NAVIGATION/POSITIONING CONTROL OF MOBILE ROBOTS FOR CONSTRUCTION

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ABSTRACT

Mobile robots at construction sites, compared with those used in the past in factories, are required to possess particularly high levels of mobile techniques such as ability to establish free paths of navigation, position determination of high accuracy, use under severe environmental conditions, and autonomous navigation. Especially, for autonomous navigation, position recognition and guidance techniques are important matters for development. Four cases developed up to this time are described in this report.

1. INTRODUCTION

Working space at a construction site is spread out and, accordingly, there is a strong demand for robots possessing mobility functions. Numerous mobile robots have been developed so far headed by floor finishing robots and inspection robots. With these mobility functions, effects achieved in certain types of tasks have been large improvements in working efficiencies and elimination of conventional temporary works. However, new technical problems have arisen such as methods of positioning control and motive power supply, and safety measures for humans and robots.

The special nature of positioning control at construction sites is briefly discussed and four cases of development are described here.

2. SPECIAL NATURE OF MOBILE ROBOTS AT CONSTRUCTION SITES

Robots for construction work possessing mobility functions have been developed for twenty-odd tasks in building and civil works combined. The tasks all involved working while moving over broad areas, with the spaces moved across being varied such as vertical planes, horizontal planes, or three-dimensional spaces. Moreover, compared with a mobile robot in a factory where conditions are of set pattern, these robots all require accurate positioning and are subject to especially difficult restrictive conditions which may be sorted out and listed up as follows.

. Working space at a construction site changes with the progress of work and travel paths will be altered at all times. Consequently, a means by which any path can be set out is called for.

. Obstacles to movement often appear as working space changes and high-level functions are needed to recognize and avoid such obstacles.

. The working space may be outdoors, underground, or underwater, and the robot must be usable even under severe environmental conditions.

. Performing tasks while travelling is main so that position measurement in real time and a high degree of accuracy in positioning are required.

. Especially high reliability is required of a construction robot, and a number of positioning systems must be concurrently available.

. During construction, workers and robots carry out tasks intermingled with each other, and it is absolutely necessary for safety measures to be provided for such a situation.

3. PRESENT STATE OF MOVEMENT AND POSITIONING CONTROL TECHNOLOGIES

Most mobile robots used, mainly in manufacturing, have been guided over paths of cables or light-reflecting tapes installed on floors. In contrast, in construction and non-manufacturing operations, robots with functions to confirm their present positions on any travel path instead of fixed routes, and navigating properly while automatically making corrections (autonomous navigation) are needed. For such robots capable of autonomous navigation, both position recognition technology for accurately grasping present positions and guidance technology for making corrections toward the target position are important objects of development.

Methods of recognition for determining positions studied and developed so far are classified centering on sensors and shown in Fig. 1.

1) Methods of Determining Positions from Amounts of Movement of Robots Themselves (Internal Measuring Sensor)

With a system of this kind, distances moved and amounts of changes in direction of the robot proper are calculated at all times. A drawback is that any errors will be cumulative, but such a method is adopted most often because of simplicity. Due to the drawback, corrections must be made between the position calculated by the robot and the actual position after each fixed distance travelled or after each fixed amount of time elapsed.

2) Methods of Determining Position from Outside Reference Points (External Measuring Sensor)

In this kind of system, information on the absolute positions of reference points set up outside the robot are inputted beforehand. The robot calculates its own absolute position while measuring its position relative to these outside reference points. A feature is that even if errors were to occur they will not be cumulative.

3) Combinations of Internal Measuring and External Measuring Sensors

This is a system combining the advantages of the two systems mentioned above. Whenever information on outside reference points cannot be obtained, the position is determined from the robot's own amount of travel. And, when information on the absolute positions of reference points is again obtained, the robot's own coordinates based on amounts of movement are corrected so that high accuracy and reliability are secured.

4. EXAMPLES OF DEVELOPMENT

4.1 Position Determination System of Wall Inspection Robot

4.1.1 Outline of "Kabedoda," a Wall Inspection Robot

The wall inspection robot was developed for inspecting deterioration of exterior walls of reinforced concrete structures. This robot sucks on to walls and ceilings by crawlers with numerous vacuum suction cells and is capable of two-dimensional travel. With various kinds of instruments mounted on the robot, spalling, cracking, etc. of the finish layer (tile, mortar, concrete, etc.) of the exterior surface are investigated and recorded. The principal specifications are given in Table 1.

