Development of Automatic Segment Assembly Robot for Shield Tunneling Machine

Yukihisa Hirasawa, Hisayoshi Hashimoto, Yasuo Mori
Takami Kusaki, and Takeshi Kamei

Hitachi Construction Machinery Co., Ltd.
650, Kandatsu-machi, Tsuchiura-shi, Ibaraki-ken, 300 Japan

Abstract

The automatic segment assembly robot has been adopted on a shield machine used in a subway construction project for a 600-m tunnel construction. The robot was implemented successfully and operated throughout the project without having any practical problems concerning assembly accuracy or the time required for segment assembly. Moreover, the robot was further improved by shortening the time required for segment assembly and by improving component performance. For example, the performance of the vision sensor used for segment positioning was improved.

1. Introduction

Providing better work environments and achieving labor-saving have become indispensable requirement in today's construction work sites. The operation of control systems for shield machines, such as excavation, soil discharge, and tunnel face support control, has already been automated to a great extent, thus achieving labor saving. However, the automation for the support facilities, such as material transportation and segment erection work, has lagged behind.

In segment erection work, heavy objects have to be erected in high locations, involving increased work and potential hazards. For this reason, labor-saving automation has long been awaited for segment erection work so as to secure safety, to reduce hard manual labor, and to improve work accuracy.

To solve these problems, we have developed an automatic segment assembly robot. The robot has already been adopted on a shield machine used for a subway construction.

The results are included in this report along with the outline of the automatic segment assembly robot. Also included in this report are our new targets to further improve the robot and the actions taken to realize these targets.

2. Outline of Automatic Segment Assembly Robot

2.1 Target Specifications and Physical Constituent Elements

The segments used with this robot are the reinforced-concrete (RC) core type segments. The largest of the segments weighs 4.8 tons. The outer diameter, inner diameter, and the width of the segment are 9500 mm, 8440 mm, and 1200 mm, respectively. Our target specifications of the automatic segment assembly robot, which is to handle the above segments, were as follows:

1) Positioning Accuracy: ± 1 mm per segment
2) Assembly Time: 80 Minutes per ring (10 minutes per segment on average)

The automatic segment assembly robot is a remote-control-combined type and consists of a yawing and pitching ring, erector, segment supply device, and transfer hoist. With this robot, segments are supplied, clamped, raised, and first roughly and then precisely positioned. All is done automatically.

2.2 System Construction

The erector is secured to the shield machine body via the yawing and pitching ring. The yawing and pitching ring is a device to position the slewing surface of the erector nearly parallel to the surface of the previously assembled ring. The erector has seven degrees of freedom: three in translation (x, y, z), three in rotation (rolling: θx; pitching: θy; yawing: θz), and one in slewing (θs). The segment supply device receives a segment from the segment transfer hoist and places the segment in position under the erector. (See Fig. 1.)

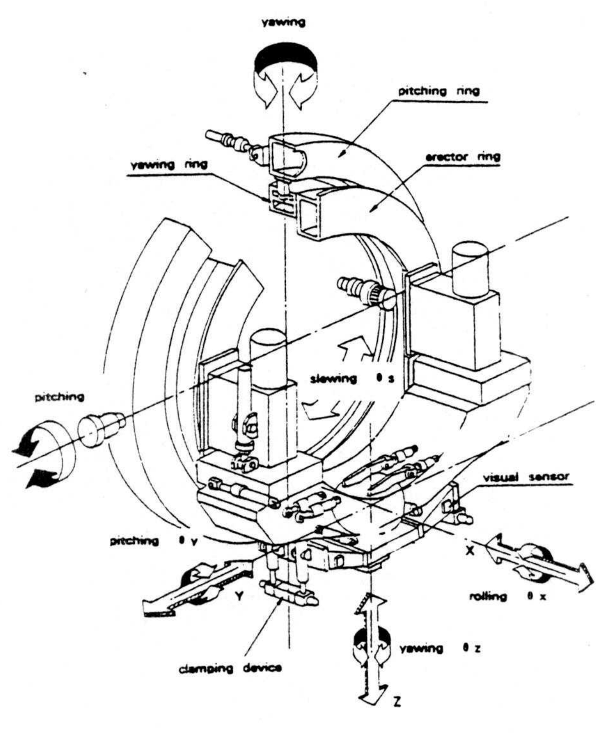

Fig. 1 Construction of Erector

The operating range and maximum velocity of the erector are shown in Table 1. Also, the specifications of the sensors are shown in Table 2.

