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Parallel gripper with displacement-magnification mechanism and extendable finger mechanism

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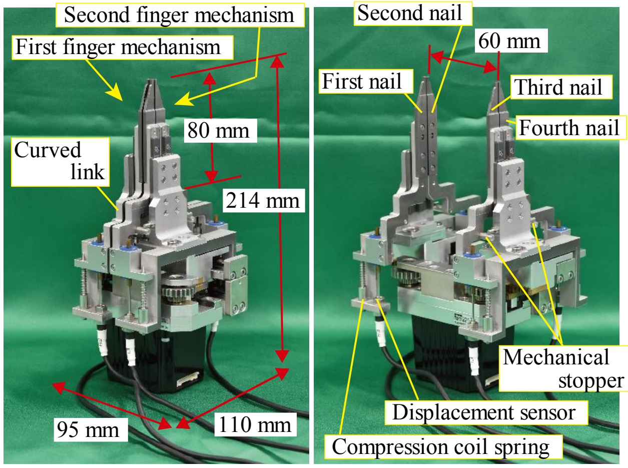
Abstract— **We propose a gripper displacement-magnification mechanism and an extendable finger mechanism, both of which can be attached to a commercially available parallel gripper. We then verify the operation of the mechanism in order to expand applications of the parallel gripper. The displacement-magnification mechanism has a stacked rack-and-pinion system that doubles displacement. The extendable finger mechanism has two nails that extend and contract, reducing impact force and detecting changes in product height from expansion and contraction amounts. The parallel gripper has a width of 95 mm, a depth of 110 mm, and a height of 214 mm and weighs 1.36 kg. It has an open/close stroke of 60 mm, a gripping force of 7.4 N, and an opening/closing speed of 100 mm/s or more. Further, it was confirmed that the ends and inclinations of products can be reliably detected using the extending/contracting nail. The mechanism verification confirmed that our parallel gripper achieved the desired performance and is therefore useful.**

I. INTRODUCTION

In recent years in Japan, it has become increasingly difficult to find workers for manufacturing facilities due to the declining birthrate and aging population. Automating a process such as removing products from a box by using a robotic hand instead of a human hand is seen as being indispensable in dealing with worker shortages.

Of the various robotic hands that have been developed to date [1–3], parallel grippers, in which a finger mechanism moves linearly to grasp products, have simple mechanisms, simple control, and high operational reliability. Therefore, parallel grippers are widely used in manufacturing facilities. Parallel grippers are also used in robot competitions because they are easy to handle [4]. Commercially available parallel grippers with small open/close stroke are compact and lightweight, but the size of products that can be grasped is limited. Commercially available parallel grippers with large displacement amounts have a large base in the opening and closing direction, so the base may contact the edge of the box. Therefore, the application range of small parallel grippers has been expanded by providing mechanisms for increasing the gripper stroke. In addition, the height of the products may not be accurately recognized by a recognition device such as a camera. Inaccurate recognition with a parallel gripper using a simple rigid finger mechanism can lead to products being damaged when the finger mechanism makes contact with the products. To prevent this from happening, finger mechanisms are equipped with a mechanism for reducing the impact force and a means of detecting the heights of the products.



(a) Closed state (b) Opened state

Fig. 1 Developed parallel gripper.

In general, it is desirable that the open/close stroke, opening/closing speed, and gripping force of parallel grippers are all large enough to improve productivity. However, a gripper incorporating all the contradictory characteristics described above will have a complex mechanism, and this reduces its operational reliability. Therefore, in this study, we aimed to improve operational reliability by using a simple mechanism so that the gripper can be quickly and widely adopted at manufacturing facilities. In a previous study, a displacement-magnification mechanism that combines a piezoelectric actuator and an elastic hinge has been proposed [5–6]. However, elastic hinges with low rigidity are not suited to applications in which large loads are generated, such as robotic hands for holding objects. Up to now, no compact displacement-magnification mechanism that can be easily attached to commercially available parallel grippers has been proposed. Therefore, in this study, while bearing in the mind the contradictory nature of the relationship between the stroke of the robotic hand and the gripping force, we developed a mechanism that increased the gripper stroke but did not significantly reduce the opening/closing speed. In a previous study, a method was proposed for mounting a nail member on a finger mechanism to improve gripping ability, and a thin object placed on a flat surface is hooked on a nail and bent to grip [7]. In addition, a configuration for arranging a force sensor between a fingertip and a nail member has been proposed in order to improve object sensing ability [8]. In past studies we also considered a problem with an existing gripper configuration in which elastic parts and a contact sensor are arranged in the finger mechanism to prevent damage to products [9]. The problem with this finger mechanism is that it cannot enter gaps between products

