G.H. Watson, R.L. Tucker and J.K. Walters (Editors)

Development of Segment Bolt Tightening Robot

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Abstract

(1) We have developed a manipulator for handling large, heavy objects for construction work, and applied it to bolt tightening work for shielded tunnel segments.
(2) The manipulator is vertical multi-articulated type, with 6 axis of freedom, and a handling capacity of 500kgf by a 2.5m long arm.
(3) The robot equipped two set of manipulator with bolt tightener. 120 bolts (ø30mm) of one segment ring which is 11.3m in diameter will be tighten by this robot in one hour.
(4) The manipulator performs positioning automatically, by recognizing the position of each bolts with an image sensor mounted at the top of its arm.

1. Introduction

In Japan, there is very active utilization of underground space, so the shielded tunneling method is indispensable to the development of social infrastructure. In recent years, construction projects have become increasingly large scale, and demand for automation and greater sophistication has increased due to the need to ensure safety, improve quality and achieve labor-savings etc.

For these reasons, automation has become a fixture of tunneling work, and active attempts are currently being made to automate tunneling direction control, and provide automation for tunnel lining work including the segment assembly. Other than this, however, no attempts are being made to automate incidental work.

We have developed a large-scale, heavy object manipulator to automatic these incidental tasks, and have applied it to automation of segment bolt tightening work. This paper reports mainly on the development of a tightening robot for segments which outer diameter 11.3m.

2. Current state of automation for the shielded tunneling method

In the shielded tunneling method, the primary tasks are excavation and lining work like segment assembly. On the other hand, there are various types of incidental work, like material transport, rail laying and segment bolt tightening after assembly. Much of this work involves repetition of simple tasks, and progress is being made with automation in many areas. Fig. 1 gives a flowchart of the main types of work in the shielded tunneling method, and Table 1 shows the results of a survey concerning the current state of automation for each type of work.

As you can see from Table 1 , automation is being actively employed in excavation, segment assembly and material transport, but automation is still lacking for incidental work like tie and rail laying and segment bolt tightening.

The main reason for this is that incident work has low importance and is difficult to automate due to its complexity. However, the final goal is a work system involving only a minimal number of maintenance personnel (2-3 persons), so automating these incidental works is an important topic for study and development.

As a common element for automating these incident works, we have developed a large and heavy object handling manipulator, and have applied it to segment bolt tightening work.

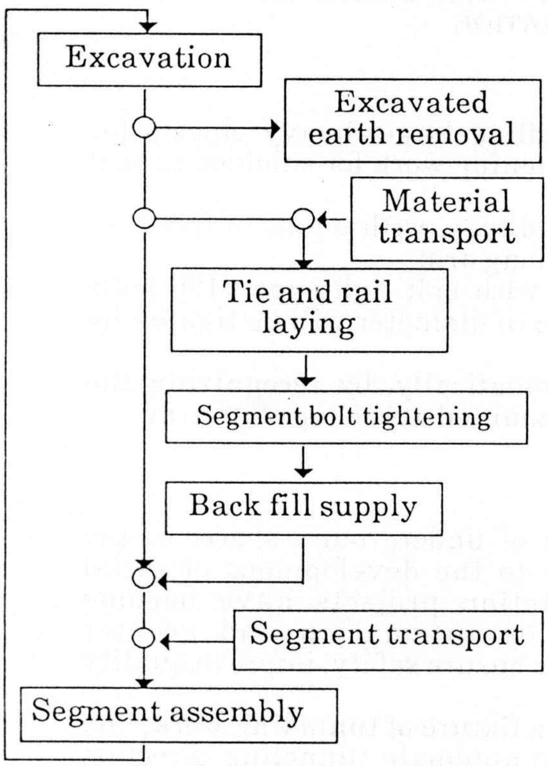

Fig. 1. Shielded tunneling method work flowchart

Table 1. Current state of automation

	Implemented	Under development	Not planned
Excavation	○		
Tunneling direction control	○		
Excavating ground control	○		
Segment assembly	○		
Segment bolt tightening		○	
Material transport	○		
Tie and rail laying			○
pipe extension	○		
wire extension			○