Table 1 Range and Velocity of Actuators

	Range	Velocity(Max)
X-axis	200 mm	40 mm/s
Y-axis	200 mm	40 mm/s
Z-axis	1200 mm	40 mm/s
Rolling	± 1.5 deg	0.41 deg/s
Yawing	± 1.5 deg	0.41 deg/s
Pitching	± 1.5 deg	0.60 deg/s
Slewing	± 200 deg	0.6 rpm

Table 2 Specification of Sensors

Angle sensor (Slewing Motor)	Absolute encoder $1.28*10^{-4}$ rad/pulse
Stroke sensor (Cylinders)	6.3 μm/pulse
Vision sensor	Laser light: λ=810nm, 50mW Camera: 40*40mm, 0.1mm/pixel

2.3 Automatic Segment Assembly Procedure

The flow of the automatic segment assembly procedure is explained below:

1) Segment Supply: Segments brought by the transfer hoist are supplied and positioned under the erector by the segment supply device.
2) Segment Clamping: After inserting fittings into the bolt holes of the segment, the clamping device up-own cylinders lift and secure the segment.
3) Rough Positioning: Using previously calculated design data for segment positions, target positions are calculated, and segments are positioned approximately 200 mm away from the target positions.
4) Fine Positioning: Using the vision-sensor-used light-section method, three segment end-meeting areas are sensed to detect gaps and level differences. The main computer computes deviations to be compensated, for both position (Δx, Δy, Δz) and pose ($\Delta\theta$x, $\Delta\theta$y, $\Delta\theta$z), using the sensed gaps and level differences. Then the computer operates the actuators to align two sides of the segment. In this compensation stage, only six degrees of freedom are controlled. The slewing is left uncontrolled.
5) Bolt Tightening: Bolts are inserted and tightened manually.

2.4 Operation Method

The operator commences segment assembly by pushing the "OK" key on the automatic control switch box in response to instructions on the work-process display (status panel) while confirming the actual assembly process visually. Should the result of automatic fine positioning be unsatisfactory, the operator can correct positioning errors by temporarily switching to the manual-remote control switch box to control each degree of freedom for the erector using normal (fast and slow) speed mode or inching speed mode.

3. Results

The automatic segment assembly robot was used extensively throughout a 600-m tunnel construction project involved in all 508 rings.

3.1 Segment Positioning Accuracy

Figure 2 shows the position errors after fine positioning in the actual tunnel construction site. The X-axis gap was 2.5 mm, which is equal to the predetermined target value. (The existence of the segment seal was considered when determining the target value for the X-axis gap.) All axis displacement converged to less than 1 mm of the target values after two trials of compensation in this sample case. Bolt insertion was achieved smoothly, and the segment was assembled easily. Moreover, no manual compensation using the manual-remote-control switch box was needed in this sample case. In many other cases, the segments were assembled with minimum manual positioning, i.e., requiring some pushing of buttons.

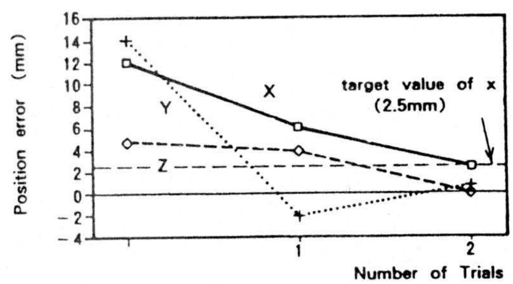

Fig. 2 Position Error

3.2 Ring Assembly Time

The time needed to assemble each ring is shown in Fig. 3. During the initial stage excavation, the average assembly time per ring took more than two hours. The initial adjustment, and control software debugging and modification were performed on site. The segment assembly was performed while giving working crews operating instructions. However, as the crews skill developed, the average assembly time decreased. After further modification of the control software, the average assembly times further decreased, ranging from 84 minutes to 87 minutes in the later stage of the project. The average assembly times per ring were as follows:

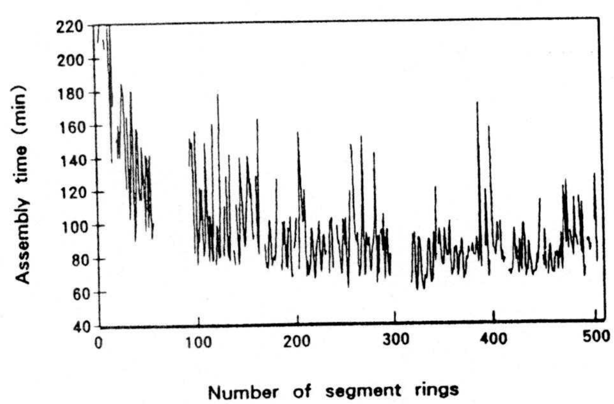

Fig. 3 Assembly Time of All Rings

Initial Stage Excavation:	February to April	:	154 minutes
Main Excavation :	May	:	106 minutes
	June	:	98 minutes
	July	:	85 minutes
	August	:	84 minutes
	September to August	:	87 minutes

As the project proceeded, differences in skill development between the two crews became obvious. One crew was able to assemble a ring in less than 70 minutes.

