheral line is drawn on the rock surface of the face with paint at a fixed radius. As a result, the following problems are encountered in the actual surveying:

(1) Surveying operations have to be carried out in a short period while taking advantage of intervals in the continuous series of tunneling operations, placing a burden on the surveyor. Normally, these operations require one hour with three to five workers. Photo 1 shows the procedure for conventional surveying operations.

(2) The survey control point has to be placed at the center of the tunnel, where damage tends to be deep in the ground, thus causing problems of installation and preservation.

(3) During straight tunneling three to seven aligners are installed along the length of the tunnel on the wall, with excavation following the laser beam, labor is required to manage the complex set-up of aligners. As it uses a straight beam, the method cannot be used for curved tunnels.

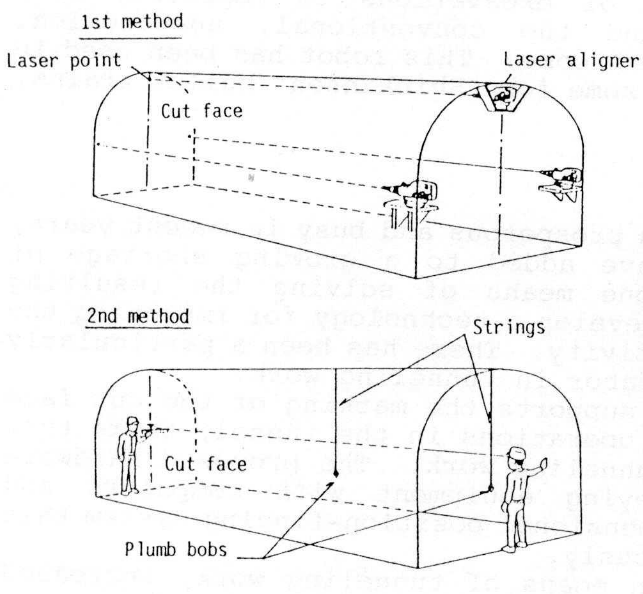

Fig. 1 1st method: Laser aligners, 2nd method: Plumb bobs

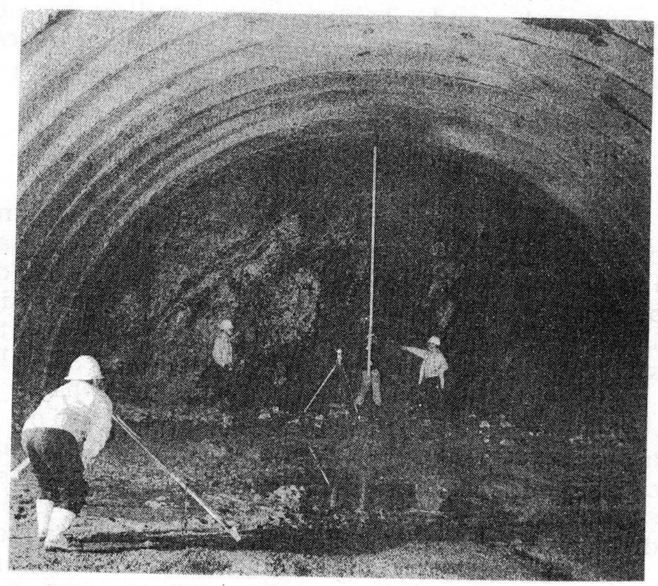

Photo 1 Conventional surveying operations

The aim in developing this robot was to overcome these problems, making it possible to determine the tunnel section and drilling positions, etc., simply with a single setting. Quite different from the fixed laser aligners of the conventional system, this robot features control of a galvanometer scanner by computer. By scanning a laser at high speed, an outline of the excavation section, etc is drawn on the tunnel cut face.

3. SUMMARY OF MARKING ROBOT

While the conventional method shines the laser beam at several laser aligners fixed relative to the cut face, this robot uses a system in which computer-controlled laser beams from a single laser marking robot irradiate the correct tunnel section and the drilling pattern, etc., continuously and accurately plotting them.