3. Structure of segment bolt tightening robot

Fig. 2 shows the overall mechanism of the segment bolt tightening robot. The robot support cart can travel on the rails and two manipulators installed on the lifting lowering masts which fixed on the both side of the support cart. The bolt tightener is set at the top of the manipulator arm. The sensors at the tip of the manipulators recognize bolts to enable tightening. The robot automates the entire process, from bolt detection to positioning and bolt tightening.

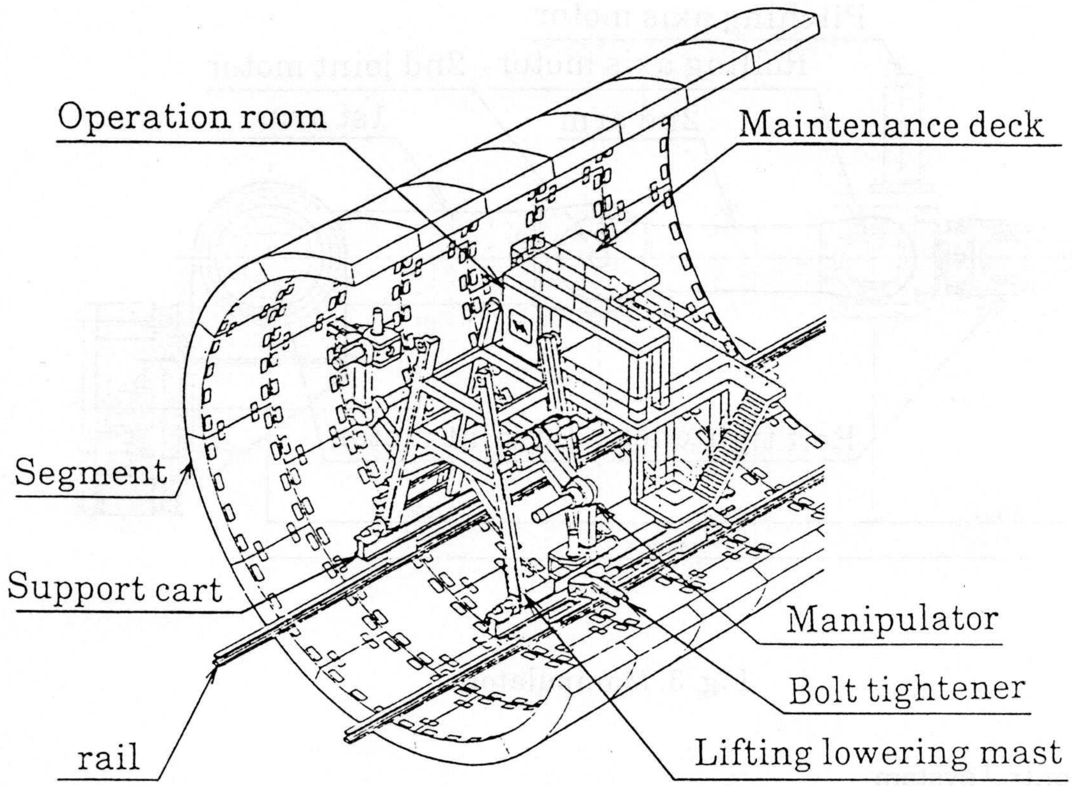

Fig. 2. Segment bolt Tightening Robot

3.1 Support cart

The support cart is the robot's base frame, and is equipped with manipulators.

The cart propels itself through the tunnel, up to the segment tightening position which is the current work point. The support cart has lifting-lowering masts on both sides to raise and lower the manipulator, and an operation room and maintenance deck.