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because the fingers are too thick. Therefore, in developing our finger mechanism, we decided to arrange the elastic parts and the contact sensor such that the configuration has a finger mechanism that is thin.

In this study, we aimed to expand the applications of parallel grippers, and thus we proposed and verified the operation of a displacement-magnification mechanism and a finger mechanism with fingers that are both extendable and thin, as well as attachable on a commercially available parallel gripper. The developed parallel gripper is shown in Fig. 1. The displacement-magnification mechanism has a stacked rack-and-pinion system that doubles displacement. The extendable finger mechanism has two nails that extend and contract, reducing impact force and detecting changes in product height from expansion and contraction amounts. In this paper, we report on the design process, the specific mechanism and system configurations, and results of verifying the mechanisms' operations.

II. DEVELOPMENT CONCEPT

The development concept of the parallel gripper in this study is to double the displacement while preventing damage to products by mounting a modular displacement-magnification mechanism and an extendable finger mechanism on a commercially available parallel gripper that horizontally opens and closes. The required performance and design were determined in consideration of the development concept and the environment at the manufacturing site where the gripper will be used. Figure 2 shows the commercial parallel gripper (Taiyo ESG2) used in this study, and Table I shows its specifications. This parallel gripper is inexpensive and readily available, and synchronously opens and closes with one degree of freedom. The basic performance and design are given below:

- The mechanism configuration was devised so that the closed parallel gripper would be compact, with a width of 95 mm, a depth of 110 mm, and a height of 220 mm or less, weighing no more than 2.0 kg. Even when the displacement-magnification mechanism is mounted on the parallel gripper, the gripper width in the closed state is maintained at 95 mm as before, because if the width (opening and closing direction) of the parallel gripper becomes large when gripping an object, it may contact the edge of the box.
- The depth of the box in the installation environment, namely, the assembly process at a manufacturing site, was 50 mm. Therefore, the desired length of the finger mechanism was set to 50 mm or greater.
- The desired open/close stroke is 60 mm, which is twice that of commercially available parallel grippers. However, the width of the developed parallel gripper was kept at 95 mm in the closed state. Therefore, after taking into consideration the losses of the transmission mechanism, we decided to aim for an opening/closing speed of 100 mm/s or more.

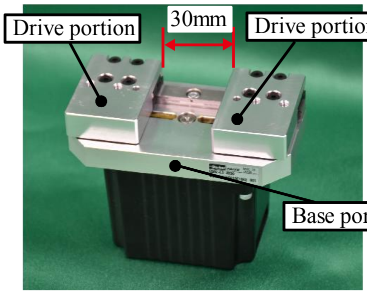


Fig. 2 Commercially available parallel gripper (Taiyo ESG2).

TABLE I Specifications for a commercially available parallel gripper (Taiyo ESG2).

Parameter	Value
Maximum gripping force (N)	15
Open/close stroke (mm)	30
Maximum speed (mm/sec)	150
Dimensions (mm)	W95 × D54 × H72
Mass (kg)	0.4

TABLE II Specifications of the developed parallel gripper.

