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SHIELD-SEGMENT ERECTION ROBOT

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ABSTRACT

This paper discusses a robot capable of handling segments which are, in dimensions, of the greatest class in the world. The robot has been developed as part of a series of innovations for automatization and robotization of the shield method now used most frequently in tunnel construction.

The robot erects, in the form of ring, segments weighing 4.3 tons a piece. Each ring erected is huge, 12.5 m in outer diameter and 1.1 m wide. The robot goes forward 1.1 m every time it finishes erection of a ring.

With the advancement, the position of the robot in relation to the erected segment changes. In this condition, the robot detects the position and inclination of the erected segments in order to install correctly the succeeding ring. This process was a bottleneck in full robotization of the steps to be performed in the shield-driven tunneling, as it was difficult to mount automatically heavy and large segments. The robot presented here has solved this problem and is now executing the extension of Tohoku Shinkansen line.

1. Introduction

In various industries, requirements for higher productivity, enhanced safety and ameliorated quality have given impetus to automatization and robotization of work processes.

The construction industry is not an exception. Energetic research and development are being carried out by general contractors and machine makers. Automated devices have been created over the years and are actually used in sites.

Such trend is found in the shield-driven tunneling also. But, perfect automatization or robotization has been difficult for this method. Why? Because it involves some works for which automated operation is hard to perform satisfactorily. Erection of segments is a typical example. In this process, the conventional method and manual erector are still used, spending much labor and time.
The segment-erection robot discussed in this paper is an innovative strategy in tunnel construction.

2. Actual State and Problems of the Segment Erection

The shield tunneling machine advances by reaction against the erected segment ring which prevents collapse of ground and forms the primary lining. The ring is constituted of segments conceived to permit easy erection.

Now, consider an example of 6-segment-divided ring (this is for simplifying explanation; the actual ring is divided in 11). The ring is composed of 3 kinds of segment as is shown in Fig.-1. Of the 6 segments, three are standard type (A-segment), two are key-mating type (B-segment) and the remaining one is key-type (K-segment).
The conventional process is illustrated in Fig.-2. Segments lowered through the vertical shaft are transported by a battery locomotive toward the back of the shield machine, and shifted by an electric hoist up to the tail of shield machine. Then, the ring is formed by operating a manual elector. Erection is performed from A-segments. Finally, the key-type segment is mounted.
Such manual steps have been causing problems with respect to manpower, product quality control and work environment, as follows.

1) Problems of manpower
It is difficult to furnish sufficiently skilled labors, because of aging population.
There is a risk of potential error in operation and in signing between workers (a work team is constituted of three to six persons).

2) Problems of quality control
The erection speed and accuracy vary, with the skill of workers, to a significant extent : troubles such as broken edge or crack in segments, misalignment of joints may occur when using unqualified workers.

3) Problems of work environment
In most of shield tunneling sites, works are executed in a hot and humid air, at an elevated and unstable stage.
As segments are heavy (several tons per piece), their handling is in fact very hard.

3. Problems in Automatization of Segment Erection

In makers' shop, the work process is standardized and the environment is well accommodated so that work pieces may be set on a table having accurate flatness of surface. Thanks to such favorable conditions, a robot can be practically used only if it presents a high repeatability. But, with the segment erection, there are more delicate problems. The position and posture of segments being carried in and those of erected segments are changing incessantly in relation to the axis of the robot. Consequently, it is vital, for ensuring good product quality, to detect correctly the changing position and posture by a lot of sensors. As segments have a large weight, precise erection needs high sensing capability as well as highly accurate positioning.
Various problems other than those mentioned above are grouped in external elements and internal elements, and listed in Tables 1 and 2 respectively, where their solutions are given also.

4. Automatic Segment Erection System

This system performs automatically and sequentially a series of actions, that is, "gripping" of segments provided by the automatic segment feeder installed at the back of the robot, "displacement" to a predetermined position and "fixing" at this position. The sensors are installed with high accuracy on the robot and shield machine. These sensors detect exactly the position and posture of provided and erected segments. The data thus detected are subject to processings by computer, i.e., "axis correction calculation," "displacement calculation" and "comparative calculation," for controlling the actuator.

