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AUTOMATIC MEASUREMENT SYSTEM OF TUNNEL PROFILE

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ABSTRACT

This paper discusses an automatic measurement system used for checking the accuracy of tunnel profile. Such checks, in all work phases from construction to maintenance after completion, requires measurements as well as analysis and assessment of data obtained. This sophisticated system has been developed through high-level automatization of all these tasks (partially robotized).

The system has two functions which support the measurement, i) positioning and ii) detection. The capability i) teaches the installation position of the measurement device. This position in a coordinate system is detected by the function ii).

These functions detailed here are elements essential for future construction robots.

1. Introduction

In recent tunnel construction, the NATAM (New Austrian Tunneling Method) is most widely used because of its rationalized processes. In this connection, increased emphasis is on the tunneling accuracy for ensuring higher quality and efficiency of the work as well as less cost. On the other hand, reconstruction of aged tunnels will be increased in number. For reconstructions, it is vital to measure rapidly and exactly the profile of tunnel, without interrupting other services in the tunnel. The automatic system discussed here satisfies this requirement. If the system is used, tunnel profile measurement, analysis and assessment of obtained data are performed with minimum labor and time, while other works are continuing.

As far as the construction industry is concerned, we are still in the primary stage of the history of robots. The system developed is not, in the strict sense, fully automated. But it has attained the automation level really effective in practical use, embodying new functions. Some of these functions may form essential elements of future constrution robots and some may be utilized in robotization before long.

First, this paper gives general explanation of the capabilities of the system. Secondly, it discusses in detail the "essential elements".

2. Tunnel-profile measurement devices : how are they actually used and how should they be developed ?

2.1 Actual state and problems

The conventional devices were large in size, requiring much time and labor. So they were not suitable for routine checks. A compact type has been recently developed, which incorporates electro-optical distance meter, encoder and stepping motor. It has simplified remarkably the measurement itself. However, installation process of the device has not yet been improved, though it is of primary significance in the series of measurement tasks. Actually, the installation needs aid by another team of measurement, obliging to interrupt the tunneling work. Besides this, as for processing measurement data, there is almost no method which satisfies requirements of site or suitable for routine checks.

2.2 Development scheme of the system

Taking into account the above situation, the scheme was established to creat a system which can be used for routine checks, placing emphasis upon automatization and labor saving.
The main aims of the development are :

1 rationalized placement of the measurement device, requiring less labor
  - functions of positioning and position detection

2 system of high freeness in displacement
  - unit carriage

3 3-D (three dimensional) measurement system
  - robot running on a monorail

4 versatile system
  - general-purpose data processing system

3. Performances of the system developed

The system can be applied to the checks of :

1 accuracy of profile immediately after excavation (Fig. 1)
  - checking if the excavation is correctly done so that the profile is conform to the design (this check is executed between mucking and concrete spraying)

2 thickness of sprayed concrete
  - checking if the thickness agrees with the designed value (measurement point is the same as that of 1)

3 thickness of secondary lining (Fig. 2)
  - checking if the designed space for secondary lining is available (prior to applying sheets, detailed 3-D profile measurement is carried out)

4 checking of the finished lining profile (Fig. 3)
  - checking if the finished lining profile corresponds exactly to that of design (many profiles to be measured in long span at one time)

See also Table 1.

4. Essential elements developed

4.1 Softwares of measurement control and data processing

For providing the system with versatility and multi-function, a high performance personal computer NEC PC-98LT was selected. In the former system, control and data processing were respectively done by a separate computer. But the PC-98LT is capable of executing the both tasks and calculating at a much higher speed. New softwares for control and data analysis have been developed. By the softwares, not only data processing but also graphic display are available on the spot.

4.2 Positioning function in the unit carriage system

This system is comprised of an automotive carriage on which a large battery and measurement device are mounted. This configuration allows to measure continuously many profiles in a wide span (without long-time interruption).

It is provided with a positioning function as described in the following.

1) Method

The measurement device is aligned with a laser beam which is parallel to the tunnel axis and passes through known coordinates on the plane of a tunnel profile.

