# Motion Analysis of Hydraulic Excavator in Excavating and Loading Work for Autonomous Control

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Abstract:

Civil engineering executions still involve extensive dangerous distressful work, so improving the safety of these wretched work environments must be ensured. In Japan, construction site workers are aging and there is fear of shortages of experienced workers and young workers. Improving civil engineering work by executing it using computers and robotic technology is counted on to resolve these problems.

The authors studied autonomous control technology for excavation and loading work using hydraulic excavators. This report presents the results of using a hydraulic excavator equipped with sensors to measure and analyze its motions when it is used for excavation and loading work under the control of an operator.

Keywords: hydraulic excavator, excavation and loading work, autonomous control, motion analysis

## 1. INTRODUCTION

Civil engineering is still often dangerous and extremely unpleasant work executed at disaster restoration sites, in underground space, or in tunnels. These wretched work environments must be improved and their safety guaranteed. In Japan, the falling birth rate and aging of society are contributing to the aging of workers on construction sites, resulting in fear of a future shortage of young workers and experienced workers. The application of computer and robotic technologies that have advanced remarkably in recent years to the execution of civil engineering works is counted on to resolve these problems by advancing civil engineering work executions.

We are researching autonomous control technology for excavation and loading work by hydraulic excavators that is one type of mechanized execution work in order to create robotic construction machinery capable of performing such work with a certain degree of autonomy.

This research is based on the motion of a hydraulic excavator when it is operated by an experienced operator and its purpose is the development of autonomous control technology for construction machinery that permits the machinery to be used to perform work efficiently. Therefore, the motion of construction machinery operated by experienced operators was measured and analyzed, methods of automatically preparing motion plans based on the results were researched, and control technology to control a hydraulic excavator according to the motion plan that has been automatically prepared was studied.

This paper reports the results of using a sensor-equipped hydraulic excavator to measure and analyze the angle of the upper rotating body, lengths of the hydraulic cylinders of the boom, arm, and bucket, the upper and lower hydraulic pressure of each cylinder, and the quantity of movement of operating levers when a hydraulic excavator is used for excavation and loading work by multiple operators under multiple working conditions.

## 2. MEASURING EXPERIMENT

We performed experiments to measure the motion of a hydraulic excavator when it is operated by human operators. The purpose of measuring experiments was to obtain basic data to analyze the motion of a hydraulic excavator according to the skills of an operator with a high degree of skill. By analyzing the measured data, we clarified the skills of an experienced operator and planned the development of an autonomous control system that can operate machinery efficiently based on these skills.

The items measured by the experiments were the quantity of motion of levers as operating information, angle of rotation and angle of inclination of the upper rotating unit as machine body information, the length and hydraulic pressure of each hydraulic cylinder, and motion pictures of the state of the experiment as visual information.

One effective method of clarifying the skills of an experienced operator is to compare the motions when hydraulic excavators are operated by operators with varying degrees of experience. Four operators operated the hydraulic excavator during these experiments: two operators with long experience, one operator with medium experience, and one with low experience.

The work performed for the measuring experiments was excavation and loading work. The conditions of the excavation work were excavation of a ditch with depth of

1.0 m and the width of the excavator bucket on flat ground. Loading work was done by dumping the soil after rotating it about 90° to the left. In order to measure variations in excavation motions under different conditions, the experiment was done under three conditions with varying distance between the hydraulic excavator and the excavation start location. The following are the three excavation start location conditions.

Case 1. Excavation start location is far from the hydraulic excavator (6m from the front end of its crawlers)

Case 2. Excavation start location is near the hydraulic shovel (4.5m from the front end of the crawlers)

Case 3 Excavation start location is located where the operator can easily begin excavation (standard) location.