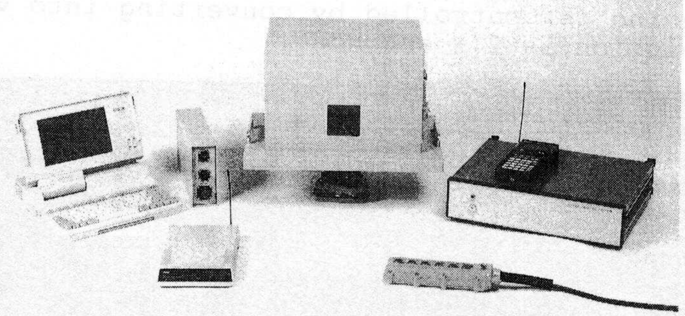

Photo 2 Complete laser marking robot

(1) System composition and features (refer to Fig. 2)

o Personal computer

o Laser marking robot

Light source: He-Ne laser (wavelength 632.8 nm output 0.5 mW to 1 mW)
Spot size: 10 mm in diameter
Irradiation angle: Width of 40° in both horizontal and vertical directions
Error: ±5 mm/100 m
Accuracy of electronic distance measurement: ± (5 mm + 5 ppm x Dm)
Project distance: 300 m
Power source: AC-100 V
Operating temperature range: -10° to 40°C
Weight: 15 kg

o Radio robot

(2) Method of position finding

The plane alignment, longitudinal alignment, and planned irradiation pattern are registered in the equipment before operations begin. By guiding the laser beam to the center of a reflecting mirror on the face, the coordinates of the face are obtained according to signals from the built-in electronic distance measuring instrument and the angle of the mirror's surface. Alternatively, by directly inputting the station number cut, the cut face position is determined. The design pattern is projected onto this cut face from the registered data file, with three-dimensional coordinates calculated for every irradiation point. This completes position finding. Photo 2 shows the laser marking robot for position finding.

The swing angle of the irradiation point can be obtained using the following equation (refer to Fig. 3):

$$\phi = \arctan (y/x) - T$$

$$\theta = \arctan (\sqrt{(x^2 + y^2)}/z)$$

where,

ϕ: horizontal angle

θ: vertical cangle

T: direciton of robot

The angle for scanning is controlled by converting into voltage amount, in which angular resolution is 2.2 seconds.