4-1 Basic Actions of Segment Erection Robot

The segment automatic feeder provides segments to under the robot, which will be, by the robot, gripped and fixed with a high accuracy to segments already erected. For allowing this, the robot should be capable of exact positioning in a limited space, as shown in Fig.-3. Three movements, i.e., gyrating, heaving and sliding are available as with the conventional manual erector. In addition, the robot is endowed with three other degrees of freedom, that is, pitching, yawing and rolling. All of these six movements are controlled by computer on the basis of data from the sensors.

These are main characteristics of the basic movements of the robot which is now practically used.

1	Gyrating control	:	θ	+/-220°
2	Heaving control	:	Y	1350 mm
3	Sliding control	:	Z	550 mm
4	Pitching control	:	θ_x	+/-5.5°
5	Yawing control	:	θ_y	+/-5.5°
6	Rolling control	:	θ_z	+/-5.5°
7	Handling weight	:		4300 kg

4-2 Automatic Segment Feeder

Segments are carried by a battery locomotive, etc., from the tunnel entrance to the back of the shield machine. The automatic segment feeder transfers the segments carried in to a position where segments can be gripped by the robot.

For more efficient space utilization, the feeder should be installed at a upper position in the tunnel.
In our system, however, it is installed in a lower position. This layout is based on the arrangement of the conventional method.

The feeder has a double structure composed of
- a slidable frame
- a segment carriage which transfers segments up to under the robot.

This configuration avoids interfering with segment erection works.

4-3 Driving Device

Almost all the actions of the robot are done by means of hydraulic pressure. Segments weigh 4300 kg a piece. Their handling requires actuators of large capacity. Besides this, highly accurate positioning control is essential. We have selected a hydraulic driving device as it satisfies these two requirements.

4-4 Sensor System

The segment-erection robot must be given the capability of detecting with high accuracy the position and posture of segments carried to the shield-machine tail as well as those of segments already erected. As for determining the segment-fastening positions (pin or bolt hole positions), direct detection would ensure the highest accuracy. But, our system applies, considering problems with respect to space and environment, indirect detection which consists in measurement of the inner surface of segment.

Now, we are going to discuss the sensing method of the robot.

(1) Internal sensor system
This system recognizes the position and posture of the robot itself, comprising stroke sensor, rotation detector, etc. which detect the movements listed in 4-1.

(2) External sensor system
This system detects the position of segments provided and that of segments erected, by sensors installed on the robot and shield machine.

(a) Measurement of posture in pitching direction : θ_x
The pitching measurement of the segment erected is executed in this manner:
A plane of the erected ring end is obtained by measuring the stroke of shield jack. On the basis of the plane, is computed the angle in pitching direction of each segment piece at a gyrating angle. The angle is corrected by compensating the error between robot axis and shield-machine axis. The angle corrected is converted into a stroke of pitching-control cylinder, for numerically controlling this cylinder.

(b) Measurement of posture in yawing direction : θ_y
This is done in the same manner as that of pitching, for numerically controlling the yawing-control cylinder.

(c) Measurement of posture in rolling direction : θ_z
By measuring three points (by S3-, S2- and S4-sensors : see Fig.-4) on the inner surface of segments erected, the posture of a segment to be erected is adjusted in rolling direction, and a distortion of the segment ring is computed for controlling to locate the fixing points in an optimum manner.

(d) Measurement of posture of the adjacent segment
The pitching direction of the adjacent segment is measured (on S11 and S13 or S12 and S14 : See Fig.-4), to check and control misalignment of the provided segment positioned by numerical control.

(e) Measurement of the pin hole position
For positioning the segment (A-segment) to be set first in a ring, a reference is marked on the segment already installed. The position of the reference mark is detected by an optical sensor, to do fine correction in the gyrating direction. (See Fig.-5)

(f) Measurement of the segment provided (gripped)
The provided segment is sometimes gripped by the robot in an inaccurate manner. So, its posture is measured (S11 to S14 : See Fig.-4) and fed back to the measurement result of the erected segment.