2) Essential elements

- double target : the measurement direction and position are aligned with a laser beam. (Fig. 4)
- adjuster for making a laser beam strike the given position of the target (XY-table, lifter with pantagraph) (Photo 1)
- outrigger provided with double-tube jacks which allows to set rapidly the carriage even on an irregular roadbed (Photo 1)

The system works according to the sequence :

Step 1 : The carriage is moved to the succeeding measurement position.
Step 2 : The carriage is set horizontally by means of the jacks.
Step 3 : Adjusting the lifting jacks, the xy-table and the rotation device, the laser beam is aligned with the collimation line of two targets.
Step 4 : Inputting the division of the graduation on target struck by the laser beam (input of machine height)
Step 5 : Start of measurement. Finish of measurement. Then back to the Step 1 for the next measurement.

The system is capable of measuring 15 or more profiles per hour. This is the result of execution obtained up to now.

4.3 Positioning and position detection at face

At the face, a laser beam is projected for indicating the direction of excavation. The beam passes through a point of fixed coordinates with respect to the tunnel profile (Fig. 5). Setting the measurement position and detection of position are performed, taking the beam as the reference coordinates.

A reflector has been invented. It reflects the beam at a right angle to set and detect, on the basis of the coordinate of the reflection point, the measurement device position (Photo 2).

The sequence of operations :

Step 1 : The reflector is set at a prescribed position, as is shown in Fig. 6, for reflecting perpendicularly the laser beam indicating the excavation direction. By letting the beam strike the target, the device-setting position and the measurement direction (normal to the tunnel axis) are determined.

Step 2 : Using the distance measurement function provided in the device itself, the distance (L) and angle of elevation (θ) to the reflector target are determined.

Step 3 : On finishing measurement, data analysis is done immediately and the position of the measurement device is instantaneously inputted to the system. Then, profile measurement starts.

Measurement of profiles by the system can be executed in a short time (about 10 minutes/profile) with a little labor (minimum one or two persons). Consequently, the system can be used for routine checks, as it measures during an interval between works, i.e., excavation-mucking -concrete spraying. Moreover, the data obtained are indicated in real time to workers on site, by the function of playback explained below which has been newly developed for the system.

4.4 Playback

This function assesses immediately the measurement results obtained at the face, and indicates defective areas such as underprofile, overprofile (Fig. 1). The indication is directly done, pointing the defective areas on the wall by the visible laser beam of the measurement device. Thanks to such an indication, the workers of excavation can know, on site and in real time, the actual situation in the tunnel. Accordingly, corrections are executed more effectively.

4.5 3-D measurement robot

When a very minute measurement is required in both sectional and longitudinal directions (for instance, availability of the lining thickness for the secondary lining) the most useful method is to measure three-dimensionally and express graphically.

For performing 3-D measurement:

1 many profiles should be measured at a small pitch in both sectional and longitudinal directions,
2 each measured profile should form a right angle with the tunnel axis, and
3 each measurement-pitch angle from the start point to the end point of a profile should exactly coincide with that of another profile.

This robot is provided with a configuration which satisfies these conditions. It runs on a monorail to execute measurement automatically and continuously. (Fig. 2)

4.5.1 Essential elements of 3-D measurement robot

1 Monorail
Slide rails are mounted on aluminum square pipes. The carriage catches the rail between journals and slides on it.

Rail length : 1.8 m/span x 7 = 12.6 m (corresponds to one lot of secondary lining form)

2 Istallation of the monorail
Rails are laid, using supports equipped with double-jack legs and fine-adjustment device. The legs ensure exact installation even on an extremely irregular roadbed. The fine-adjustment device compensates torsion of rail and vertical and horizontal errors.
The installation accuracy can be ensured, if correct linearity is obtained. This purpose is easily achieved by the device we have invented, which uses laser beam of the measurement device (Fig. 7).

3 Detection of the measurement-device position on the monorail
It is sufficient to detect the start and end points of the rail to determine the position, because, based on the linearity of the rail, the position can be obtained directly from the travelled distance.

4 Travelling robot
According to the control data, the robot travels a given distance and confirms the distance travelled. Then, it sends to the computer the data of the travel. After one profile has been measured, it moves to the next preset position to repeat the preset number of measurements. All these steps are automatically performed at every preset position. (Photo 3, Fig. 8)
The capability of the automotive carriage:

running accuracy	1 mm
profile measurement pitch	0.5

5 3-D analysis system
The system analyzes the measurement data and provides alternative assessments, e.g., by 3-D display, extended display, allowing selection suitable for satisfying requirements.
Of all the alternatives, the extended display is practically the most useful, an example of which is shown in Fig.9.