Parameter	Value
Open/close stroke (mm)	60
Finger mechanism length (mm)	80
Nail expansion/contraction(mm)	17
Dimensions (mm)	W95 × D110 × H214
Mass (kg)	1.36

- The object to be gripped was an aluminum industrial part with assumed mass W of 0.3 kg. The finger surface of the parallel gripper was made of aluminum. The coefficient of friction depends on the grasped object, and so cannot be set by design. In this paper, the friction coefficient μ due to dry friction between aluminum was assumed to be 0.3. The gripping force P (N) was obtained by multiplying the assumed mass W and gravitational acceleration, and then dividing this value by the friction coefficient μ and the number of fingers. We decided to aim for a gripping force of 4.9 N or higher.
- In order to reduce the impact force and measure the change in the height of the products, we decided to aim for a finger mechanism with a nail extension of 10 mm or more.

III. DEVELOPED PARALLEL GRIPPER

A. Structure

The structure of the developed parallel gripper is shown in Figs. 3–6, and the specifications are shown in Table II. Because the total mass of the developed parallel gripper is 1.36 kg and the mass of the commercially available parallel gripper is 0.4 kg, the mass of the added mechanisms is 0.96 kg. Each mechanism is outlined below. Here, the movable portion of the commercially available parallel gripper is referred to as the drive portion. Because each finger mechanism has the same structure, only one finger mechanism will be described.

(a) Displacement-magnification mechanism

The displacement-magnification mechanism consists of two sets of rack-and-pinion systems. The rack-and-pinion system of the first finger mechanism consists of a first rack, a third rack, and Gear A. The rack-and-pinion system of the second finger mechanism consists of a second rack, a fourth rack, and Gear B. The first and second racks are connected to the drive portion. Gear A and Gear B rotate on a rotating shaft provided on the base portion. Both the first and second guide portions have a structure in which two sets of guiderails overlap.

Gear A comprises two gears, A1 and A2, with different diameters on the same axis. Gear A1 and Gear A2 are integrally connected to form Gear A. Gear A1 meshes with the first rack and Gear A2 meshes with the third rack. The diameter of Gear A1 is smaller than that of Gear A2. The movement of the first and third racks engaged with Gear A is as follows: The pitch circle diameter of Gear A1 in Gear A is D_a, and the pitch circle diameter of Gear A2 is D_b. When the drive portion is driven to move the first rack in the horizontal direction, Gear A1 meshes with the rotating first rack and Gear A2 also rotates at the same rotational speed as the rotating shaft. Then, as Gear A2 rotates, the third rack moves in the horizontal direction. At this time, the ratio between the moving distance l_1 of the first rack and the moving distance l_3 of the third rack can be derived in advance. When Gears A1 and A2 make one rotation, the moving distance l_1 of the first rack becomes πD_a and the moving distance l_3 of the third rack is πD_b. In other words, the value obtained by multiplying the diameter ratio of gears A1 and A2 by the movement amount l_1 of the first rack is the movement amount l_3 of the third rack, and thus the following equation is established:

$$l_3 = l_1 (D_b / D_a). \tag{1}$$

The pitch circle diameter of gear A1 is $D_a = 12$, the pitch circle diameter of gear A2 is $D_b = 24$, and the movement distance ratio is 2. If loss is ignored, the distance traveled is double the output relative to the input. Regarding the opening/closing speed, which is the time derivative of the movement amount, the output is twice the input.

Furthermore, the relationship between the moving force F_1 of the first rack and the moving force F_3 of the third rack is expressed by the following equation. Here, the moving force F_1 of the first rack corresponds to the gripping force of a commercially available parallel gripper. The movement force F_3 of the third rack corresponds to the gripping force of the developed parallel gripper.

$$F_3 = F_1 (D_a / D_b). \tag{2}$$

From the above formula, if loss is ignored, the gripping force of the developed parallel gripper is half that of the commercially available parallel gripper.

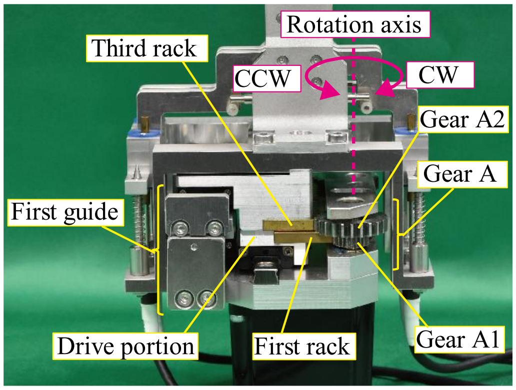


Fig. 3 Expanded side view of the developed parallel gripper.

