Automation and Robotics in Construction X
G.H. Watson, R.L. Tucker and J.K. Walters (Editors)

Self-Supported Segment Assembly Robot for the Shield Tunneling Method

Keizo Kazama[a], Hisateru Ueda[a], Akihiro Higashide[a] and Yoshimitsu Kumao[b]

[a]OBAYASHI CORPORATION, 2-3, Kandatsukasa-cho, Chiyoda-ku, Tokyo 101, Japan

[b]MITSUBISHI HEAVY INDUSTRIES, LTD., Kobe Shipyard & Engine Works, 1-1-1, Wadasaki-Cho, Hyogo-ku, Kobe 652, Japan

Abstract

The self-supported segment assembly robot, [O-SERO]*, has been developed through several fundamental experiments and a series of assembly tests in the factory, then applied to a real project. 70 no.s of segment ring (inside diameter: 6.0 meters) were assembled in the tunnel. The assembly process is full automatically done by this robot instead of skilled workers. One of distinctive features is that the self-supported robot is independent from a shield machine while usual assembly equipments are supported from shield machines. The robot is supported from the inside of a primary lining (assembled segment rings) and its attitude follows the attitude of a primary lining. The paper is intended to present 1) the features of the self-supported segment assembly robot and its control system 2) the structure and mechanism of the robot 3) the results of the assembly tests and application to the real project.
(*O-SERO ; Obayashi - Segment Erection RObot)

1.CIRCUMSTANCES AND TARGETS OF DEVELOPMENT

In the conventional method, as a primary lining, several pieces of segments are manually assembled and bolted up by skilled workers with a erector equipment inside tail of a shield machine. However, the automation system for this assembly work has been expected to be developed to resolve the following problems; 1) the workability and the quality have been poor because of the shortage of skilled workers. 2) it is dangerous to assemble segments on a high deck within a limited space. 3) the required torque for bolt-up is quite big in case of a large diameter tunnel and it's impossible to manually bolt up segments. Several automation systems have been reported to be developed, however, the assembly time by a robot was more than twice as it by workers. And also, the development cost and production cost were suspected to be very expensive. Therefore, it was considered that these systems could not be practically applied to a project.

Before the development started, we decided the following three points as the targets considering the defects of other pre-developed assembly systems:

① The assembly time should be shortened so far as it by skilled workers.
② The robot should have such a structure that enables itself to be reusable for more than one project.
③ Some parts of the assembly process by skilled workers should be introduced to it by the robot.

With regard to the first target, the robot is difficult to be applied to a project if the assembly time is comparatively longer than it by the conventional method because the assembling segments is a critical work for a shield project.

About the second target, it is poor economy to full depreciate an assembly robot for just one project because it costs quite expensive. From this point of view, in order to encourage the possibility of re-use, the segments for the system are determined to be the most widely used type in Japan even though this type may not be suitable for the automation.

In point of the third target, it is considered that there are two alternatives to design an automatic system for such an assembly job. One way is that the automatic process is designed to simulate the assembly process by skilled workers. The other is that it is designed without employing any know-how of skilled workers. Most of the pre-developed systems was designed on the basis of the second way. For example, a segment piece was positioned in order to align all of its bolt holes to their counterparts at the same time. The positioning mechanism of the robot has six degrees of freedom, so the process for positioning should become quite complex and require long time. Therefore, we have attempted to simulate the assembly process by skilled workers to make the positioning control simple.

2.OUTLINE OF ASSEMBLY SYSTEM

The Figure 1. shows the sketch of the robot in a shield tunnel. One of the reasons why the self-supported type is selected is that this type of structure enables itself to be reused for another project with minimum modification. Another reason is that during the assembly process, the relative positions and attitudes between the robot and the primary lining can be kept constant unlike an ordinary erector equipment. So, once the rotation plane of the robot is adjusted and locked before the assembly starts, two of six freedoms, pitching and yawing, need not to be controlled again until the assembly of one ring is finished.

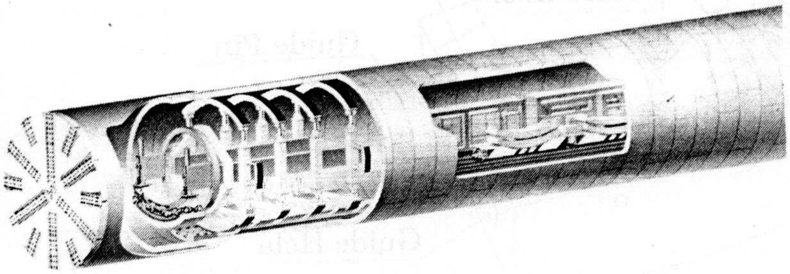

Figure 1. Sketch of Self-Supported Segment Assembly Robot in Tunnel

2.1.Elector Equipment

The elector equipment includes the mechanisms to grip a segment piece, to position it, to bolt it up, and to adjust the rotation plane.