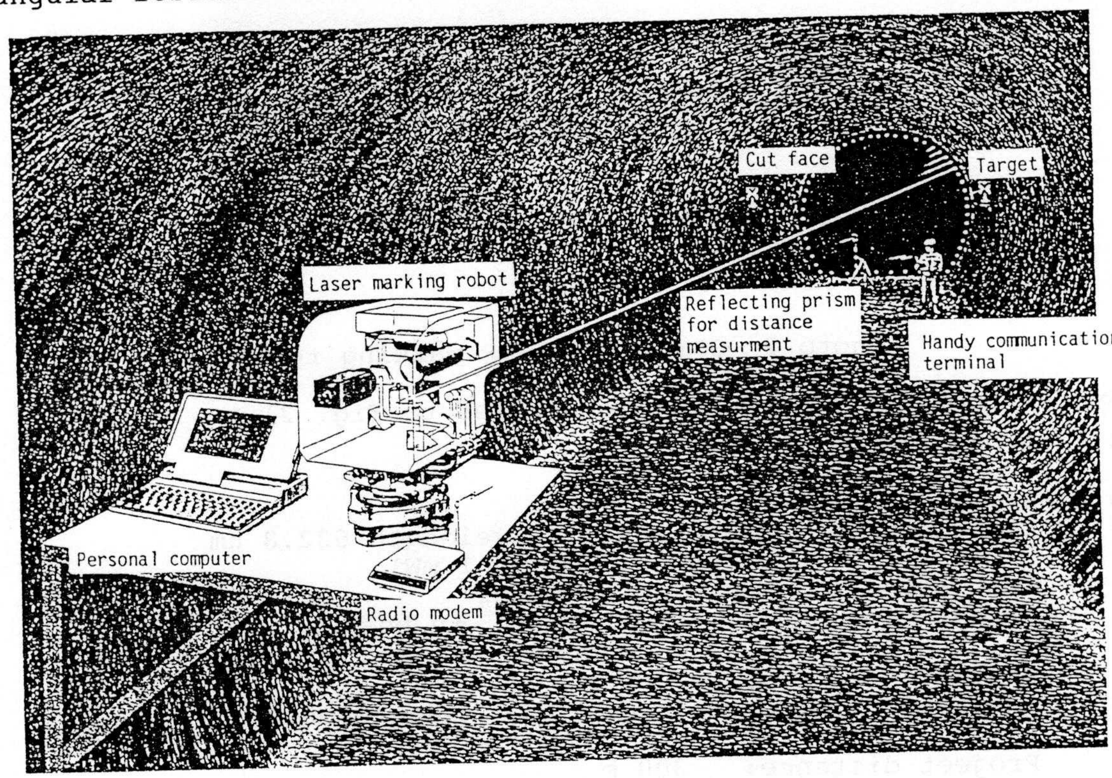

Fig. 2 Marking robot composition

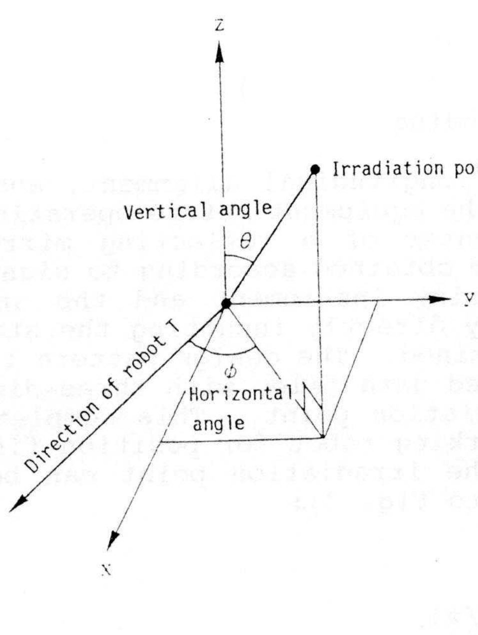

Fig. 3 Indication of swing angle of the robot

4. FEATURES OF MARKING ROBOT

(1) Structure of total system

(a) A three-dimensional surveying method is adopted in which position finding is managed on-line by the robot to determine point coordinates on the radiation plane after plane alignment, longitudinal alignment, and irradiation pattern are registered in advance.

(b) It is possible to register a free configuration consisting of 200 points, including the peripheral line and blasting pattern for the designed section, etc., and the designated irradiation points can be illuminated.

(c) Since the time for which one point is radiated can be set freely and the pattern can be refreshed repeatedly at high speed, no marking paint is required at all.

(d) The robot can be installed anywhere and it operates flawlessly and with high accuracy.

(2) Equipment

(a) The system relies on the after image, with the irradiation pattern being refreshed repeatedly at a high scanning speed, so no marking is required. The surface of a scanner mirror that rotates precisely around the x- and y-axes can be controlled by computer. Angular numerical data are converted into an analog voltage, and the mirror surface is rotated and controlled by this voltage.

(b) The robot is compact as a result of efforts to make it small and light.

(c) To enable multiple communications with the computer, the robot is equipped with a communications selector. The following can be controlled by computer using the communications selector.

- o Choice between auxiliary electronic TAKIOmeter and built-in electronic distance measuring instrument
- o Switch button for forwarding the position on the irradiated surface
- o Radio communications

(3) Unique functions of robot

This robot has a number of unique functions as described below.

(a) Simultaneous irradiation of two sections

This robot allows the simultaneous irradiation of two sections. This allows it to be applied to the micro-bench method, in which the excavation of the lower half lags behind the upper half.

Photo 3 shows the simultaneous irradiation of the lower and upper sections.

(b) Built-in electronic distance measuring instrument

The robot has a built-in electronic distance measuring instrument that can detect the position of the face in three dimensions, automatically matching the optical axis of the electronic distance measuring instrument with that of the laser beam. For this reason, measurement of distance to the irradiation point is simply done by the computer, improving the accuracy of position finding. The three-dimensional coordinates of the position can be readily calculated from the angle of the mirror surface of the scanner.