3.2 Manipulators

Fig. 3 shows the manipulators which form the core of this robot. Each manipulator has 6 joints and 6 degrees of freedom, so the basic structure is the same as an industrial robot. Each joint has a high torque servo motor designed for construction with large, heavy objects. In particular, large special-purpose motors are not used to drive the 1st arm (which requires the most torque). Instead, a synchronous operation using 2 servo-motors is employed in order to lower costs and increase the handling load capacity.

A bolt tightener (composed of a gripper which holds the bolt, and a nut runner which turns the nut) and a bolt sensor which detects the bolt position are installed at the tip of the manipulator.

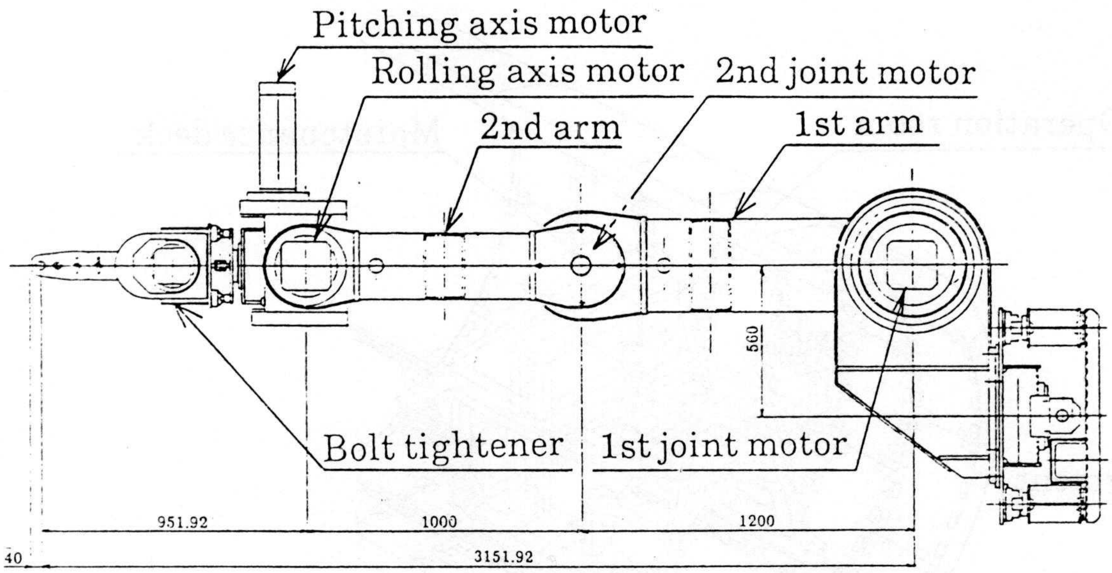

Fig. 3. Manipulator

3.3 Control system

The control system is composed of sensors arranged at various parts of the robots, controllers which control each of the actuators, and a monitoring system which manages and displays data relating to sensors and controllers. Fig. 4 shows the control system block diagram. The top-level preside controller, servo controllers for actuator sensors and other devices are connected by communication lines. Fig. 5 shows the bolt tightening operation flowchart.

The flow of bolt tightening operation is as follows :

(1) The support cart advances by 1 ring, and moves to the segment position to be tightened next. → Support cart advance

(2) The manipulator is moved to near the bolt coordinates through pre-programmed sequential numerical control. → Rough positioning

(3) The bolt-box is detected by a television camera, and the center of the box is found through image processing. Then the bolt tightener is inserted. → Bolt box sensing

(4) A bolt is detected in the bolt box by an ultrasonic sensor, and the bolt is grasped by the gripper. → Bolt sensing

(5) Tightener is performed by a nut runner.

(6) The manipulator returns to rough positioning.