5. Conclusion

The main purpose in the development of the system is to create essential elements for positioning the measurement device and, by so doing, to utilize to the maximum extent the capabilities of the existing measurement system. Referring to the result obtained, it can be said that the purpose is achieved.
The system embodies different levels of automatization. The 3-D measurement is a typical example of the highest level. On the contrary, some functions, displacement by carriage for instance, are largely supported by workers' operation, though basic technologies have been already developed so that these functions may be in future fully automated.

To what level should we pursue automatization ? It is not easy to answer to this question when the constuction industry is concerned. Except for works in hazardous environment, full automatization is not necessarily the best solution, even if the state of the art might enable it. This is an intrinsic difficulty in development of construction robots. What causes such difficulty? When analyzing construction works, it is known that various processes cannot be divided into two clear categories, works by machines and works by human workers. On the other hand, recent improvement of construction machines is conspicuous.

Efficiency and capacity of machines are growing larger and larger. So, almost all processes not yet mechanized are by nature delicate, containing factors which impede robotization. Such processes are in fact performed on the basis of intuitive judgement of human workers. Consequently, combination of automated systems with minimum human labor, developed, on the basis of the demand and supply of the market, may be the most realistic solution in the field of construction. This philosophy will hold also in future development.
The automatization of the system discussed here is of the level which ensures good harmony with the actual situation of construction sites.