(3) Detectors
The main detectors used in the robot are :

1 Optical rotary encoder
2 Resolver
3 Differential transformer
4 Pressure detector
5 Optical sensor

Various parameters such as cylinder stroke, distance, angle, position of reference mark, hydraulic pressure are detected by these detectors and inputted into the computer.

4-5 Control method

The robot is, recognizing by the internal sensor system its position and posture, controlled by the computer according to a programmed erection sequence. (For the erection flow, see Fig.-6)

The shield machine on which the robot is mounted advances by reaction against segment rings erected one by one. Accordingly, the movement axes of the robot in relation to the erected segment ring are always changing. In such condition, the position and posture of the erected segments are detected continuously, and, based on detected data, both numerical and adaptive controls are performed. The positioning functions such as posture control should present high accuracy. To satisfy this requirement, the response of actuator and the calculation are speeded up to the possible maximum extent by improvement both in hardware and software, considering that delay in the response or calculation may cause hunting. Besides the speeding up, both feed back control and predicative control are used. The control flow is shown in Fig.-7.

5. Experimental Robot and Practical Robot

In order to find effective solutions of the problems mentioned in the article 3, we fabricated, before a practical application, an experimental robot for conducting various tests in a shop (Photo-1).

The robot was mounted on a shield machine of about 3 m in diameter, for handling segments weighing about 200 kg per piece. The items verified by the test are:

(1) Positioning accuracy
 Y, θ_X, θ_Y, θ_Z; within +/- 0.3 mm
 θ ; +/- 1.5 mm (on the inner surface of segment)
(2) Erection control sequence
 Based on a program prepared by analyzing the action sequence of a skilled worker
(3) Correction of deformed segment ring
(4) Response to inclination of segment
(5) Erection time

Considering that in the actual site heavier segments are handled (4,300 kg/piece), we studied again, in design and fabrication of the practical robot, focusing our attention on the positioning accuracy. The practical robot is applied to the work of Okachimachi tunnel of the Tohoku Shinkansen Line (extension of about 500m from Ueno and Tokyo stations) and is now working there successfully. (Photo-2, Photo-3)

(Specification of the segments used in the work)

1. Type : Reinforced concrete segment
2. Outer diameter : 12,500 mm
3. Thickness : 400 mm
4. Width : 1,100 mm
5. Number of segment pieces constituting a ring : 11
6. Weight : 4,300 kg/piece (max.)
7. Number of segment rings : 444

6. Conclusion

The segment erection robot is proved practicable in the actual use, but its perfection in performance is expected further, with improvements.

Construction industry is behindhand with robotization in comparison with other industries. Its reason is in the fact that robots themselves are complicated structurally, because they have been developed on the basis of conventional working processes exclusively used by workers, but not by robots. As a future solution, the working methods and robots should be studied in their close relationship, and the connection points with other working processes is needed to be examined further for effective application of robots. For this, in the projet-planning stage, a sufficient study as well should be conducted concerning the proceeding and succeeding processes.