4.1.2 Functions Required and Conditions for Position Determination System

The major demands on and conditions for the position determination system of this robot were as follows.

. To investigate deterioration moving two-dimensionally on the wall, the robot's position must also be measurable two-dimensionally.

. Measuring operations would be continuous and after each time a fixed distance has been travelled. Measurements in real time interlocked with movements of the robot must be possible.

. As the robot will travel across the wall by itself, the position determination apparatus is to be made as small and lightweight as practicable.

4.1.3 Position Measurement System

Thus, a method of measuring position, calculating the absolute robot position from two reference points on the ground was adopted. The two points are provided with position detectors which keep fine wires at fixed tensions in accordance with robot movements, and output in real time and on line lengths of wires pulled out. As shown in Fig. 2, the lengths of L1 and L2 are transmitted to a computer for recording navigation of the robot, and the location of the robot (X, Y) is calculated by triangulation. This calculation is obtained with each cycle for a fixed period of time, and recording is done together with the results when deterioration is discovered.

4.1.4 Measurement Accuracy and Other Matters

The lengths of wire cables are measured by encoder. Linearities are good and favorable results are indicated. The distribution of errors due to this system applied to a wall surface of 15 x 10 m is shown in Fig. 3. It was found that the accuracy was comparatively high with an average of 4.8 cm.

With this system there are advantages such as 1) no apparatus mounted on the robot proper so no weight to be borne, 2) errors not cumulative because of measurement of absolute position, 3) low development cost because of simple principle, and also easy maintenance.

4.2 Position Determination System of Clean Room Inspection Robot

4.2.1 Outline of Robot

This robot performs inspection work for ascertaining and maintaining performance of clean rooms in place of humans to release them from monotonous and hard inspection work, reduce dust from such work, and improve inspection accuracy. Leak tests to detect leaks from ceiling filters and cleanliness tests to measure dust are performed moving through the clean room. The principal specifications of the robot are given in Table 2.

4.2.2 Functions Required and Conditions for Position Determination System

The chief demands on and conditions for the position determination system of this robot were as follows.

. Accuracy of position of about ±5 cm and correct posture (direction) are required during a leak test.

. It is necessary for movement to be over the allowable route and measurements made at the designated positions for the cleanliness test. These positions are changed from time to time so that the method must be one that can follow the changes.

. Floors are mostly gratings, and slipping of wheels is expected. Conventional paths such as of electromagnetic guidance cannot be provided.

. Facilities to disturb flow of air inside the room cannot be provided.

4.2.3 Positioning Control System

In view of these conditions, the method adopted for this robot was to attach marks to the ceiling and floor and determine positions by these marks for navigation of high precision. The marks, arranged at 1- to 2-m intervals along the travel path of the robot, reflect light emitted from the robot proper back to the robot. The robot recognizes marks by visual sensor, a CCD camera, calculates the direction faced and the position of the robot proper from the locations of the marks in the image and determines the correct position by feedback to the next navigation control (see Fig. 4). The following two control systems are employed for this robot depending on the measurement task to be performed.

During a leak test, data on the travel path inside the clean room and measurement activities are automatically transmitted based on input of data such as room size, filter dimensions, and ceiling height, and travelling and measuring are done based on these activities data. When travelling, the position is determined by marks attached to wood strips on the ceiling. During a cleanliness test, judgments are made for right, left, and U turns, measurements, and passing from the pattern of marks provided on the floor, upon which tasks are performed. The robot can be given instructions for action by means of the arrangement of marks.

4.2.4 Measurement Accuracy and Other Matters

Errors in stopped positions at the various filters during leak tests are shown in Fig. 5. Positions are determined with very high accuracy of 0.4 cm on average, deviation being 1.3 cm. With this system there are such advantages as 1) travel paths are established by marks readily installed or changed, 2) the sensor is a visual one so that the construction of the floor is not significant, and 3) high accuracy can be obtained.