We performed the experiment five times for each of the four operators with differing levels of experience for each of the three cases with differing excavation start locations. The time of the excavation and loading works during each

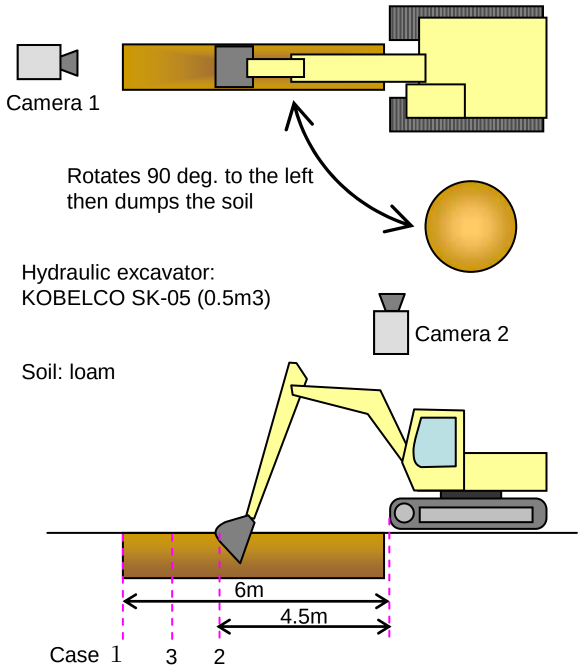



**Fig. 1 Outline of the Measurement Experiment**

experiment was either 5 minutes or until the work was completed. Figure 1 shows an outline of the experiment.

## 3. Motion analysis

We analyzed the motion of the construction machinery operated by the experience operators in order to develop autonomous control technology for robot construction machinery that can be used to perform work efficiently based on the motion of construction machinery operated by experienced operators. We analyzed excavation and loading work by dividing it into five work elements as shown in Figure 2. The analysis was an analysis of data characteristic of the start and completion of each work element and the motion of a hydraulic excavator during each work element. This paper reports on result of the analysis of (2) Excavation.

### 3.1 Analysis of data characteristic of the start and completion of the work elements

In order for autonomous robot construction machinery to perform work autonomously, it is necessary for the construction machinery to judge the start and completion of each work element of the work.

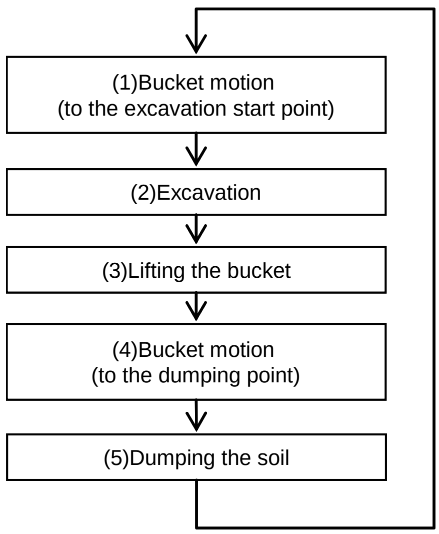



**Fig.2 Basic Elements of Excavating and Loading Work**

(1) Start of excavation

Excavation start condition is the tip of the bucket placed on the ground at the excavation start location. The operator

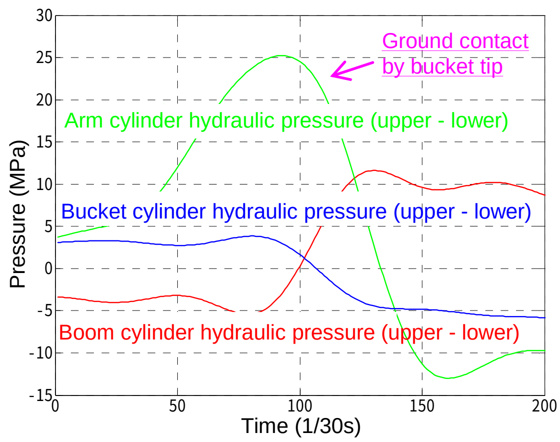
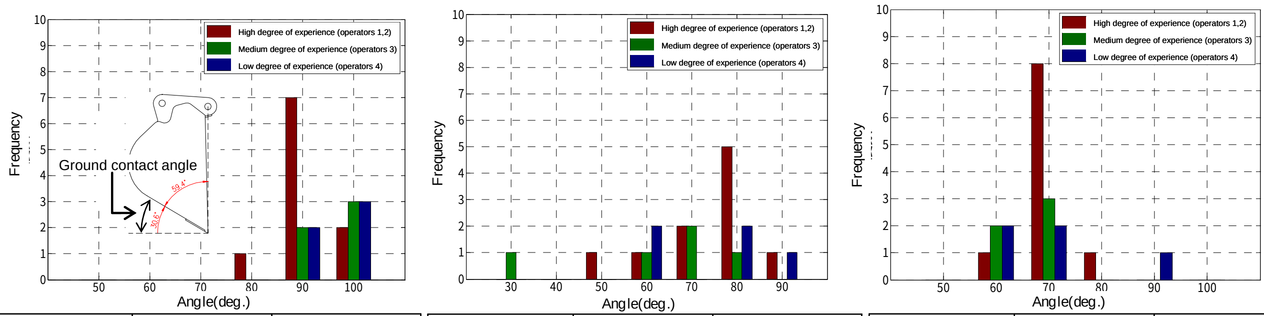