4. New Targets Set After the Application of the Robot

Our new targets set after the application of the robot are listed below.

1) Shortening of assembly time

Time required to assemble a segment is approximately 10 minutes. Shorter than 10 minutes is desired.

2) Improvement of vision sensor

In terms of positioning accuracy, the results varied widely. Also, time required in segment positioning was too long. The vision sensors shall be modified to improve the positioning accuracy and clamping accuracy.

3) Establishment of easier manual-remote-control switch box operation procedure

Operation of the manual-remote-control switch box is troublesome.
It takes too long before one feels comfortable in operating the switch box.

5. Actions Taken to Improve the Robot

Research has been performed to further improve the robot. The outline of two actions taken are explained below:

5.1 Shortening Assembly Time

Time required to assemble a segment was approximately 10 minutes. We have set a new target assembly time of five minutes per a segment and have proposed the following items as means to shorten assembly time:

(1) To increase actuator speed.
(2) To shorten the time required for sensing.
(3) To abolish repetitions in positioning.

The measure to achieve the item (3) is explained below.

In the automatic segment assembly procedure, repetitions of the automatic positioning and/or manual position modification have been necessary to complete segment rings. On the contrary, in conventional manual segment assembly practice, operators intentionally modify segment positions so that no repetition of positioning is required to complete segment rings. We have adopted these operators' know-how to our automatic segment assembly robot. This is to abolish loss time generated by repetitions and position modifications, as follows.

1) Method to easily assemble the segment "k"

The segments "A's", which are located on the bottom side of rings, are assembled first. Next the segments "B1" and "B2", and the last the segment "k" are assembled. The segments are designed to form a true circle. However, if they are to be assembled precisely to form a true circle, automatic insertion of the segment "k" becomes impractical.

Insertion of the segment "k" becomes easier if the segment "k" side of the segments "B1" and "B2" are slightly opened outward. (See Fig. 4.a) Further extending this idea, the opening for the segment "k" becomes slightly larger for easier insertion if the segment "A's" and "B's" are positioned slightly outward.

2) Compensation method to cope with deviation

Although the segments are designed to form a true circle, assembled rings can deviate from being true circle due to their own weight and/or soil pressure. If the segments are simply aligned with the previously assembled ones, the form of the rings will deviate from being true circle, making insertion of the bolts impossible in the end. To avoid this from occurring, the segments are positioned not only by aligning the sides of the segments but also by adjusting segment position within the tolerance of the

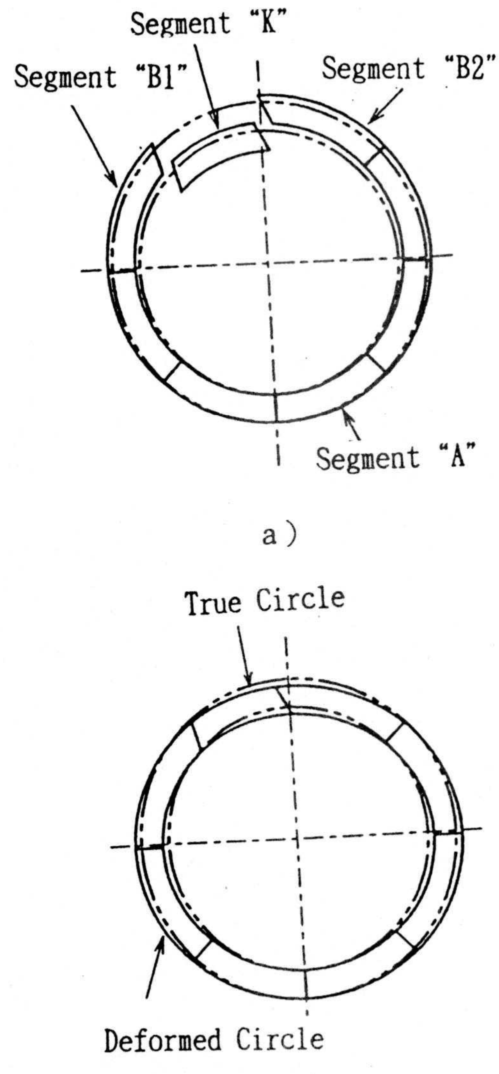

Fig. 4 Segment Assembly Method

clearance between the bolt and the bolt hole. The above mentioned adjustment can be repeated for the consecutive segments until the ring form is true circle overall. (See Fig. 4 . b)