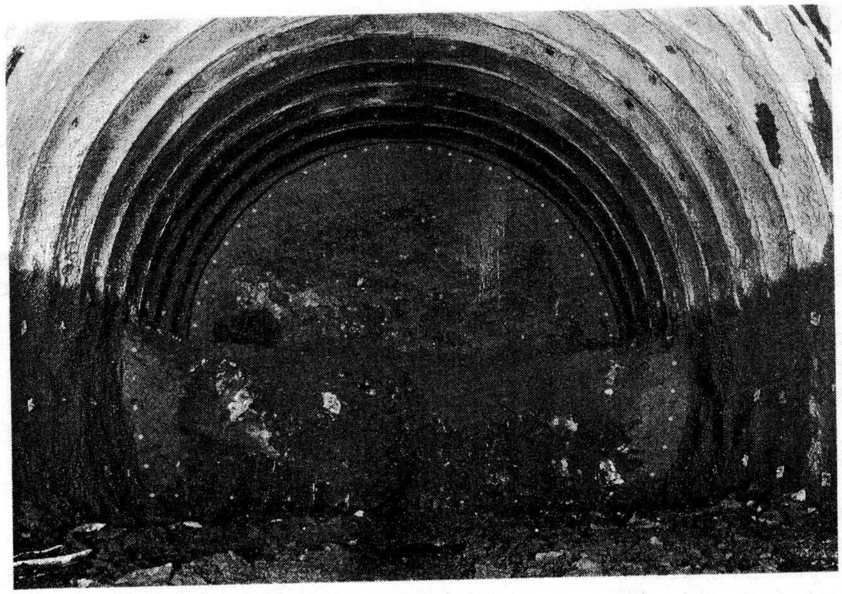

Photo 3 Simultaneous irradiation of two sections

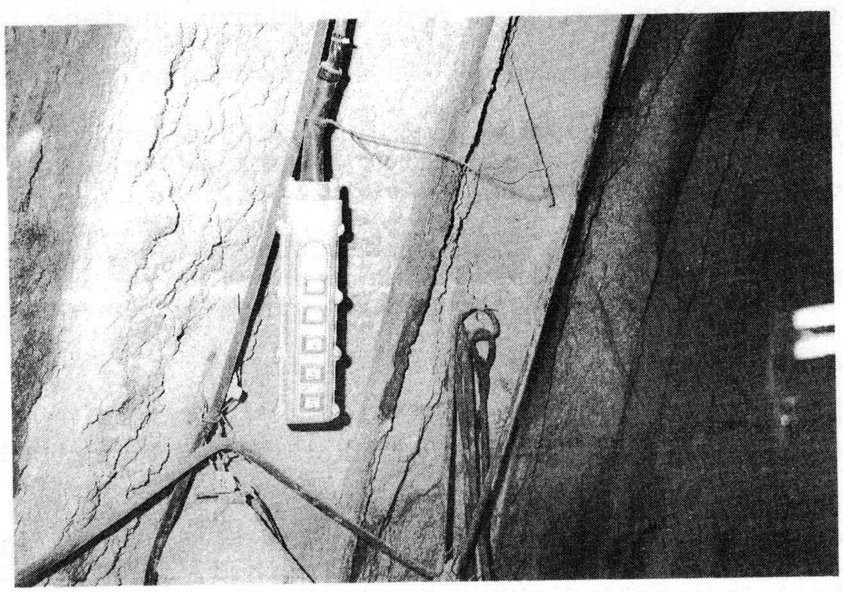

Photo 4 Button for changing irradiation

(c) Button to change irradiation position.

The face is advanced by sending the irradiation position by single-key operation after registering the position of the face, because the planned position can be assumed in advance. By installing this button, any operator can change the irradiation for up to five sections. (Refer to Photo 4.)

In addition to the above main functions, coefficients of magnification for the x- and y-axes can be input to adjust the size of the irradiated area, while changes in the irradiation speed from manual to high speed (0.025 sec. per point) can be made.