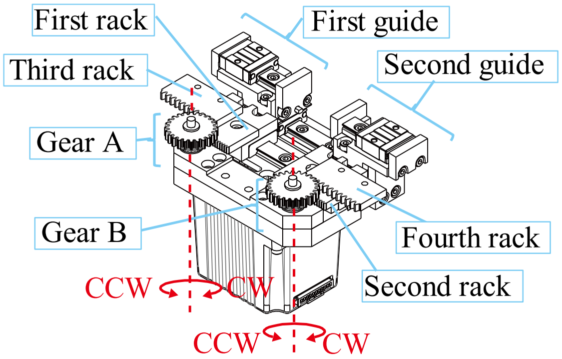
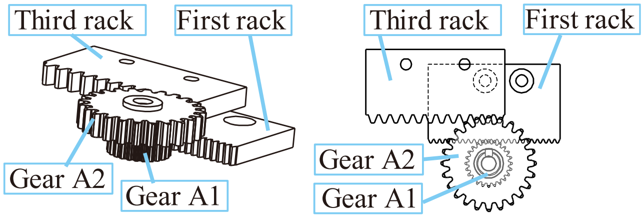


Fig. 4 Perspective view of displacement-magnification mechanism.



(a) Perspective view (b) Plan view

Fig. 5 Rack-and-pinion system for gear A.

(b) Finger mechanism

The first finger mechanism is connected to the third rack and the first guide. The second finger mechanism is connected to the fourth rack and the second guide. Each finger mechanism has two nails that extend and contract. Each nail is connected to a displacement sensor (LP15-014-R5) for measuring the amount of expansion/contraction and to a compression coil spring via a curved link. The compression spring coil is for maintaining the positioning of the nail. The displacement sensor inserts a metal rod inside the metal pipe, and the output voltage (1 to 5 V) changes when the metal rod moves in the measurement area (14 mm). The greater the amount of metal rod inserted into the metal pipe, the lower the output voltage. The configuration is such that the output voltage of the displacement sensor rises when the nail extends, and the output voltage of the displacement sensor decreases when the nail shortens. The shape of the curved link is devised so that the curved link does not come into contact with other members when each nail extends and contracts. The movement range of the nail is set by the curved link coming into contact with a mechanical stopper. The developed parallel gripper has a total of four displacement sensors.

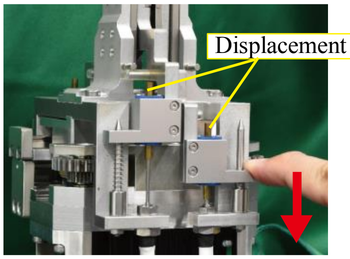


Fig. 6 Displacement sensor for measuring.

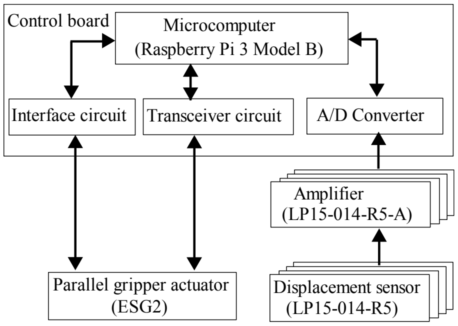


Fig. 7 Overview of drive control system configuration.

(c) Drive control system

Figure 7 shows the configuration of the drive control system. The control unit is a single microcomputer (Raspberry Pi 3 Model B) and it controls the opening/closing operation of the parallel gripper. The amount of expansion/contraction of the finger mechanism is detected by a displacement sensor (LP15-014-R5), which is input into the control unit via the displacement sensor amplifier (LP15-014-R5-A) and the A/D converter on the developed board. The displacement sensor is connected to the developed electronic circuit board via the GPIO terminal of the microcomputer. The external host system controller and the control unit of the parallel gripper can communicate with each other wirelessly or by a wired connection.