**Fig. 3 Example of Fluctuation of the Upper and Lower Pressure Differential of each Hydraulic Cylinder at Ground Contact Time**




(1) Experiment case 1 Far

| Degree of experience | Average | Standard Differential |
|---|---|---|
| High | 90.0 deg. | 4.9 deg. |
| Medium | 96.2 deg. | 5.9 deg. |
| Low | 96.0 deg. | 4.4 deg. |

(2) Experiment case 3 Medium

| Degree of experience | Average | Standard Differential |
|---|---|---|
| High | 72.1 deg. | 10.8 deg. |
| Medium | 62.0 deg. | 18.6 deg. |
| Low | 73.1 deg. | 13.4 deg. |

(3) Experiment case 2 Near

| Degree of experience | Average | Standard Differential |
|---|---|---|
| High | 68.2 deg. | 5.2 deg. |
| Medium | 65.9 deg. | 7.7 deg. |
| Low | 68.6 deg. | 11.5 deg. |

**Fig.4 Ground Contact Angle of the Bucket (Start of Excavation)**

confirms that it is grounded visually and judges it by the reaction.

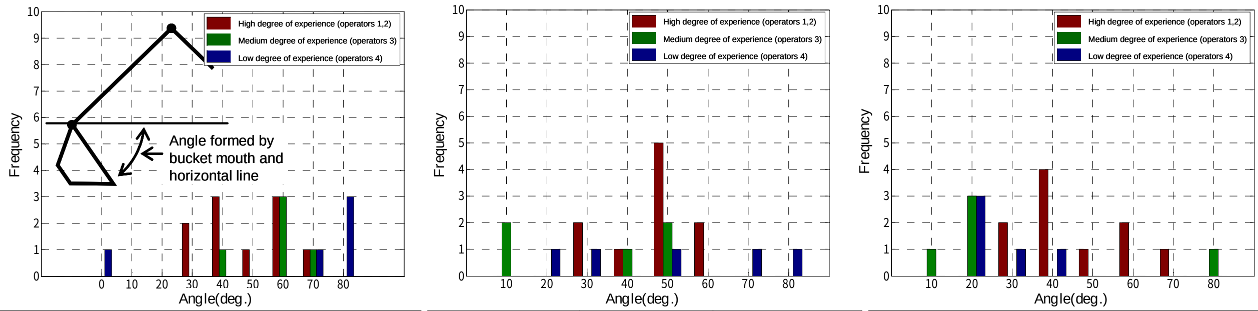
We focused on the fluctuation of the upper and lower vertical hydraulic pressure differential of each cylinder of the boom, arm, and bucket as data that characterizes the start of excavation. Figure 3 shows examples of the fluctuation of the upper and lower vertical hydraulic pressure differential of each cylinder at approximately the time when the bucket is grounded. Figure 3 reveals that the negative-positive values of the upper and lower vertical hydraulic pressure differential of the boom and bucket cylinders are reversed near the time that the bucket is grounded. This is assumed to occur because the load produced by the self-weight of the work equipment on the front—the boom, arm, and bucket—was reduced by the reaction from the ground produced by the grounding. It is possible to judge the start of excavating by using this data.