The mechanism for griping a segment piece is shown in Figure 2. The gripping device is buried in the segment piece, and the robot inserts its gripping hook into the gripping device and rotate it. Then, the gripping hook is pulled up until the segment piece is gripped tightly. The relative position is adjusted by inserting guide pins into guide holes on the surface of the segment.

The positioning mechanism has six degrees of freedom, and controls the position and attitude of the segment piece by means of hydraulic actuators.

The bolt-up device, totally 13 no.s equipped, are arranged for respective bolt boxes of three types of segment pieces. This device positions a set of hexagon-headed bolt and nut, fed in advance, to the center of a bolt hole, inserts the bolt, and then tightens them.

The mechanism for adjusting the rotation plane consists of a pitching and a yawing frame. The pitching frame is supported from main beams of the self - support equipment, the yawing frame is supported from the pitching frame through pin connections and the bearing for rotation is installed in the yawing frame. The rotation plane is adjusted to be parallel with the last assembled segment ring by controlling the attitudes of both frames.

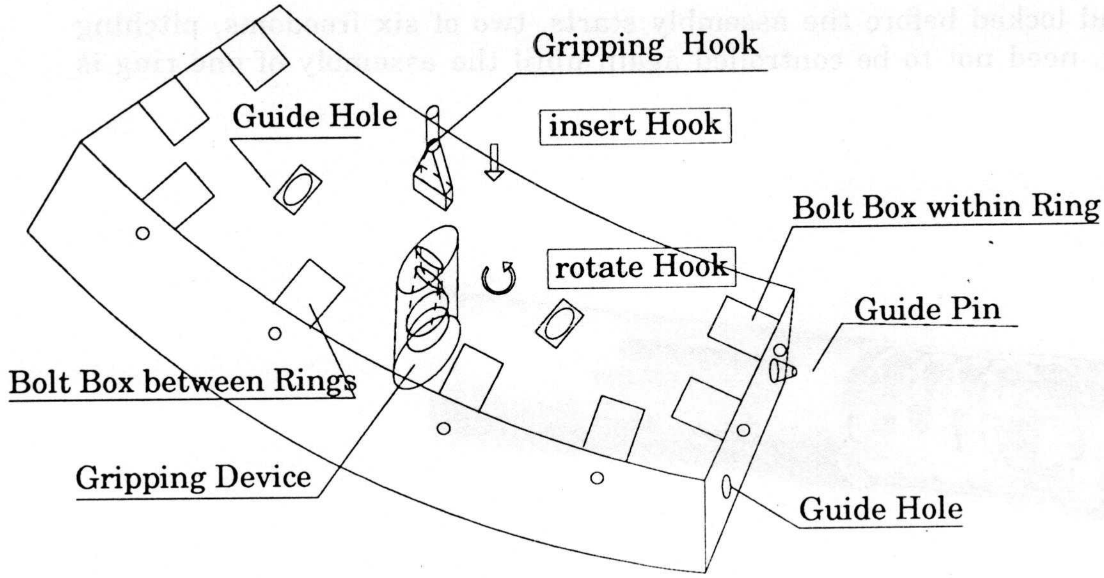

Figure 2. Sketch of Gripping Mechanism

2.2. Segment Feeder

The segment feeder is a conveyor suspended from the main beams. It stocks six pieces of the segments, feeds the foremost segment piece to the gripping position of the erector equipment and transport segments forward by one piece length at each time. And also, the position and attitude of the foremost segment is adjusted to be constant before it is fed to the erector equipment.

2.3. Self-Support Equipment

The self-support equipment consists of main beams, four sets of supporting frames including upper supporting arches and lower supporting shoes and a transportation mechanism. During the assembly process, the main beams are supported by the foremost and aftermost supporting frames. When the robot is transported forward, it is supported by middle two supporting frames through four sets of rollers and is slid by a transportation mechanism.

2.4. Specifications

The specifications of the assembly robot and the segment is described in the Table 1. The front view of [O-SERO] in the factory is shown in Figure 3. When it is employed in a tunnel, it is located behind a shield machine.