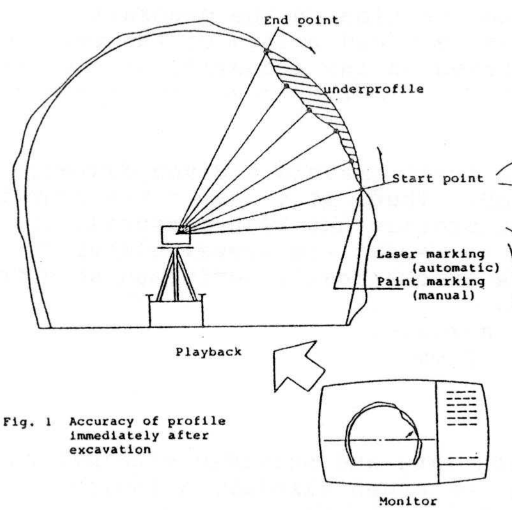

Fig. 1 Accuracy of profile immediately after excavation

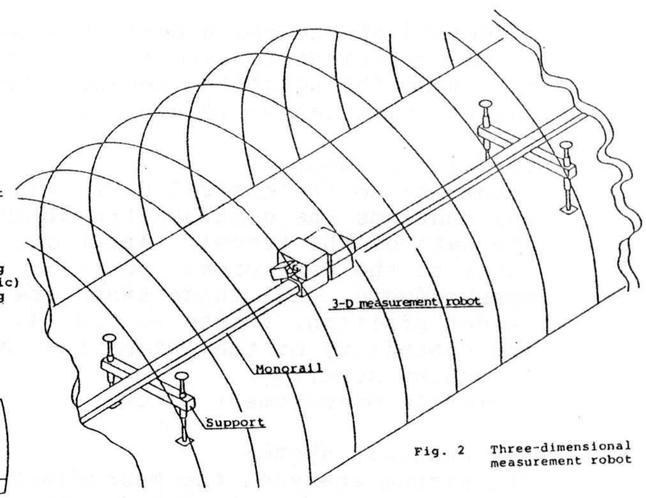

Fig. 2 Three-dimensional measurement robot

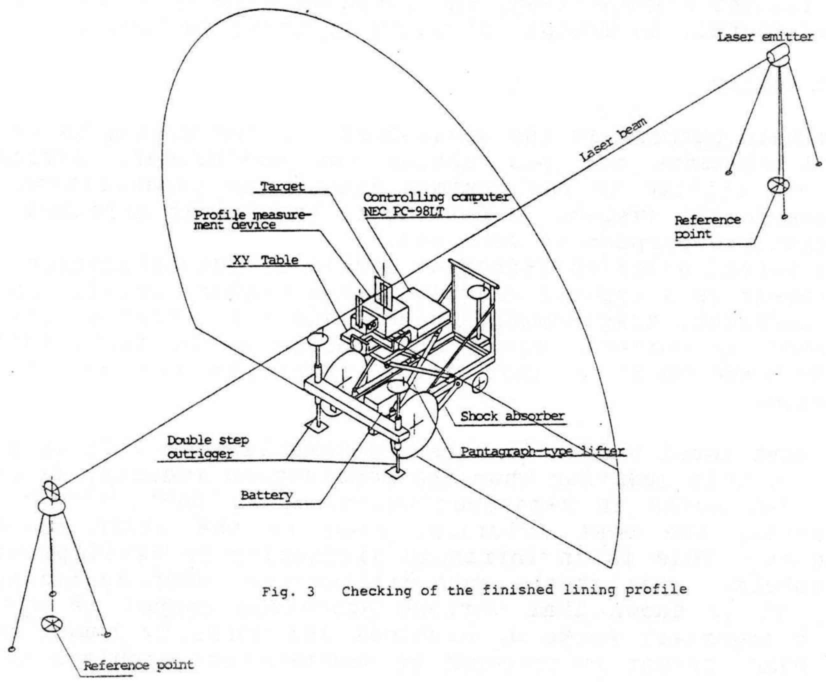

Fig. 3 Checking of the finished lining profile

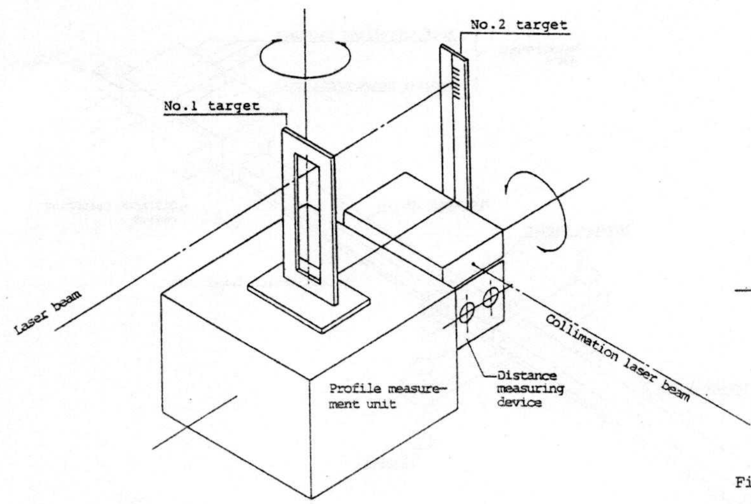