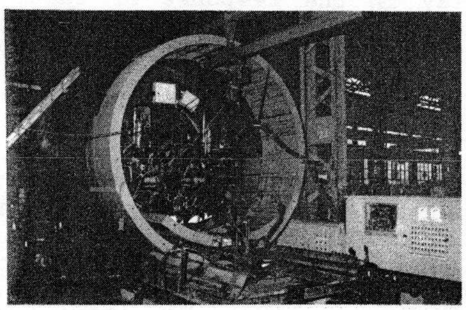

Photo-1 Experimental Equipment

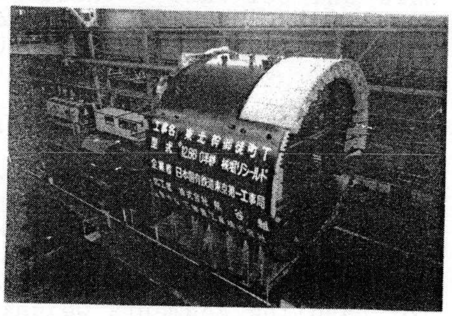

Photo-2

Shield-tunneling Machine on which the Robot is Mounted

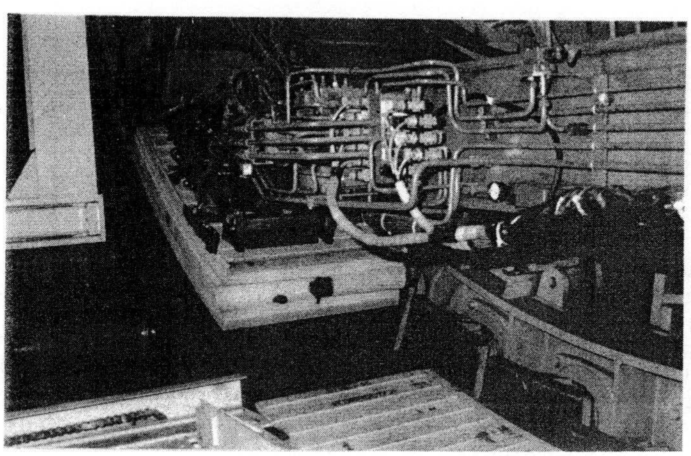

Photo-3

View of Segment Erection

Table-1 Problems and solutions (external elements)

	Problems	Solution
Shield-tunneling machine	Pitching, yawing and rolling	Correction by 3-dimensional posture control and sensing
	The position and posture varies during segment erection also	Correction by continuous sensing
	Inconvenient contact between shield machine and segment ring erected	Use of true-roundness maintaining device
Segment	Different segment forms	Installation of sensors
	Errors in fabrication	Sensing
	Deformation and erection error	Sensing
	Displacement during backfill grouting	Continuous sensing
Conditions of site	Limited space Humidity, dust, soil, vibration	Use of small actuator Enclosed construction and anti-vibration structure

Table-2 Problems and solutions (internal elements)

	Problems	Solutions
Construction of the robot	Handling of heavy works Interference between segment-segment Requirement for high accuracy of positioning	Hydraulic driving Providing a damping function Adaptive control and feedback control
Driving device	Handling of heavy works Requirement for highly accurate positioning Flexibility required Limited work place	Hydraulic driving Special hydraulic control Pressure relief in hydraulic circuit Hydraulic system
Sensing system	Requirement for highly accurate detection Adverse environment Many detection points Objects to be detected changes in position continuously	By rotary encoder Enclosed type Sensors well arranged By continuous sensing
Transport equipment	Limited work space Misalignment in relation to the robot axis	Use of compact equipment Compensation by sensing