The working devices of a hydraulic excavator have redundancy. Therefore, when the location to start excavation is set and the tip of the bucket is grounded at that location, it is impossible to uniformly set the attitude of the hydraulic excavator at the grounding time. So we focused on the angle of the bucket at grounding time. It can be assumed that the bucket's contact angle should be an angle that reduces the resistance of the ground to its insertion while considering the excavation motion after insertion of the bucket. Figure 4 shows the results of plotting the bucket contact angles when it contacts the ground. Based on the frequency distribution of operators with a high level of experience in the graph in Figure 4, in experiment case 1, the ground contact angle is concentrated near 90°. In experiment case 2, the ground contact angle is concentrated near 70°. In experiment case 3, it is concentrated near 80°. Consequently, if the distance to the excavation start point is short, the ground contact angle declines. At excavation start time, the boom is lowered and the bucket's excavation motion inserts the bucket into the ground. When excavation begins, the lowering of the boom and the excavation motion of the bucket insert the bucket into the ground. It can, therefore, be hypothesized that the motion of the bucket during insertion causes circular motion centered on the boom foot pin and aligns the bottom surface of the bucket in the tangent direction of the circle, lowering the insertion resistance. It is, therefore, assumed that the closer the excavation start location, the smaller the ground contact angle.

(2) Completion of the excavation (start of lifting)

The conditions for the completion of excavation are the bucket filled with soil and the attitude of the work devices of the hydraulic excavator in excavation completed status (specifically, arm raising and excavation motion of the bucked are advanced, and continuing the excavation motion is ineffective). The operator makes this judgment by visually confirming that there is soil inside the bucket and the state of the work devices of the hydraulic excavator; the position and attitude of the bucket for example.

We focused on the angle formed by the bucket mouth and a horizontal plane as data that characterizes the completion of excavating and start of lifting. Figure 5 are graphs plotting the angles of the bucket mouth and horizontal plane when excavation is completed. The frequency distribution of operators with high level of experience in the graphs in Figure 5 show that the angles of the bucket mouth and a horizontal plane at the completion of excavation were concentrated near 50°. It can be assumed that when the bucket angle is equal to or higher than a certain angle, excavation is concluded and lifting begins, because this is an attitude that would make it difficult for soil to enter the bucket even if the excavation were continued. It is possible to judge when excavating work is completed using this data. But it is impossible to clarify that enough soil is inside the bucket using this data. So it is necessary to also use data that can be applied to estimate the quantity of soil inside the bucket: differences between the track of the bucket tip and the present topography, fluctuation of the upper and lower pressure differential of the hydraulic cylinders, or the fall of the speed of motion of the arm caused by the rise of the excavation load.




| Degree of experience | Average | Standard Differential |
|---|---|---|
| High | 48.4 deg. | 13.9 deg. |
| Medium | 57.7 deg. | 10.5 deg. |
| Low | 62.2 deg. | 34.8 deg. |

(1) Experiment case 1 Far

| Degree of experience | Average | Standard Differential |
|---|---|---|
| High | 47.0 deg. | 9.7 deg. |
| Medium | 35.1 deg. | 21.0 deg. |
| Low | 49.6 deg. | 23.0 deg. |

(2) Experiment case 3 Medium

| Degree of experience | Average | Standard Differential |
|---|---|---|
| High | 44.8 deg. | 13.0 deg. |
| Medium | 29.2 deg. | 25.8 deg. |
| Low | 29.0 deg. | 8.9 deg. |

(3) Experiment case 2 Near

**Fig.5 Angle of the Bucket Mouth and Horizontal Line (Excavation Completion Time)**

3.2 Analysis of the motion of the hydraulic excavator during work elements

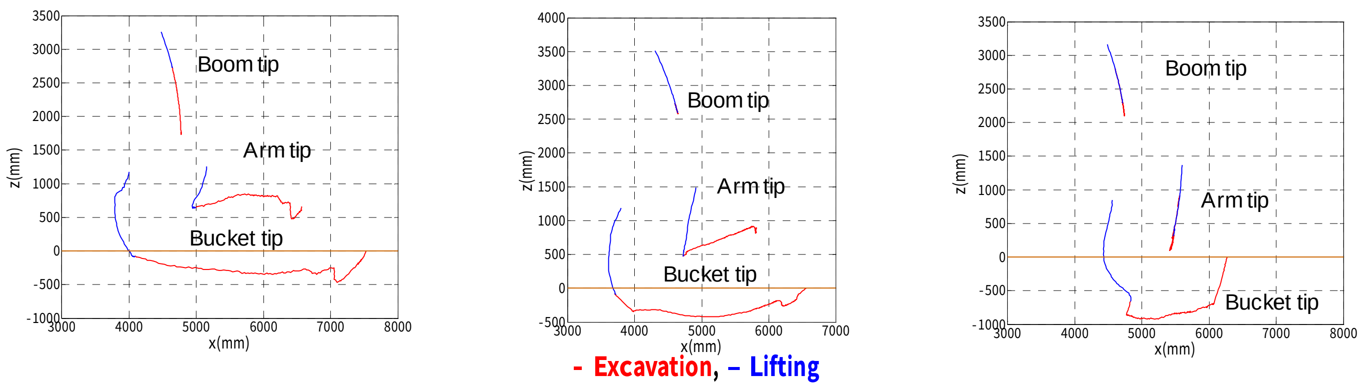
The motion of the hydraulic excavator when performing the excavation work elements is analyzed. We performed this analysis focusing on the tracks of the boom, arm and bucket tip and on the angle and the quantity of movement of the operating levers of the boom, arm and bucket at this time. In Figure 6, the tracks of the boom, arm, and bucket tip are taken as examples to present the track of 1 cycle of a trial in each experiment case by the same highly experienced operator. Figure 7 shows changes of the angles of the boom, arm and bucket during the track in Figure 6. Figure 8 also shows changes of the quantity of movement of the operating levers of the boom, arm, and bucket during the track shown in Figure 6.