For the above configuration, the operation of the parallel gripper changing from the closed state to the open state will be described here. By driving the drive portion, the first rack and the second rack are moved in opposite directions from each other along the horizontal direction. Gear A1, which meshes with and is driven by the first rack, rotates counterclockwise. Furthermore, Gear B1, which meshes with and is driven by the second rack, rotates clockwise. As a result, the third rack that meshes with Gear A2 and the fourth rack that meshes with Gear B2 move in opposite directions from each other in the horizontal direction. Therefore, the first finger mechanism and the second finger mechanism also move away from each other.

B. Detection of product height change

Figure 8 shows an example of how the change in product height is detected using each displacement sensor. As shown in Fig. 8(1), product G1 is placed horizontally on product G2. The closed parallel gripper is lowered by the manipulator. When the height information of product G1 is unknown, the first to fourth nails are brought into contact with the upper surface of product G1 so that the first to fourth sensors are displaced when contact with product G1 is made. The control device thus detects that the first to fourth nails have come into contact with product G1, and it immediately stops the descending operation of the parallel gripper. Next, as shown in Fig. 8(2), the parallel gripper drives the first and second finger mechanisms to gradually open while tracing the surface of product G1 with the first to fourth nails. When each nail no longer is in contact with product G1, the response of the displacement sensor changes significantly.

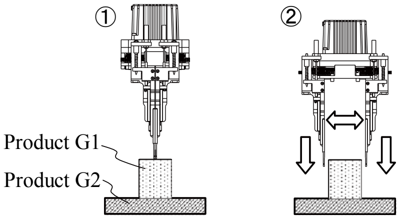


Fig. 8 Detection of product height change.

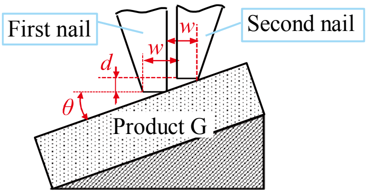


Fig. 9 Enlarged side view of nail tips.

A method for deriving the product width L_{obj} will be described here as an example of the usefulness of the developed gripper. The parallel gripper is set to closed as the initial state. L_1 is the amount of movement from the initial state of the first finger mechanism until the response of the displacement sensor of the first and second nails changes significantly. L_2 is the amount of movement from the initial state of the second finger mechanism until the response of the displacement sensor of the third and fourth nails changes substantially. From the movement amount L_1 and the movement amount L_2, the product width L_{obj} is expressed by the following equation.

$$L_{\text{obj}} = L_1 + L_2. \tag{3}$$

By using the calculated product width information for the opening/closing control of the parallel gripper, it is possible to improve the reliability of the gripping operation.

C. Relative angle detection

Figure 9 shows an enlarged side view of the nail when each nail is contacting inclined product G. A relative angle θ between the tip plane of the nail and the surface of product G is obtained from the difference in displacement amount of each nail. Specifically, when the displacement difference between the first and second nails is d and the width of the tip plane is w, the relative angle θ is expressed as

$$\theta = \tan^{-1}(d / w). \tag{4}$$

In this paper, width w of the tip plane is 3 mm. The combination of nails may be a combination of other nails.

IV. MECHANISM VERIFICATION

A. *Gripping force and opening/closing speed*

We referenced the evaluation methods we have implemented in the past [10–11]. The gripping force was measured using the experimental device shown in Fig. 10. A force gauge (DS2-500N) was brought into vertical contact with the outside of the finger mechanism, the parallel gripper was then opened in that state, and the gripping force was measured. The maximum forced was 7.4 N, and thus it was confirmed that the finger mechanism can apply the desired gripping force of 4.9 N or more.