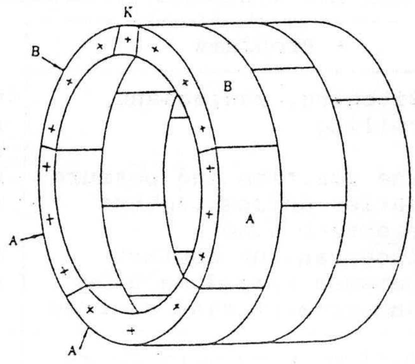

Fig.-1 Configuration of segments

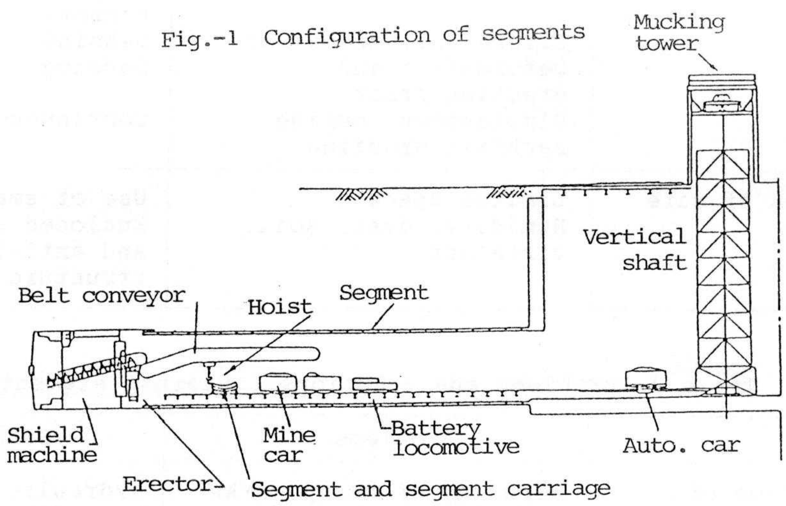

Fig.-2 Tunneling by Shield Method

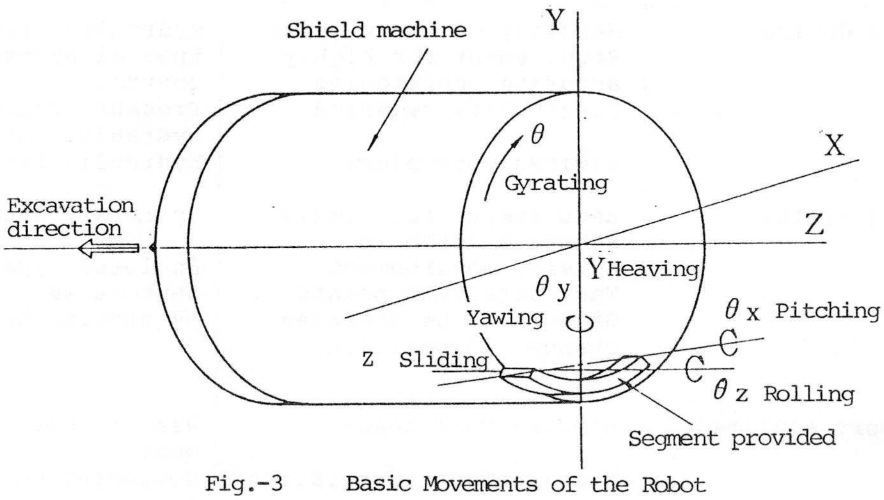

Fig.-3 Basic Movements of the Robot

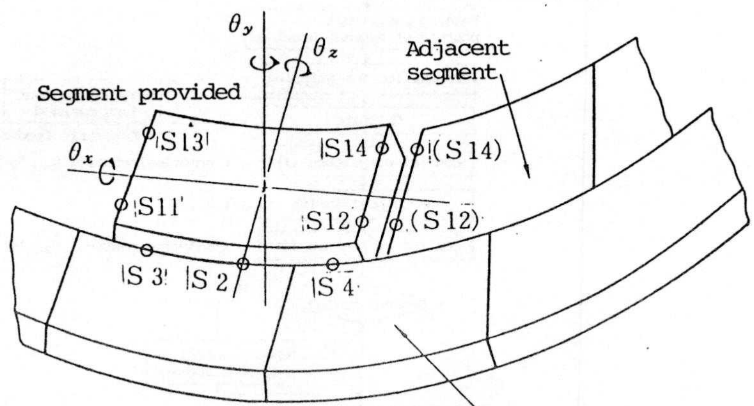