Fig. 4 Setting the profile-measurement direction by the double target system

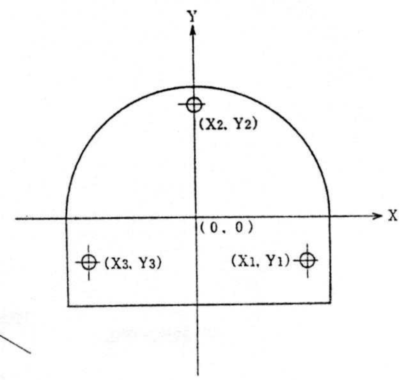

Fig. 5 Example of positioning of laser beam in a tunnel

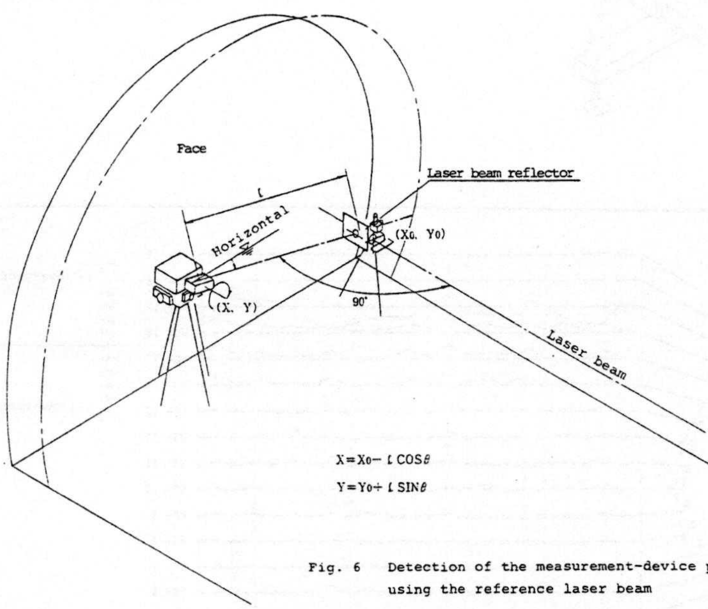

Fig. 6 Detection of the measurement-device position using the reference laser beam