5. VERIFICATION OF MARKING ROBOT SYSTEM

Verification tests and development of a more advanced system have gone ahead, taking advantage of tunnel construction work at the Shin-Akechi Tunnel (Tochigi Prefecture), the Ichinose Tunnel for the Hokuriku Shinkansen (Gunma Prefecture), the Shin-Kannon highway tunnel (Kyoto Prefecture), and others, which are being done by Taisei Corporation. While upgrades of each function and improvements to the software have been attempted, complete robotization was achieved at an early stage. The following describes particulars of how the system was verified:

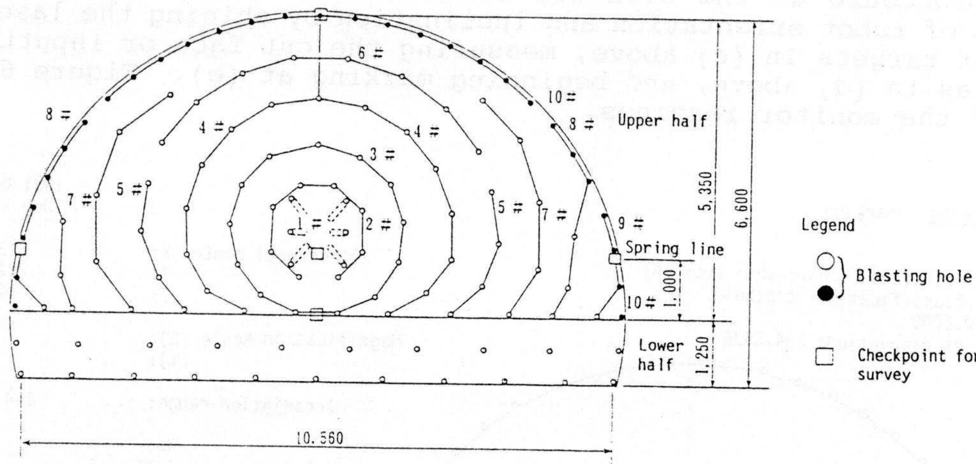

Fig. 4 Blasting pattern of planned section

(1) Method of marking

The laser marking robot was fixed on the side wall 70 m away from the tunnel face, and the three-dimensional coordinates of a pair of targets on the side walls 40 m behind of the face were obtained (refer to Fig. 5). Photo 5 shows how the laser marking robot was installed.

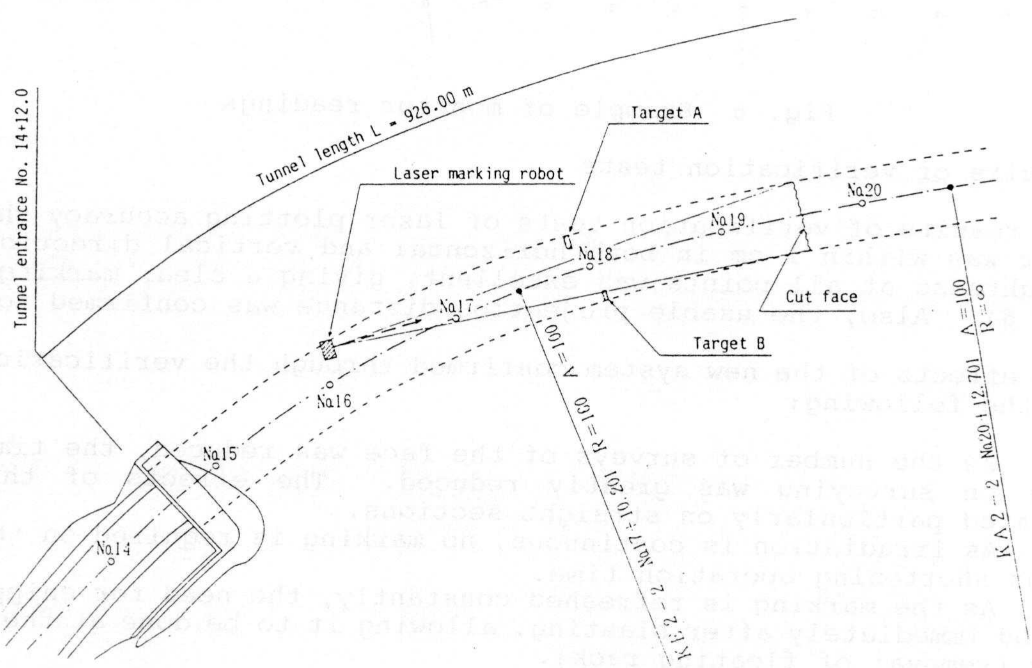

Fig. 5 Plan of test site

The computer operations used to go from initial setting to marking are as follows:

(a) Registration of the three-dimensional coordinates of the control point, robot, and target
(b) Registration of irradiation pattern coordinates and alignment
(c) Initial setting of marking robot
(d) Detection of face (measurement or input at station)
(e) Laser marking operation

The procedure at the site was to establish the initial settings for correction of robot orientation and inclination by shining the laser beam on the pair of targets in (c) above, measuring the cut face or inputting it at a station as in (d) above, and beginning marking at (e). Figure 6 gives an example of the monitor readings.

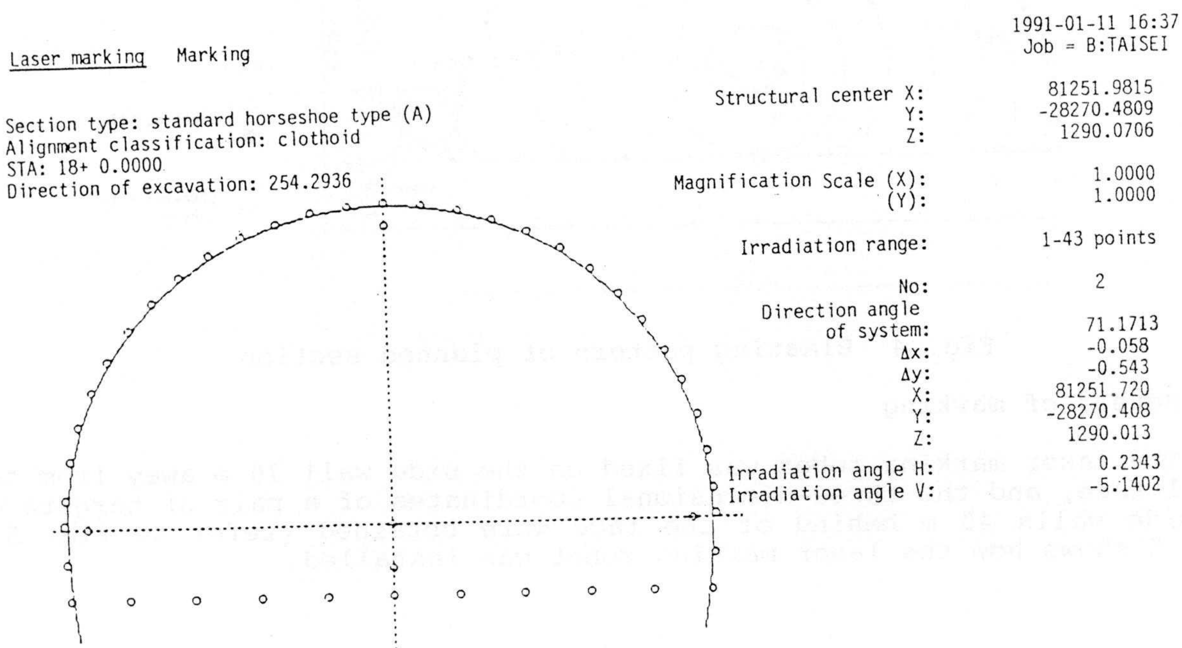

Fig. 6 Example of monitor readings

(2) Results of verification tests

The results of verification tests of laser plotting accuracy show that the error was within 1 cm in both horizontal and vertical directions, and that brightness at all points was excellent, giving a clear marking (refer to Photo 6). Also, the usable projection distance was confirmed to be 300 m.

The effects of the new system confirmed through the verification tests include the following:

(a) As the number of surveys of the face was reduced, the time spent by staff on surveying was greatly reduced. The effects of this were demonstrated particularly on straight sections.
(b) As irradiation is continuous, no marking is required on the cut face, thus shortening operation time.
(c) As the marking is refreshed constantly, the need for chipping can be checked immediately after blasting, allowing it to be done at the time of chopping (removal of floating rack).
(d) Since marking is always accurate, the drilling accuracy was improved while at the same time reducing outbreaks.

(e) It was possible to check the result of surveys in the tunnel using the laser beam.