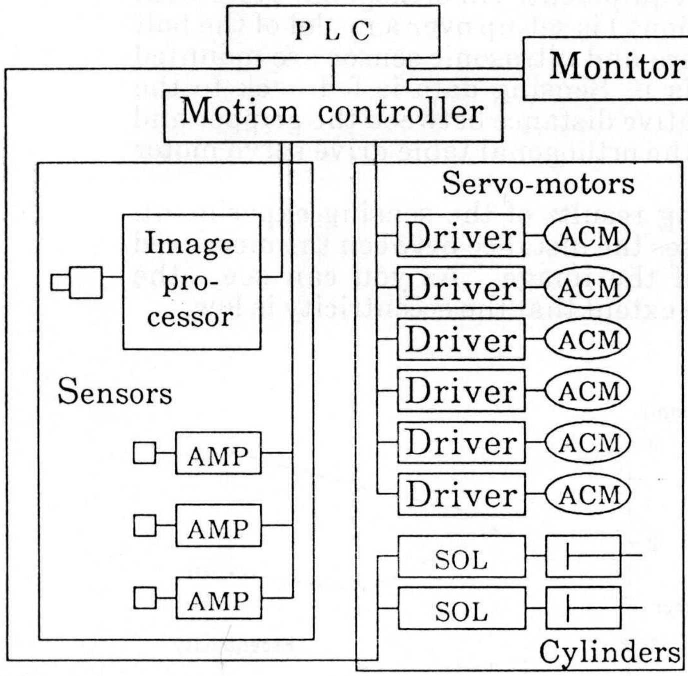

Fig. 4. Control block diagram

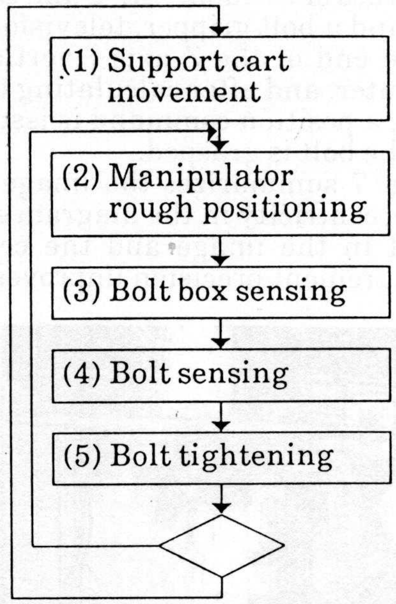

Fig. 5. Fastening operation flowchart

4. Bolt tightening robot performance confirmation

Critical points in the development of this robot were a sensing system for detecting bolts, and a manipulator capable of supporting the weight of the bolt tightener and the tightening reactive force, and performing high precision positioning.

Therefore in 1991 we tested the sensing elements, and in 1992 we confirmed performance of the manipulator through experiments using the actual equipment. At present we are conducting validation tests of function as the bolt tightening robot at our factory.

4.1 Bolt sensing experiments

The bolt sensing described above is composed of two stages. First rough positioning is performed through sequence control so that the box is captured on the television screen. The center of the box is extracted from the television image in primary sensing for bolt tightener insertion. Then a bolt in the box is detected using an ultrasonic sensor in secondary sensing so the gripper can grasp the bolt.

Fig. 6 shows the sensing experiment equipment. An orthogonal table with 3 degrees of freedom (X, Y and Z directions) is set-up over a model of the bolt box, and a bolt gripper, television camera and ultrasonic sensor are mounted at the end of the Z-axis (vertical axis). Sensing data is fed back to the computer, and after calculating the relative distance between the gripper and work, a position command is issued to the orthogonal table drive servo motor and the bolt is grasped.

Fig. 7 summarizes the image sensing results of the sensing experiment. The eccentricity in the diagram expresses the distance between the measured object in the image and the center of the image. As you can see, the measurement precision improves to the extent that the eccentricity is low.