(1) Excavation

It shows that in experiment case 1 (excavation from a far location), the complex motions—lifting the boom, withdrawing the arm, and excavating with the bucket—perform the excavation. It shows that the lever operations that withdraw the arm and excavate with the bucket perform the excavation and the boom lifting operation adjusts their motions. It is assumed that because the excavation start point is far, the excavation force is small near the excavation start point, so the boom lifting operation adjusts the track of the excavation, lowering the excavation load.

In experiment case 2 (excavation from a near location) the arm is not moved, the boom is lowered, and the excavation is done by a bucket excavation motion. Lowering the boom inserts the bucket into the ground and the excavation is done by the bucket excavation motion. This is presumably a result of the fact that because the excavation start point is near, as a result of the attitude of the bucket and the arm after the bucket has penetrated the ground, it is not effective to perform excavation by lifting the arm.

In experiment case 3 (excavation from a medium location), the excavation is performed by the combined motions of lifting the arm and excavating with the bucket. The excavation is done by operating the arm lifting lever and the bucket attitude is adjusted by the bucket excavation operation. This is data obtained by measuring excavation work from a location where operators perform excavation

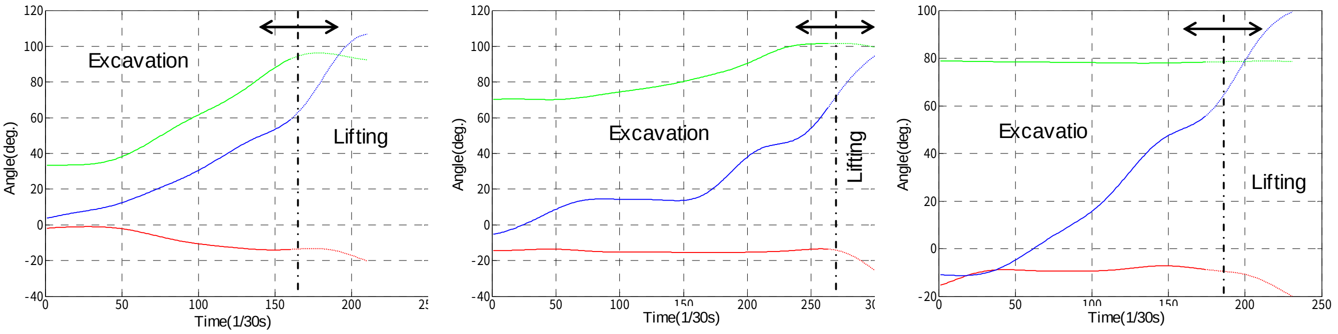



(1) Experiment case 1 Far
Operator 2, 5th trial, 1 cycle

(2) Experiment case 3 Medium
Operator 2, 3rd trial, 1 cycle

(3) Experiment case 2 Near
Operator 2, 5th trial, 1 cycle

**Fig.6 Tracks of the Tips of the Boom, Arm, and Bucket**



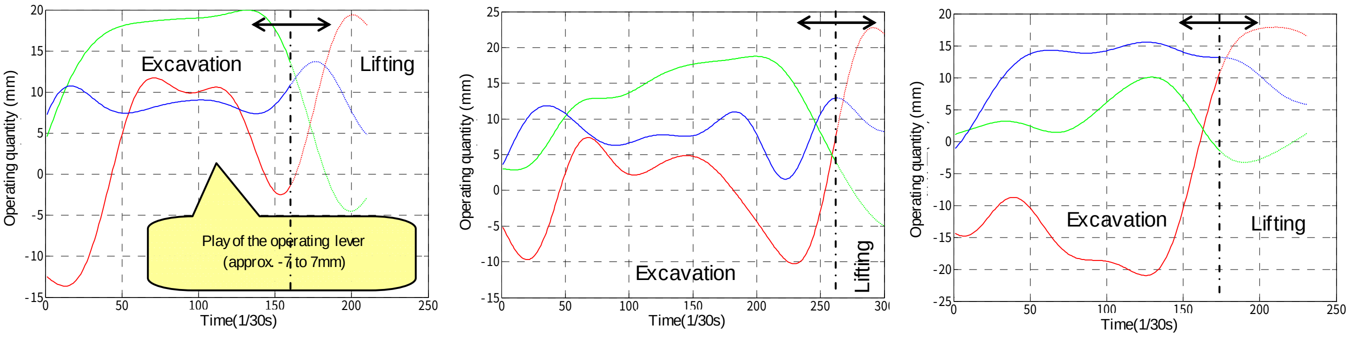

- Boom angle (lifting -, lowering +), - arm angle (lifting +, pushing -), - bucket angle (excavating +, dumping -)

(1) Experiment case 1 Far
Operator 2, 5th trial, 1 cycle

(2) Experiment case 3 Medium
Operator 2, 3rd trial, 1 cycle

(3) Experiment case 2 Near
Operator 2, 5th trial, 1 cycle

**Fig.7 Angle of the Boom, Arm, and Bucket**




- Boom operating quantity (lifting +, lowering -), - arm operating quantity (lifting +, pushing -),
- bucket operating quantity (excavating +, dumping -)

(1) Experiment case 1 Far
Operator 2, 5th trial, 1 cycle

(2) Experiment case 3 Medium
Operator 2, 3rd trial, 1 cycle

(3) Experiment case 2 Near
Operator 2, 5th trial, 1 cycle

**Fig.8 Operating Quantity of the Boom, Arm, and Bucket Operating Levers: Operating Quantity (about -20mm to +20mm)**

easily, and this is assumed to be the basic excavation operation.