4.3 Position Determination System of Floor Work Robot

4.3.1 Outline of Robot

The floor work robot is for tasks such as direct finishing of concrete floors and cleaning of floor surfaces while travelling. These tasks are comparatively simple, but have relied mainly on manual labor and were fairly gruelling because of the necessity to be in a squatting position for extended periods of time. Furthermore, in case of direct finishing work, there were problems such as the work hours reaching far into the night, so that automation had been called for from a long time ago.

The principal specifications of the robot are given in Table 3 and the appearance shown in Fig. 6.

4.3.2 Functions Required and Conditions for Position Determination System

The functions required and conditions for this robot were as follows.
. Tasks of this type are performed travelling over entire surfaces of large floors and high precision of navigation is demanded. The greater the error, the wider the overlapping necessary, for lower operating efficiency. In this case, control within about 10 cm was aimed for.
. The floor surface itself is the object of work so that paths cannot be laid down, while the ceiling will not yet be in place in many cases.
. The calculation system of travel distance is greatly affected by slipping, and a system based on external measuring sensors is required.
. The travel path differs every time and it is necessary for the method of establishing reference points not to be influenced by this.
. The space moved through is large so that the specifiable movement range

and the spacing of reference points must be made large.

4.3.3 Position Determination System

In view of the above, a laser navigator, a self-position detector using laser beams, was developed and mounted on the robot to perform navigation control while recognizing the absolute position of the robot at all times. This apparatus rotates at high speed while transmitting laser beams horizontally and reads light reflected from "corner cubes" installed outside the work area. And, as shown in Fig. 7, the X and Y coordinates of the robot proper and the direction faced are obtained in real time from the angles to the corner cubes at 3 points. Since it can be expected that there will be obstacles to laser beams at a construction site, more than 3 reference points are provided simultaneously with a minimum of 3 points visible from every position. When data from 3 points cannot be obtained, navigation is continued by the internal measuring sensor (wheel rotations) of the robot, and when a location where detection by laser can be done is reached, guidance of travel by laser is resumed. This device has the capability of detecting to a distance of approximately 50 m, and it is possible for work to be done over a wide area at once.

4.3.4 Measurement Accuracy and Other Matters

The results of errors between scheduled and actually-travelled paths measured at 1-m intervals are shown in Fig. 8. Navigation control results of fairly high accuracy with average error of 3.4 cm were obtained.

The advantages of this system are 1) travel paths can be changed freely by data without changing locations of reference points, and 2) errors are not cumulative because of navigation guided by absolute coordinates.

4.4 Automatic Guidance System for Shield Tunneling

4.4.1 Outline of Automatic Guidance System

In the shield tunneling method a shield machine is moved three-dimensionally through the ground with the tunnel constructed to the rear of the machine. Therefore, the machine must be guided correctly over the planned route, but actually, locations are only occasionally obtained about 2 to 4 times a day by surveys inside the tunnel. Advancements made in between will depend on the "feel" of the operator so that deviations are apt to occur, and this is a reason for loss of precision. To improve the precision, and also facilitate saving of labor, it has been desirable for a system to be developed that can provide automatic guidance through constant monitoring of the condition of shield driving.

To correctly guide the machine over the planned route, technology for measuring the present position and posture (direction) must first be developed. Then combining this with an automatic control system for propelling jacks, a final automatic guidance system is perfected.

4.4.2 Automatic Measurement of Present Position and Posture

In order to determine the present position and posture of the shield tunneling machine, measurement data on the driving distance and direction, pitching, rolling, etc. will be required. Automatic measurement techniques may be broadly divided into the following two kinds of systems:

1) Those with inertia sensors mounted directly on machines: As shown in Fig. 9, the position and posture variations are automatically measured with gyrocompasses and settlement gauges mounted on the machines. Since a

collimation space inside the tunnel required for laser beam systems becomes unnecessary, this is particularly effective with small-diameter shields and routes with sharp bends subject to many restraints inside the tunnel. Although this system involves the problem that cumulative errors are likely to occur, measurement errors stayed within 3 cm for continuous driving of 88 rings (79.2 m) in results of verification tests, so that a precision that is amply allowable for practical purposes is possessed.