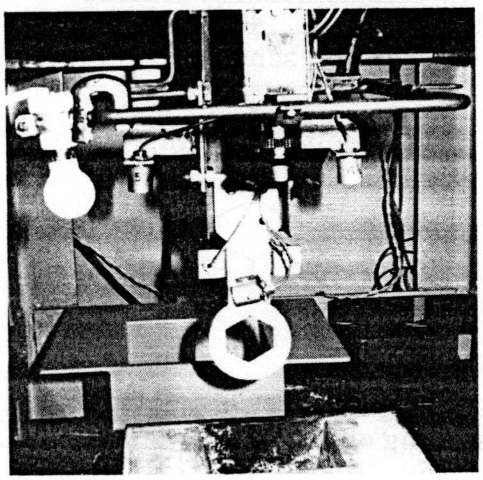

Fig. 6. Sensing experiment equipment

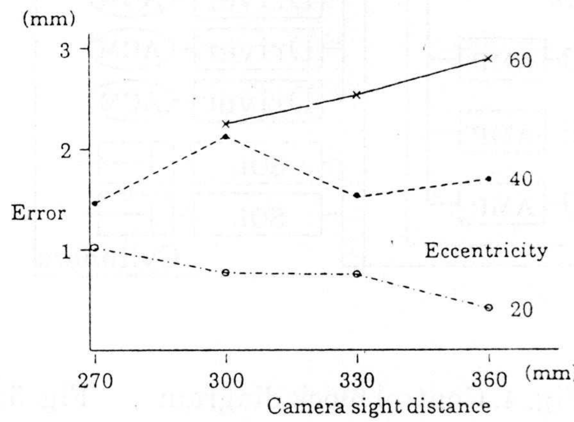

Fig. 7. Image sensing result

4.2 Actual manipulator experiments

Experiments concerning static and dynamic characteristics were conducted using 3-joint manipulator with the same specifications as the actual manipulator. The scene of the experiment is shown in Fig. 8. This picture shows the manipulator and measuring equipment used in the experiment.

The main parts of the experiment and their results are shown in Table 5. Even though the manipulator is designed for heavy objects, experiments confirmed that the system has high precision (with a positioning repeatability of ± 0.1mm) and performance greatly exceeding design specifications regrading the maximum permissible loading capacity.

In tests of dynamic characteristics it was found that residual vibration of the arm tip can be suppressed by appropriately controlling the arm speed pattern, and the system has satisfactory characteristics for use in heavy load handling.

In addition to experimental confirmation, the system was analyzed (including the robot mechanism and servo control system) using CAE(computer aided engineering) technology to ensure optimal design. As examples of robot arm motion simulation by computer, Fig. 9 shows an animation of step response, and Fig. 10 shows response of the arm tip at this time.

Table 2. Experiment Result

	Item	Main Result
1	Arm vibration characteristic	Natural frequency 4.3 Hz Residual vibration 0.5mm
2	Positional repeatability	Within +/– 0.1mm
3	Maximum permissible load capacity	Max. 970kgf, 18.8 sec.
4	Interpolation precision	Deviation 1.1mm (Arc interpolation)

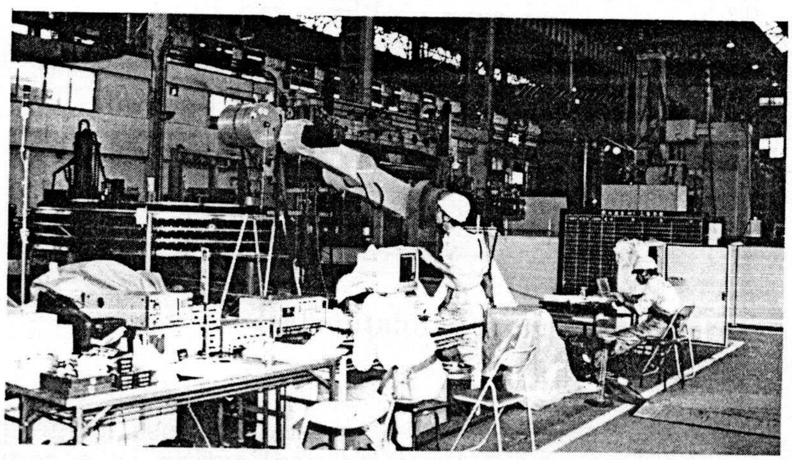

Fig. 8. Manipulator experimental set-up

4.3 Bolt tightening validation test

The validation test of robot shall be conducted until the middle of May,and after data analysis and evaluation,we plan to start on-site operation in October of this year.