Table 1.
Specifications

[O-SERO]		Segment	
Dimensions	H=6m * L=7m	Type	RC
Weight	70 ton	Dimensions	O.D.=6.5m, W=0.9m
Lift-Up Force	23 tonf	No. of Divisions	7 (A*4+B*2+K)
Bolt-Up Force	30 kgf*m	Max. Weight	2 ton
No. of Bolt-Up Devices	13	No. of Bolts	39 pieces/ring

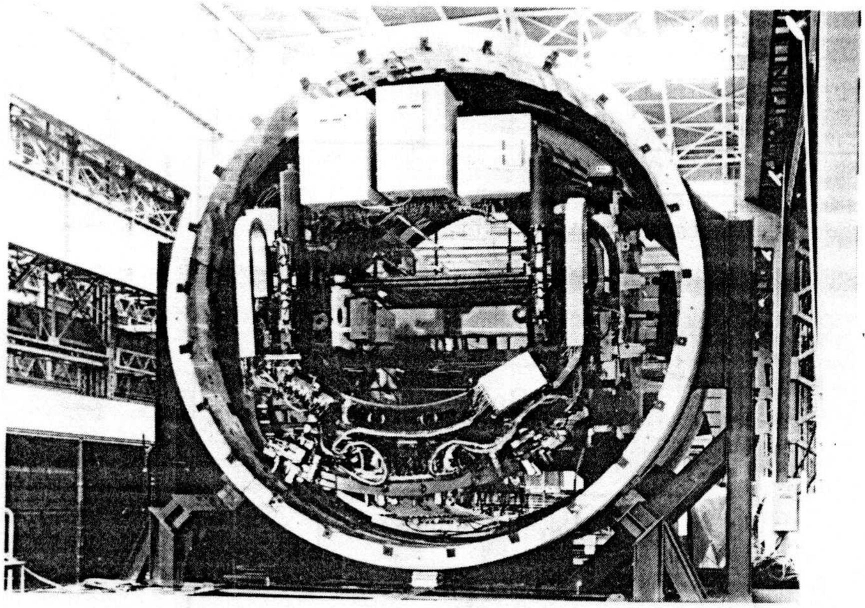

Figure 3. Front View of [O-SERO]

3. FLOW CHART OF ASSEMBLY PROCESS

The flow chart of the assembly process is shown in Figure 4.

"Pre-Sensing" is carried out only once before the assembly of the segments starts. It detects the data to analyze and to calculate 1) the relative attitude and position between the rotation plane of the robot and the the last assembled segment ring 2) the cross-section of the last assembled segment ring.

"Primary Positioning" is to bring the gripped segment piece in the adjacent position with pre-assembled segment pieces by the numerical control until the sensing devices can detect their surface.

"Fine Positioning" is to precisely align the segment by detecting its relative attitude and position with the adjoining segments. Then, the segment is rotated against the adjoining pre-assembled piece of the same ring so as to force the gripped segment to copy the attitude and position of the adjoining segment because a guide mechanism is installed between them (see Figure 2.).

Next, only the joint of two pieces of segments within a ring are bolted up first, then the relative position between the rings is detected again and adjusted by controlling only the movement in the radial direction. Finally, the joint between the rings are bolted up.