Next, the opening/closing speed was measured using the experimental device shown in Fig. 11. In the experiment, the parallel gripper was opened and closed from the closed state, and the positions of each side of the finger mechanism and the second rack were measured with the laser displacement sensor (IL-s100). The second rack is connected to the drive portion of the commercially available parallel gripper. The results are shown in Fig. 12. The vertical axis of the graph in Fig. 12 indicates displacement from the closed state of the parallel gripper, and the horizontal axis indicates the elapsed time. The amount of finger mechanism displacement was twice that of the second rack. The movement amount of the finger mechanism from the closed state to the opened state of the parallel gripper was about 30 mm, the elapsed time was about 285 ms, and the opening speed was about 105 mm/s. Finger mechanism movement from the open to the closed state was also about 30 mm, but the elapsed time was about 252 ms and the closing operation speed was about 119 mm/s. This confirmed that the finger mechanism can provide the desired opening/closing speed of 100 mm/s or higher.

B. *Experiment for detecting changes in products height*

Using the experimental apparatus shown in Fig. 13, we conducted an experiment to detect the end of a product with the nail. In the experiment, a parallel gripper was fixed to a frame. The experimental procedure was as follows: First, the initial contact position between the product and the nail was adjusted with respect to the closed parallel gripper. Next, the parallel gripper was opened, and the response change of the displacement sensor at this time was measured. The initial contact position between the product and the nail is taken to be when the nail is in contact with the end of the product surface, as shown in Fig. 13. The measurements are shown in Fig. 14. The vertical axes of the graphs in Fig. 14 indicate the voltage output value of the displacement sensor, and the horizontal axes indicate the elapsed time. Damped vibration due to elasticity of the compression coil spring of the nail is detected in the voltage output value of the displacement sensor. The damped vibrations mean it is likely there will be a reduction in the impact force of the nail, which will be due to the compression coil spring. As shown in Figs. 13 and 14, when the nail is in contact with a spot near the end of the product in the initial state, it can be seen from the response of the displacement sensor that there is a time difference between each finger mechanism reaching the end of the product. As described above, because the end of the product

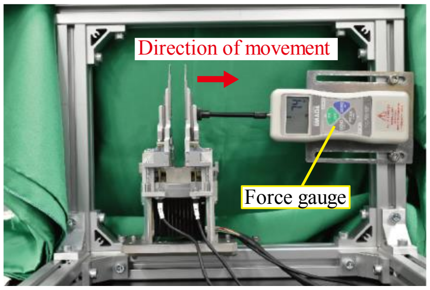


Fig. 10 Gripping force measurement experiment.

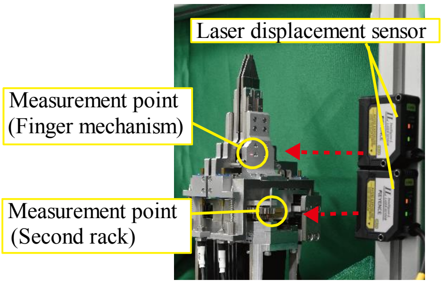


Fig. 11 Opening/closing speed measurement experiment.

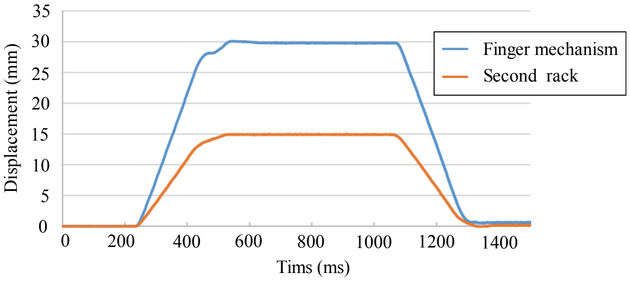


Fig. 12 Measurement result of displacement amount of opening and closing operation.

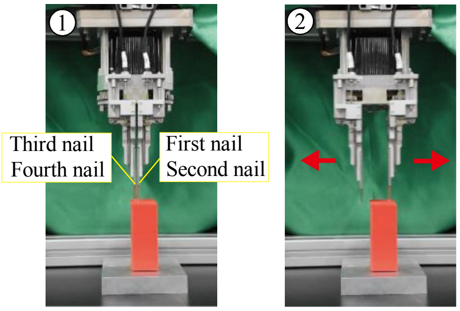


Fig. 13 Nail contacts the object edge in the initial state.