2) Those recognizing positions based on outside reference points: Although a number of systems have been proposed, the method adopted in general is to measure position and posture with a laser beam projecting apparatus having the functions of angle gauge and light-wave range finder installed inside the tunnel, with detection done by a light receiver fixed on the shield tunneling machine. At sections of bends it is necessary for combined use of laser refraction apparatus, and more frequent relocations of the laser apparatus, but since absolute position and posture information is obtained at all times, there is no accumulation of measurement errors.

4.4.3 Automatic Guidance System

An example of measurement of shield position and posture and automatic guidance by the abovementioned laser system is given here. Fig. 10 shows the structure of the automatic guidance system. Automatic controlling of the propelling jacks is done as follows.

1) The deviation and the deflection angle of the shield relative to the planned route is determined from the automatic measurement data at the time driving of the previous ring is completed. 2) The target driving angle is established so that the deviation will become 0 at n shield lengths beyond (n: set at any number). 3) The optimum pattern for using jacks is selected based on the center of force points and past performances of the jacks used. 4) When driving is started, information on the position and posture of the machine is displayed on a computer image as shown in Fig. 11. When the deviation exceeds the allowable value, a minimum number of jacks is turned OFF to make a correction. 5) When driving of one ring has been completed the data are outputted in summary form and the operation is returned to step 1) above.

This system was used for a section of about 1.1 km in an undersea shield project (diameter: 3.7 m). It was possible to make an advancement with a deviation from the planned tunnel route of only 3 cm and it was verified that construction could be performed with good precision.

5. RECAPITULATION

A brief discussion has been made on the essential features needed for mobile robots to operate under the special conditions in construction. Operations at a construction site are mostly simple, but what are demanded of mobility functions are technologies of very high levels such as free establishment of travel paths, position determination of high precision, use under severe environmental conditions, autonomous navigation, etc.

Four position determination systems were given as examples of robots developed. The 3 examples in building work involve two-dimensional movements with reference points provided outside and self-positions measured in real time. It was found that the accuracies amply satisfied the objectives. Two examples, one each of internal and external measuring sensor systems, have been described in relation to shield tunneling work. It has been confirmed that both amply satisfy requirements.

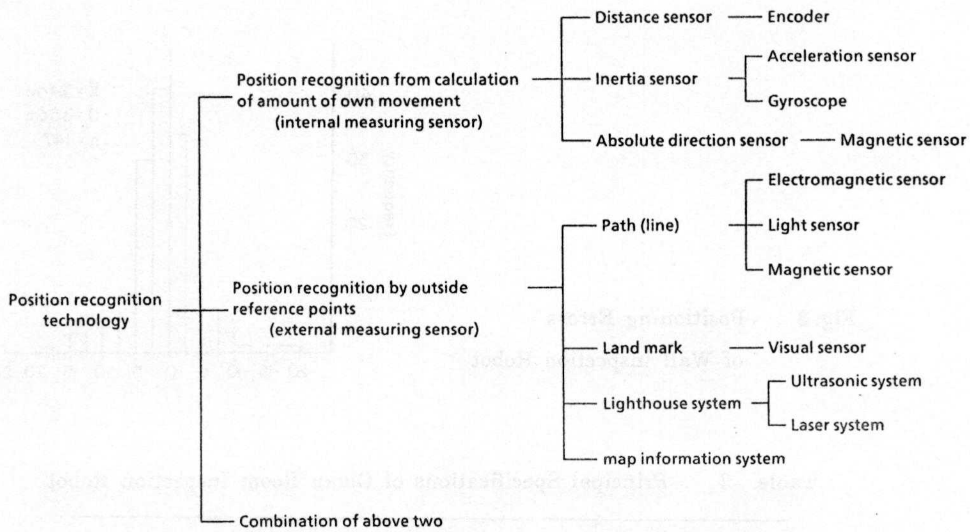

Fig. 1 Present State of Position Recognition Technologies

Table 1 Principal Specifications of Wall Inspection Robot

Composition	Wall surface traveling car + measuring instruments
Performance	Traveling speed : ascent max 5 m / min
	Movements : up, down, snaking, turning (± 90° lateral)
	Load carried : not more than 10 kg
Control	Manual operation, automatic operation
Sensor	Inclinator sensor, opening and obstacle sensor
Instrument	Ultrasonic wave measurement apparatus, TV camera
Outside dimensions	(Length) 1060 × (width) 830 × (hight) 330 mm