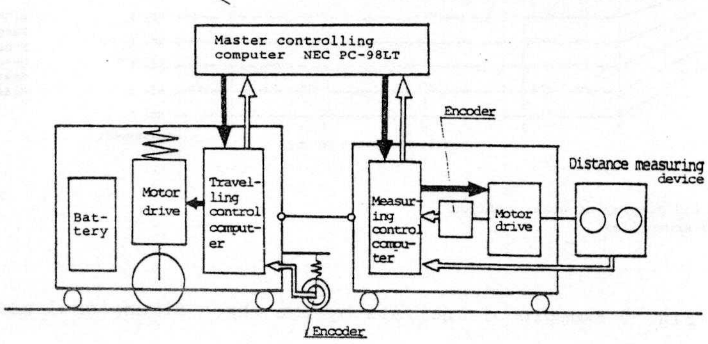

Fig. 8 Three-dimensional measurement robot

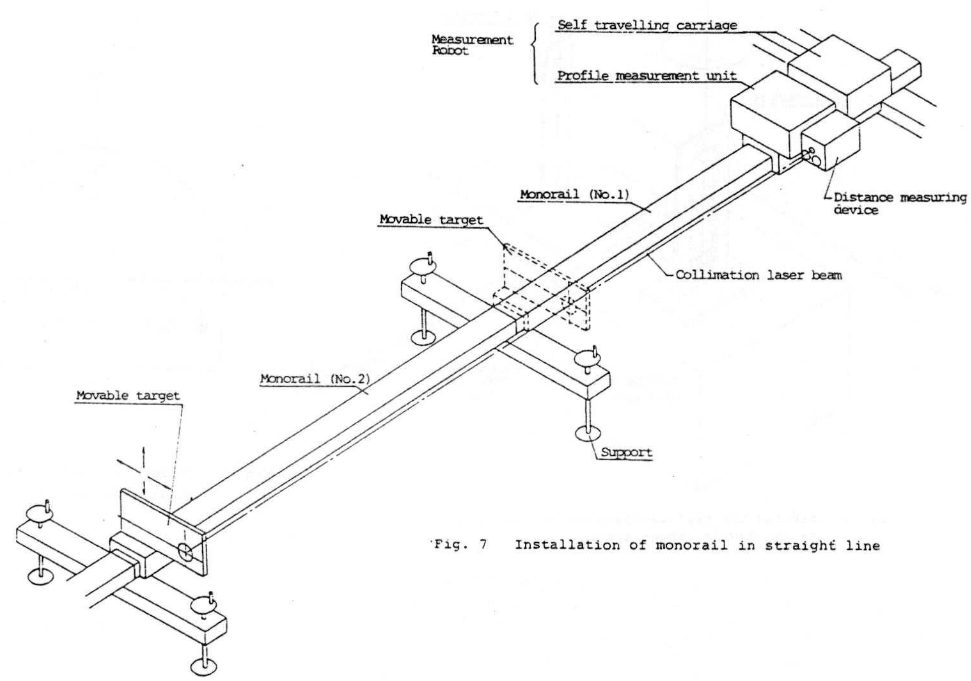

Fig. 7 Installation of monorail in straight line

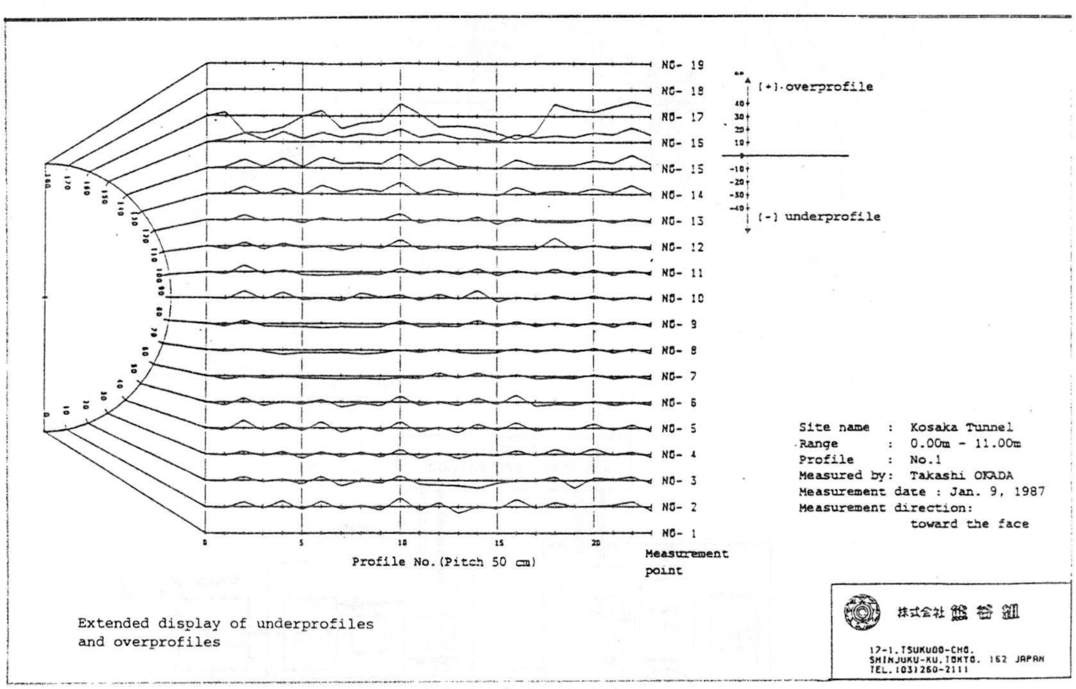

Fig. 9 Example of analysis by the three dimengional mesurement robot

Table 1 Comparison between the automatic-measurement system and the conventional system (Development items and results)

	Application	Main functions	Softwares		Performances	
			Control	Analysis/ Assessment	Automatic-measurement system	Conventional system
Indication of underprofile and overprofile at the face	Rapid measurement at the face, while other works are executed	Positioning, and detection of position	Control program for detecting position	Program for profile analysis and assessment	10 minutes/ profile with one worker	20 to 30 minutes/profile with two or three workers
	Underprofile and overprofile areas are directly indicated, by means of laser beam striking the wall (marking)		Program for indicating underprofile/overprofile and controlling playback	Program for detecting underprofile/ overprofile	Execute playback immediately after measurement to let workers verify	Not available
Unit carriage system	Continuous measurement at a constant pitch (2 to 30 m) for a long span of measurement (several hundreds to thousands m)	Automotive carriage, measurement device support, positioning the carriage	Continuous automatic measurement program, and position calculation program	Continuous analysis and assessment program	3 to 4 min./ profile with one worker	20 to 30 min./ profile with three to four workers
Continuous 3-D automatic measurement	Execute automatic measurement to perform 3-D analysis: this measurement is done continuously and rapidly at a small pitch in a short span in the tunnel-axis direction. Effective especially for checking the space (thickness) available for secondary lining.	3-D measurement robot (monorail type)	Program for controlling 3-D measurement robot	Program for 3-D measurement analysis and assessment	By one person or more Capable of measuring 20 to 30 profiles in a span (10 to 20m) within one hour, comprising the time for installing the machine	Not available