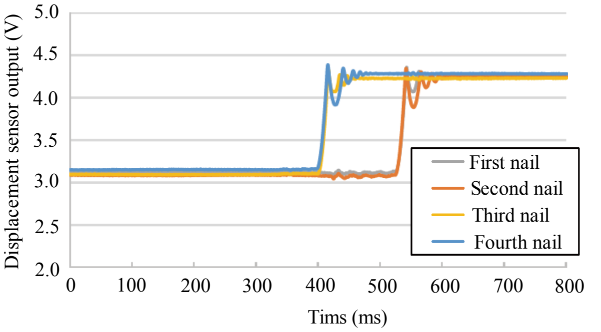


Fig. 14 Displacement sensor output with the nail in contact with the object edge in the initial state.

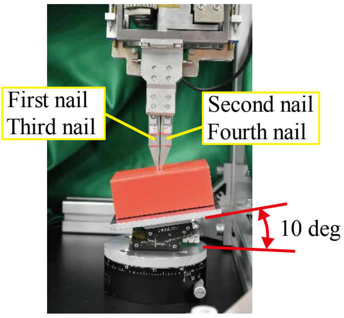


Fig. 15 Relative angle detection experiment.

TABLE III Displacement of each nail.

	First nail	Second nail	Third nail	Fourth nail
Displacement (mm)	4.7	5.3	4.6	5.2

TABLE IV Calculated relative angle.

Nail combination	Relative angle (deg)
First nail and second nail	11.3
First nail and fourth nail	9.5
Second nail and third nail	13.1
Third nail and fourth nail	11.3

can be detected from the response of the displacement sensor, this response can probably be used for controlling the opening width of the parallel gripper. In addition, this response can probably be applied to measurement of the surface shape made by moving the nail while tracing the surface of the product.

C. Relative angle detection experiment

Using the experimental apparatus shown in Fig. 15, we conducted an experiment to detect the relative angle of the product with the nail. In this experiment, a closed parallel gripper was fixed to the frame. The difference of each displacement sensor was obtained when each nail part was not in contact with the product and when each nail part was in contact with the product (Fig. 15). The product inclination angle was 10 deg. From the product catalog, the conversion factor between the displacement sensor value and displacement is 3.5 mm/V. Table III shows the displacement of each nail, and Table IV shows the calculation result of the relative angle as obtained from equation (4). All calculated relative angles contained error relative to the actual product inclination angle. In the future, we will review calibration methods for each displacement sensor and work to reduce the relative angle error.

V. CONCLUSION

In this paper, we proposed a displacement-magnification mechanism and an extendable finger mechanism with the intention of expanding the applications of parallel grippers that open and close in the horizontal direction. The two mechanisms can be attached to a commercially available parallel gripper. The displacement-magnification mechanism, which is composed of rack-and-pinion systems, achieved a displacement twice that of the commercially available parallel gripper to which it was attached. The finger mechanism, which has two nails that extend and contract, achieved a reduction in impact force and could measure the change in the height of products based on the amount of nail expansion and contraction. A series of basic performance verifications confirmed the usefulness of the developed gripper. Although the displacement-magnification mechanism was verified in this paper using only a specific parallel gripper (Taiyo ESG2), it can be applied to other commercially available parallel grippers that horizontally open and close. In addition, the dimensions of the displacement-magnification mechanism described in this paper matched the parallel gripper opening/closing stroke of 30 mm, but when applying the displacement-magnification mechanism to other commercially available parallel grippers, the rack-and-pinion gears can be realized by adjusting the diameter, arbitrary opening/closing amount, and fingertip force.

In the future, by combining the parallel gripper of this paper with the articulated manipulator, we plan to work on realizing gripping operations using relative angle data for each nail. Specifically, we will realize searching operations while pushing the object surface with the nail and by tilting the parallel gripper with a manipulator so that the relative angle becomes small.

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