(f) The marking remains accurate even if the tunnel section is large.

(g) This robot can be used for erection of the support steel used in the conventional construction method.

(h) Operation is simple, so no special operator is required and workers can handle themselves.

(i) The system eliminates the number of operations at the cut face, which may cause collapse, thus improving safety.

With these results, we believe the robot has achieved significant effects in the reduction of manpower and labor, and in improving economy and safety.

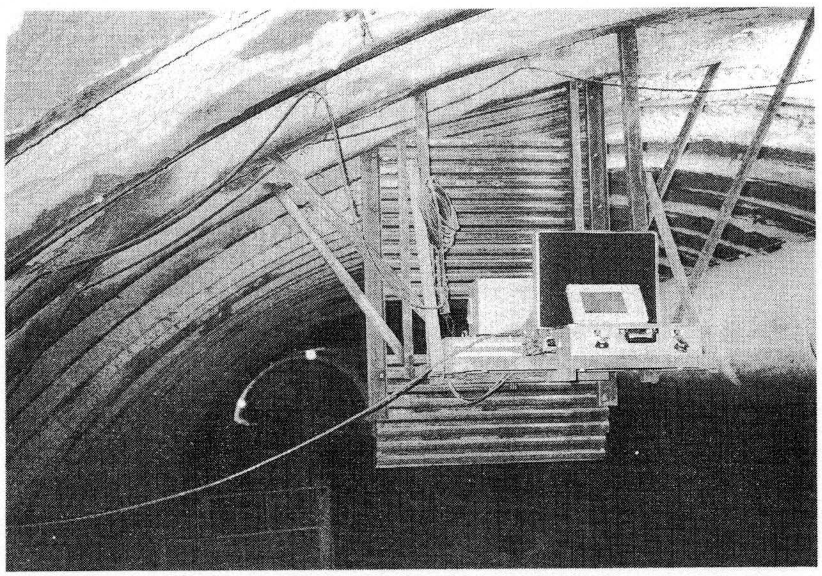

Photo 5 Installed laser marking robot

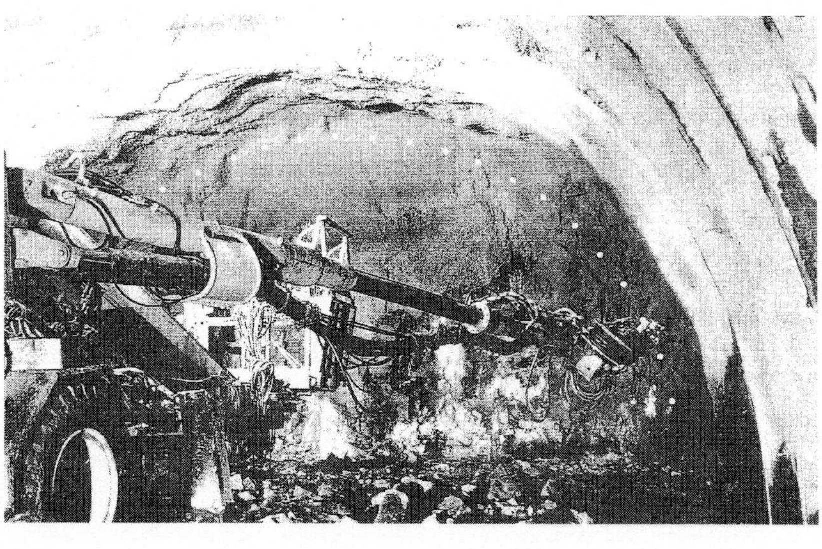

Photo 6. Laser plotting and drilling operation

6. CONCLUSION

The development of this system was based on a completely new technology for controlling a laser beam. Particular efforts were put into making the system smaller and improving the software for use in the working environment of a site. Thus the machine was given functions and improvements which make it easier to use. As a result of various verification tests, the accuracy and position finding function were checked, and its effects from an operational point of view were confirmed. The system was rated highly at each site where it was used for tunneling work. The authors consider that the initial objective of development has been achieved. This was due mostly to the valuable advice and support rendered from all those concerned in various disciplines, to whom the authors wish to express their deepest thanks.