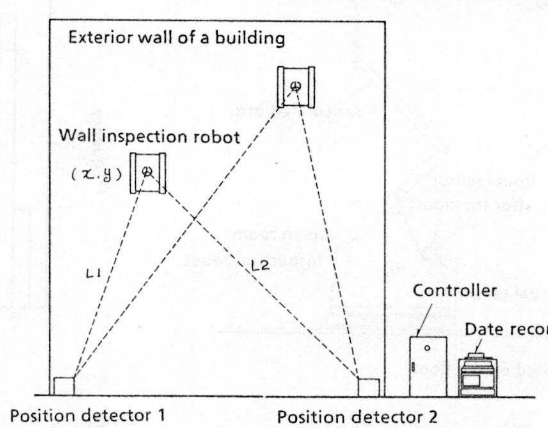

Fig. 2 Position Measurement System of Wall Inspection Robot

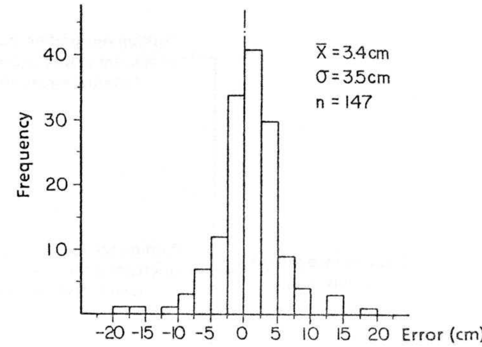

Fig. 3 Positioning Errors of Wall Inspection Robot

Table 2 Principal Specifications of Clean Room Inspection Robot

Composition	Autonomous navigation truck, articulated arm
Performance	1. Prove scanning section
	· Speed : 60 mm / s, accuracy : ≦ 2 mm
	· Range : 700 x 1500mm max / time
	2. Truck section
	· Speed : automatic, 18 m / min, manual, 36 m / min
	· Accuracy : ± 50 mm
Control	Wireless manual operation, full - automatic
Sensor	Visual sensor : CCD camera, obstacle sensor
Motive power supply	Battery (continuous 5 - 8 hr)
Outside dimensions	Truck section : 1000 x 750 x 895 mm (1590 full height)

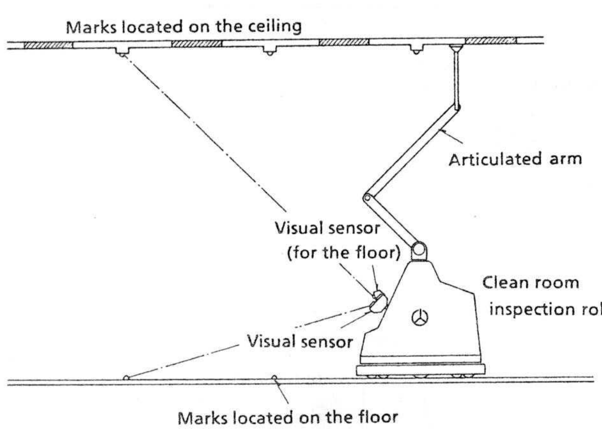

Fig. 4 Position Determination System of Clean Room Inspection Robot

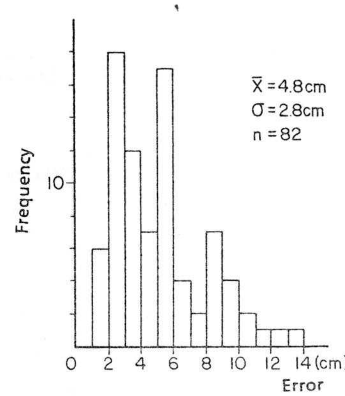

Fig. 5 Positioning Errors of Clean Room Inspection Robot

Table 3 Principal Specifications of Floor Work Robot

Composition	Autonomous navigation truck, twin trowel
Performance	Finishing capacity : av. approx. 500 m^2 / hr
	Traveling speed : 0 - 10 m / min
	Continuous operating time : 4 hr or longer
Control	Wireless manual control, full - automatic
Sensor	Opening and obstacle sensor
Motive power supply	Engine generator mounted
Outside dimensions	(Width) 1560 × (length) 1985 × (height) 1100 mm