5. 2 Modification of Vision Sensors

We have improved the vision sensor on two points discussed below:

1) Expanding the field of view

If the field of view is expanded, the resolution will be reduced. In order to accomplish expansion of the field of view while keeping the resolution level acceptable, we incorporated two cameras in one enclosure. One is located further from the shooting object to cover wider areas, the other in nearer location for better resolution. The construction of this type of vision sensor is shown in Fig. 5. A laser projector projects a slit of light across the mating surfaces while two cameras pick up images. The wide-area-covering camera is used to capture the desired area in case the image of the desired area cannot be caputured by the small-area-covering camera due to segment positioning deviation. Once the image of the desired area is captured by the wide-area-covering camera, the displaycan be switched to the small-area-covering camera to obtain better resolution if desired.

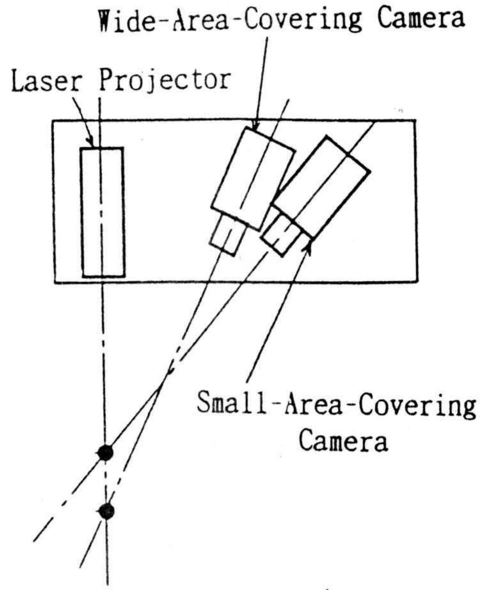

Fig. 5 Construction of Vision Sensor

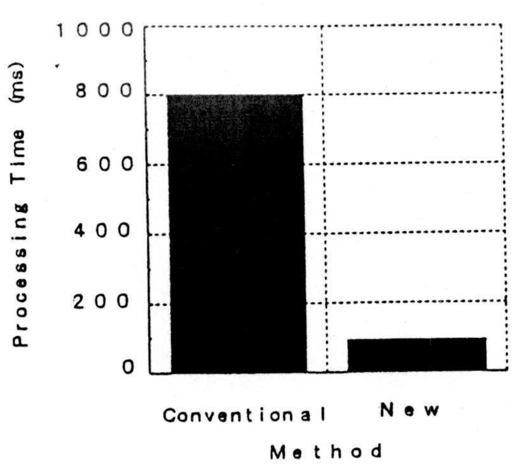

Fig. 6 Processing Speed (1ch)

2) Processing Speed

The time required for segment positioning must be reduced in order to achieve reduction of the time required for overall segment assembly. For this reason, improvement in the vision sensor processing speed was indispensable. We have altered the end point sensing method and established new algorithm for it, thus, resulting in a sharp reduction in the number of the processing steps. Also, we have adopted a highspeed image processing substrate, reducing the hardware processing time sharply. With the above mentioned measures, the vision sensor processing time is reduced to approximately one ninth of the time required previously. Previously the vision sensor processing took more than six seconds, stopping the operation for that time duration. With this improved system, the vision sensor processing takes approximately one second only. Refer to Fig. 6.

6. Conclusion

We have developed an automatic segment assembly robot and have adopted it on a shield machine used for subway construction work. It was implemented successfully and operated throughout the subway project. After completion of the subway project, we have set our new targets to further improve the robot and have taken some actions to realize them. For instance, we have further reduced the time required for segment assembly and increased the vision sensor processing speed.

Acknowledgment

We would like to express our great appreciation to the concerned people of Hazama Corporation for helping us in the implementation and operation of the robot at the work site.

Reference

Tanaka, Y., Microcomputers in Civil Engineering 10 (1995) 325-337