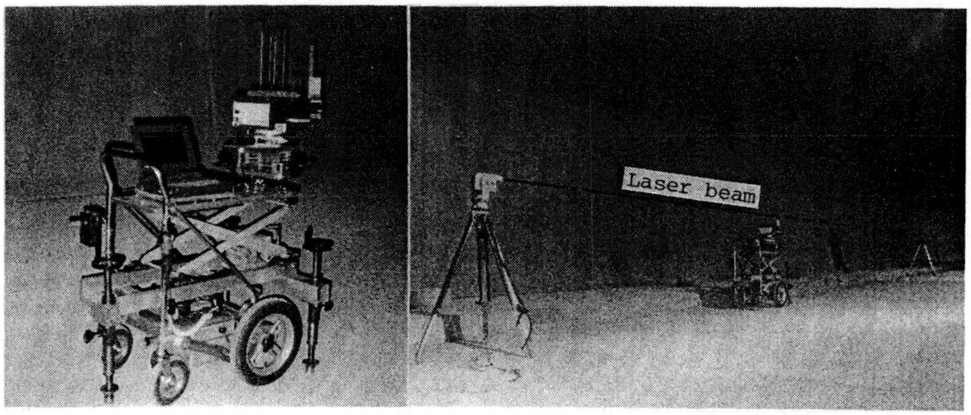

Photo 1 Unit carriage system (left) and the system in operation (right)

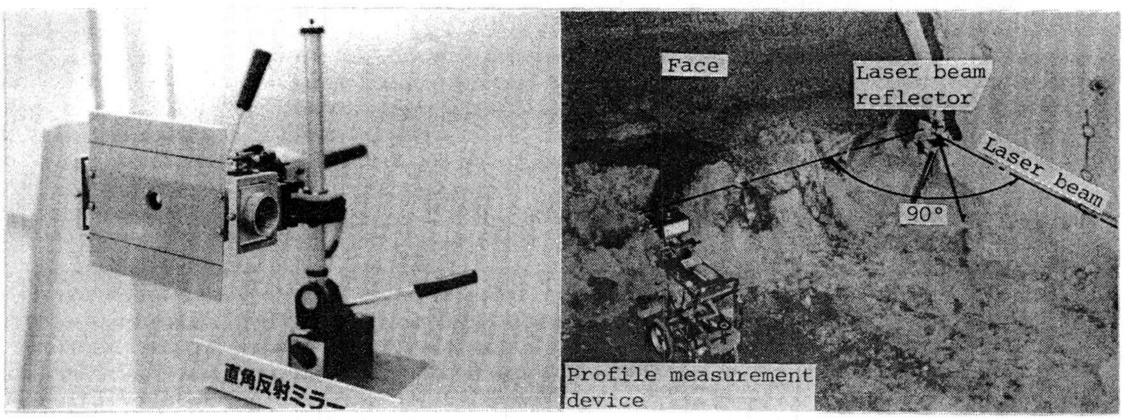

Photo 2 Laser beam reflector (left) and the reflector in operation (right)

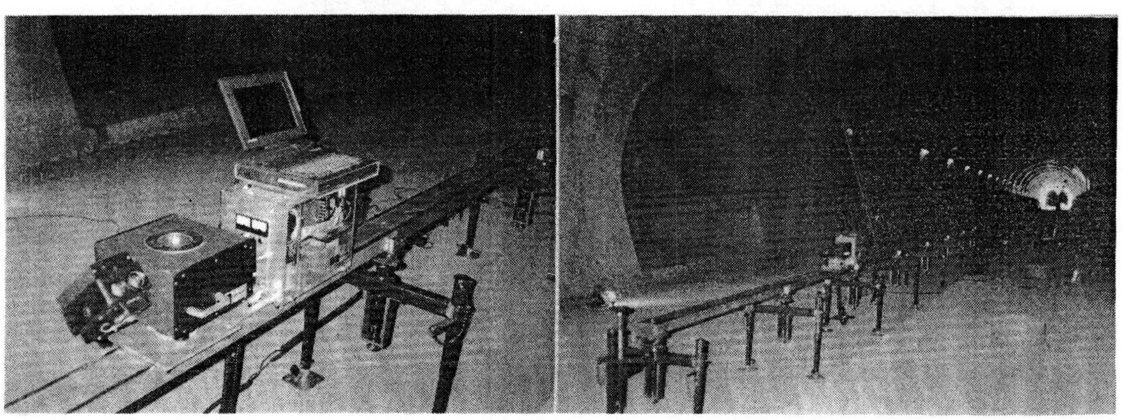

Photo 3 Automotive robot (left) and 3-D measurement (right)