Consequently, the basic excavation operation applied to plan excavation motion is lowering the boom, inserting the bucket into the ground with the bucket excavation operation, then while adjusting the bucket' s attitude by the bucket excavation operation, performing the excavation mainly by lifting the arm.

And except in experiment case 2 (excavation from a near location), the excavation depth of one excavation was about 0.5m, showing that about half of the bucket excavated in an attitude that moved it through the ground.

## 4. CONCLUSION

This paper reports on the results of performing experimental measurements of the motion of a hydraulic excavator operated by a human operator and analyzing the data obtained by the measurements in order to achieve autonomous control of excavating and loading work by hydraulic excavators based on the skill of experienced operators. The motion analysis was done by dividing excavation and loading work into five work elements.

The paper reports on the motion analysis results that are data characteristic of the start and completion of the work elements - excavation and lifting - and the results of analysis of the motion of the work elements. In the future, motion planning algorithms for hydraulic excavator excavation and loading work will be developed based on these results.

And the ground materials that are the object of the excavation and loading work by a hydraulic excavator have non-uniform properties, so it is difficult to know the properties in the entire work range before performing the work. In addition to this, the interaction of the ground with the work devices is complex and has been the object of many past research projects, but it is difficult to simply model this interaction so it can be controlled and utilized.

Based on these facts, the excavation motion is divided broadly into two parts. One is excavation motion with large excavation load and in which the interaction with the ground material has a substantial uncertain impact. This motion occurs in, for example, cases of excavation motion intended to excavate as large a quantity of soil as possible. In this case, it is good to supplement phenomenon driven control with control that adds a range limit.

The other is excavation motion with small excavation load, and in which the uncertain impact of the interaction with the ground material is minor. This occurs in cases of excavation intended to finish the shape of the object of the work after excavation has progressed. In this case, it is advisable to provide tracking control that considers the shape of the object of the work.

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