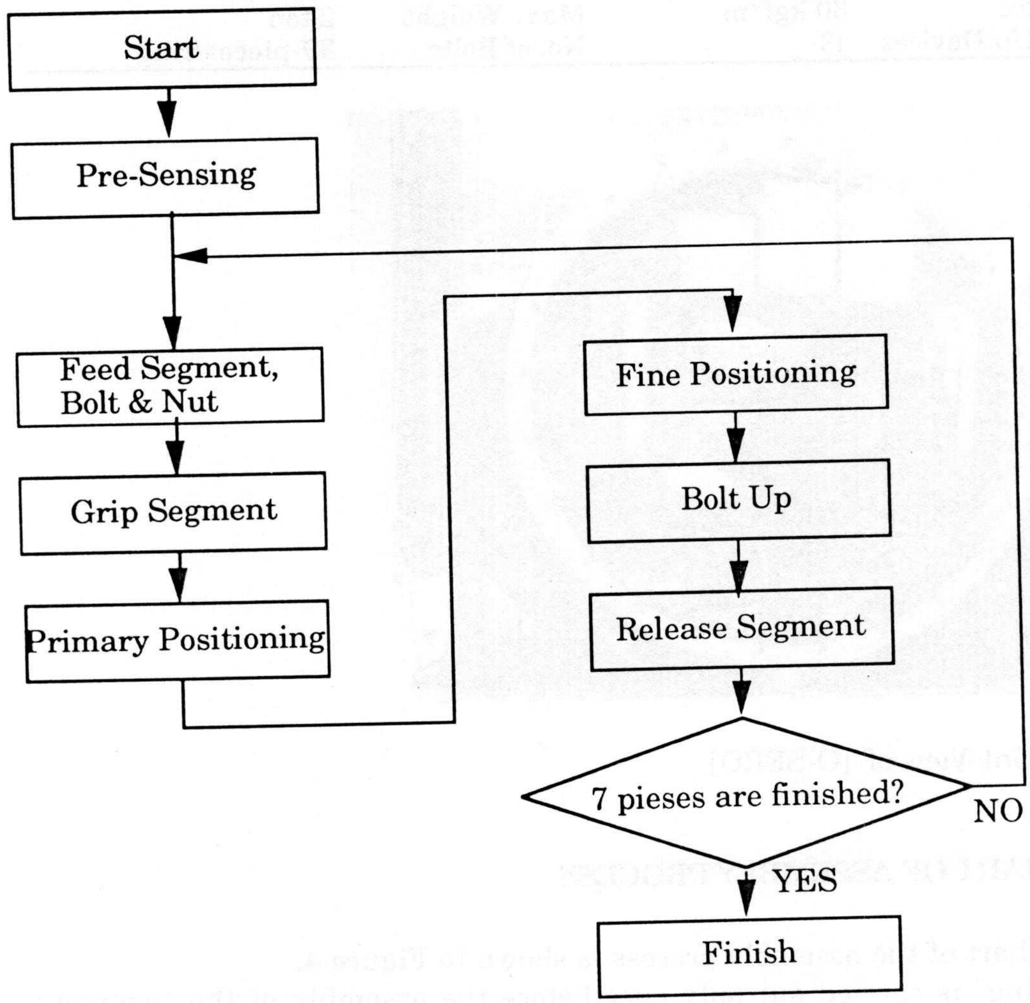

Figure 4. Flow Chart of Assembly Process

4. CIRCULAR CONTROL SYSTEM

The system, integrated with the artificial intelligence, is to analyse the cross-sectional shape of the segment ring and to control it to be a circle. The cross-section of the segment ring is designed to be a circle, however, the shape of the primary lining is transformed to some extent similar in shape to the transverse cross section of an egg because the unsymmetrical external force, such as earth pressure and back-filling grouting pressure, works on the tunnel. The cross-sectional shape of the last assembled segment ring greatly affects the automatic assembly process because a segment piece is assembled on the basis of it. If the shape is transformed so far as a certain degree, it should be impossible to assemble segments automatically.

The host computer, connected with the master controller of the robot through the Ether Network, calculates the cross-sectional shape of the previous ring by analysing the data collected during pre-sensing process, then it determines the compensatory values for each segment and transmits the values to the master controller. The robot assembles the segments by using these compensatory values, and the shape of the assembled ring becomes slightly different from it of the previous ring. After the next excavation, the host computer examines the shape of the segment ring again, which was assembled considering the compensatory values, then it studies how the compensatory values were effective to cause the ring to become close to a circle. The results of the study were accumulated and utilized when it determines new compensatory values.

5.RESULTS OF ASSEMBLY TEST AND FIELD TRIAL

5.1. Assembly Test in Factory

The assembly test was conducted in the factory for six months. The first three months was spent to confirm that the functions worked properly and performances were achieved as designed. During the next three months, the automatic processes were revised to shorten the assembly time and the circular control system was developed by way of trial.

Finally, the assembly time per piece became six to seven minutes on average, and the accumulated assembly time per ring took 40 to 50 minutes. This assembly time is almost equal to it by skilled workers.

5.2. Field Trial

From the beginning of October, 1992, the field trial of the assembly system was conducted for about one month, and 70 No.s of segment rings were automatically assembled in the tunnel.

One of the main purposes of the field trial was to examine the effectiveness of the circular control system. The max. deviation of the inside diameter of the first segment ring was more than 20 mm obtained from the recursive solution calculated by the circular control system (the inside diameter of the segment ring could not be directly measured because of the obstruction of the screw conveyor of the shield machine). In this case, it was quite difficult to automatically align all of the bolt holes of a segment piece to their counterparts. The deviation were reduced to less than 10 mm after about ten rings were assembled while modifying their cross-sectional shapes by the circular control system. Then, the automatic process was smoothly proceeded and the assembly time became almost the same as it of the assembly test in the factory. The shape of the segment rings had been properly controlled to the end of the trial with the deviation of around 10 mm.

Another main purpose was to examine the durability and the reliability of the system under the sever conditions in the tunnel. In the first ten days, the automatic assembly was sometimes interrupted by the failures of electric devices. It was considered that the humidity in the tunnel was higher than expected. This kind of troubles was resolved by improving the waterproof ability of electric devices, and any critical troubles except this did not occur during the field trial.

6.CONCLUSION

Compared with other automatic assembly systems, [O-SERO] has various kinds of characteristics due to not only its self-supported mechanism but also its unique assembly processes to which the know-how of skilled workers are introduced. Through the field trial, it was confirmed that this automation system satisfied the targets of the development and indicated the high reliability.