Prior to operation of the robot at the site, bolt tightening validation testing is conducted at the factory using actual segments in order to determine adjustment of the final model and applicability to the site, and to certify software etc.

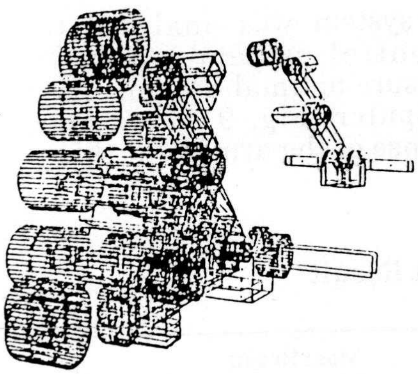

Fig. 9. Animation of step response

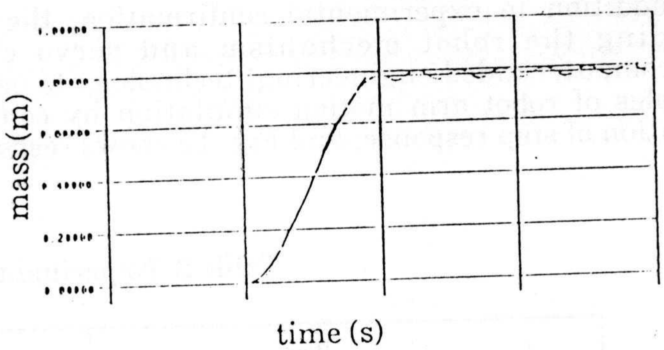

Fig. 10. Response at step input

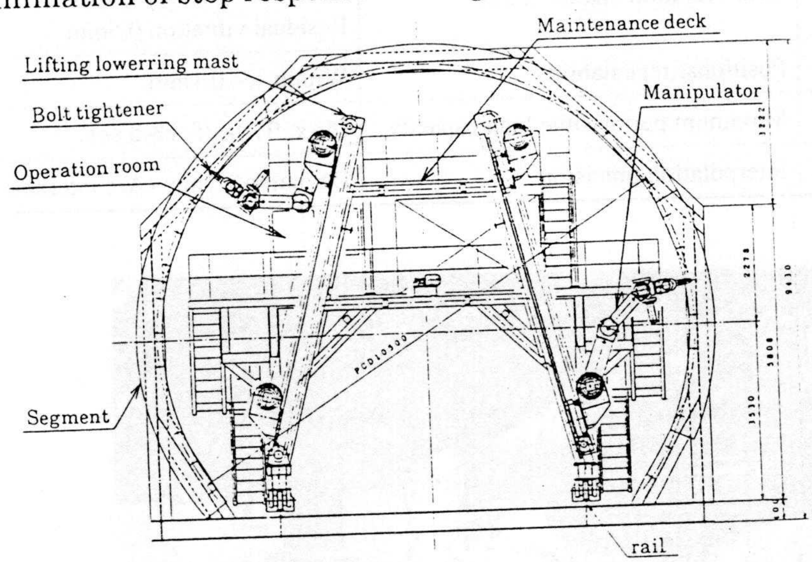

Fig. 11. In-factory validation test

5. Conclusion

This paper has described development of a general-purpose, large, high-precision manipulator, and an example of its application in a segment tightening robot.

Automation and labor-saving will continue to be critical topics at construction sites, and this general-purpose robot can play an effective role in the field. The following are the conditions which distinguish construction robots from industrial robots :

(1) Applicability to highly diverse types of workpieces
(2) Handing of large, heavy objects
(3) Self-propulsion

In the future we aim to contribute to development of automation for the construction site by striving to develop practical construction robots meeting the above needs.