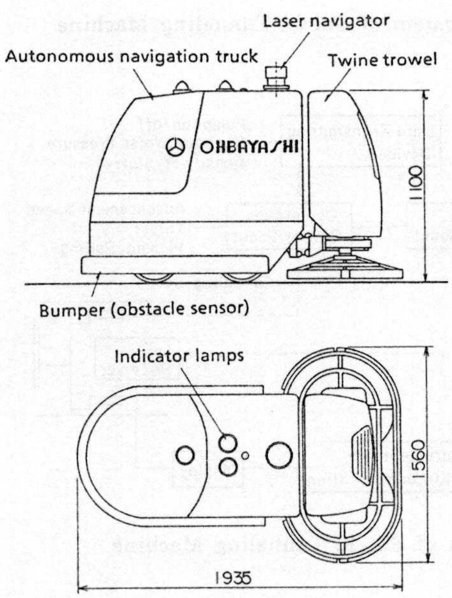

Fig. 6 Appearance of Floor Work Robot

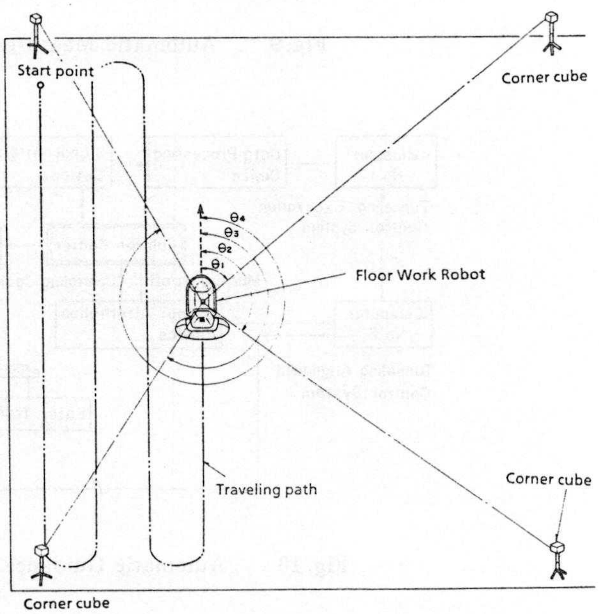

Fig. 7 Outline of Trajectory Control using Laser Navigator

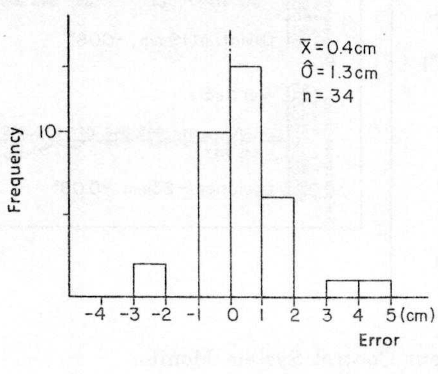

Fig. 8 Positioning Errors of Floor Work Robot