Fig.-4 Measurement of Position and Posture

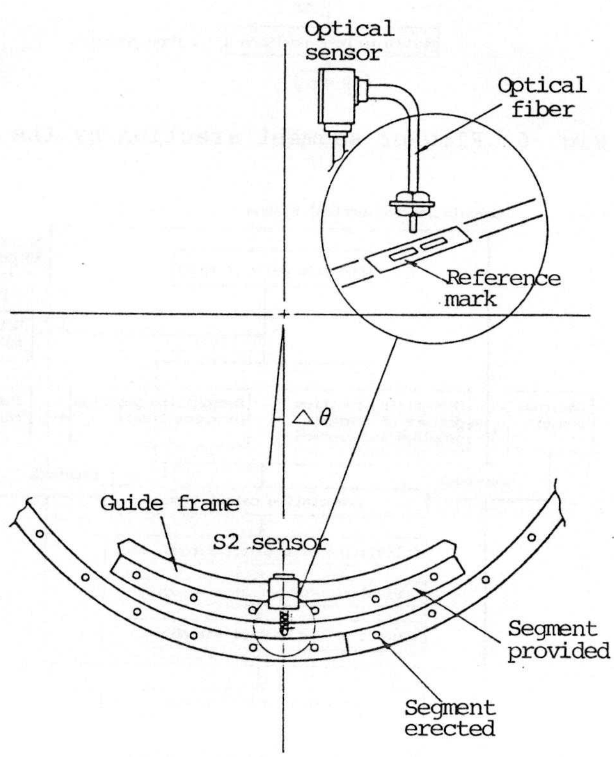

Fig.-5 Measurement of Pin Position

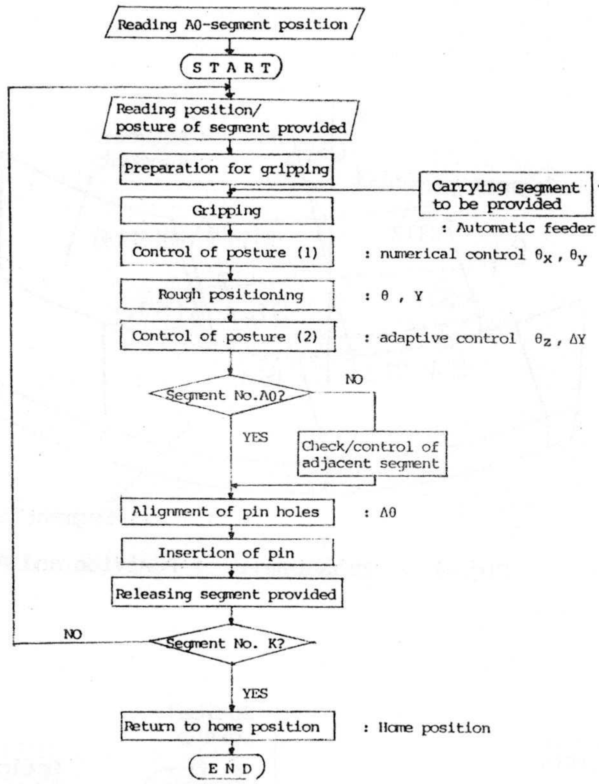

Fig.-6 Flow of segment erection by the robot

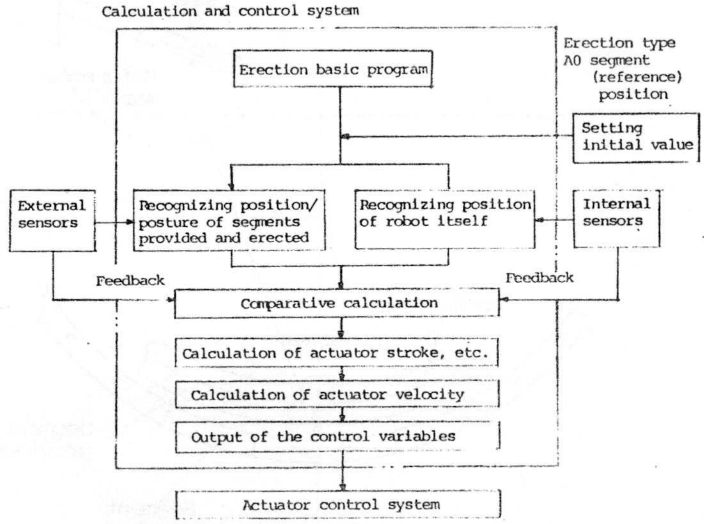

Fig.-7 Control flow