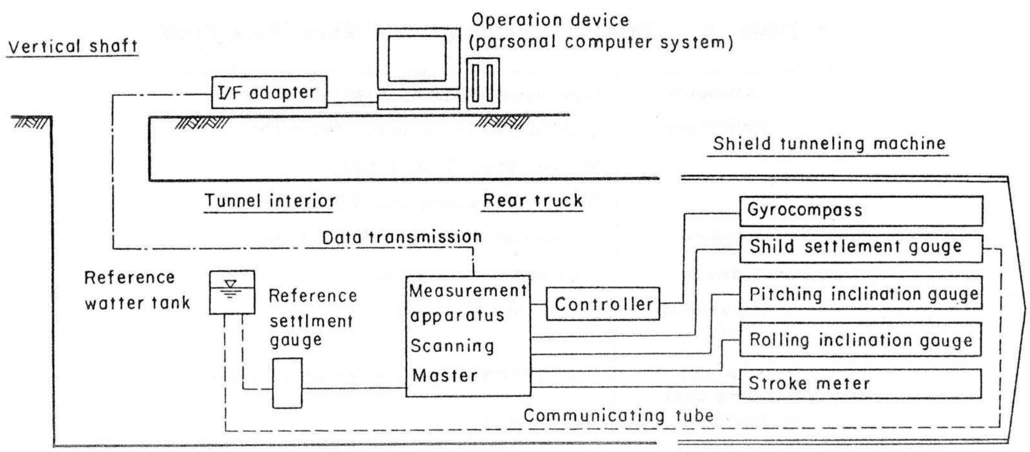

Fig. 9 Automatic Measurement System of Shield Tunneling Machine

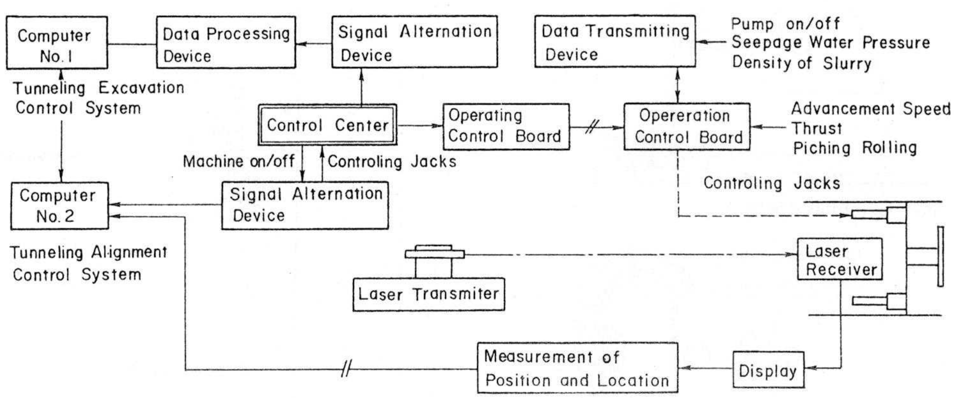

Fig. 10 Automatic Guidance System of Shield Tunneling Machine

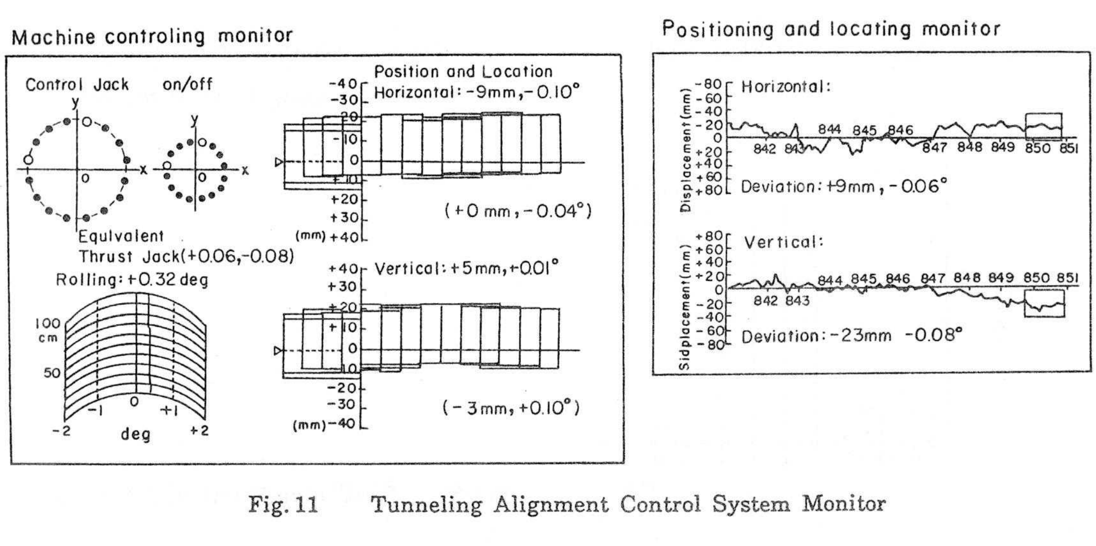

Fig. 11 Tunneling Alignment Control System Monitor