DEVELOPMENT OF A PARALLEL GRIPPER WITH AN EXTENSION NAIL MECHANISM USING A METAL BELT

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Aiming to expand the range of applications for parallel grippers, we propose an extension nail mechanism that can be mounted on a parallel gripper. We also propose an extension nail mechanism comprising a stainless steel belt, two transport belts, a triangular nail, and a drive unit. The triangular nail is connected to one end of the stainless steel belt, and the drive unit is connected near the other end. We achieve smooth sliding of the nails underneath objects by arranging the transport belts on either side of the stainless steel belt. By elastically winding one end of the stainless steel belt and each of the transport belts, the nail mechanism can be miniaturized while achieving large expansion and contraction. We achieve stable grasping operations by using the extension nail mechanism of the parallel gripper in accordance with the flexibility of the object.

KEYWORDS

robotic hand, hardware design, manufacturing robot, nail extension mechanism, parallel gripper

1 INTRODUCTION

In recent years, Japan's declining birthrate and aging population have made it difficult to secure sufficient numbers of workers at logistics sites. When automating logistics sites to mitigate this issue, robotic hands are indispensable for picking operations such as removing articles from belt conveyors. Various types of robotic hands have been developed , including two-finger [Osaki 2013, Levine 2018, Tanaka 2020], three-finger [Chen 2020, Townsend 2000, Yuan 2020], four-finger [Aukes 2014], and five-finger hands [Li 2020, Pfanne 2020]. Another robotic hand [Catalano 2014] was devised such that the joint mechanisms work together to reduce the number of motors. Other robotic hands [Fujita 2020, Hasegawa 2019, Morrison 2018] designed for use at distribution sites have also been proposed. In particular, parallel grippers, in which a finger mechanism moves linearly to grasp articles, have simple control mechanisms and high reliability, and thus are widely used at logistics sites.

Articles commonly handled at logistics sites can be roughly classified as rigid objects such as cardboard boxes or flexible objects packed in a cushioning material. When a parallel gripper grasps an article, rigid bodies generally do not deform, whereas flexible objects do and thus there is a risk of damage. Therefore, in this study we investigated grippers equipped with a mechanical element equivalent to a nail for supporting the bottom surfaces of flexible objects. Various robotic hands with fingertips equipped with a mechanical nail-like element have been proposed. Specifically, there are configurations in which a force sensor between fingertips and nail members sense objects [Kõiva 2018, Murakami 2003] as well as configurations in which a nail member is mounted on silicon rubber for passive compliance adjustment [Morita 2000]. In other methods, a thin object on a flat surface is picked up with fingertips [Babin 2018, Yoshimi 2012]. However, the structure by which the short nail member is fixed to the fingertip cannot support the entire bottom surface of a flexible object. Therefore, grasping methods for supporting the entire bottom surface of an object have been proposed. In particular, one method slides a long plate underneath objects lifted by a robotic hand [Nakamoto 2010], and another slides a long plate underneath objects through extrusion by an annular belt [Tadakuma 2013]. In methods involving the sliding of long plates, the support range of the bottom surface of the object depends on the length of the plate. Accordingly, when a long plate supporting the object's entire bottom surface is mounted on a parallel gripper, the parallel gripper becomes larger. Furthermore, if the mounting surface in contact with the annular belt has a large friction coefficient, the operation of the single annular belt may be limited. This is because the frictional force from the mounting surface makes it difficult to smoothly push out a singular annular belt. Therefore, when the friction coefficient of the mounting surface is large, it is considered effective to use two annular belts, with one stacked above the other. We therefore investigated a method for mounting a small retractable nail mechanism on a parallel gripper and supporting an object's entire bottom surface with the extended nail.

To expand the range of applications for parallel grippers, we propose an extension nail mechanism that can be mounted on the fingertip of one side of the parallel gripper (Fig. 1). In the proposed mechanism, the nail part smoothly slides underneath the object, and both miniaturization and a large expansion/contraction span of the nail part are achieved. The extended nail portions are magnetically connected to opposing fingertips in order to improve load resistance. Mechanism verifications showed that using the extension nail mechanism of the parallel gripper in accordance with the flexibility of the object achieves stable grasping operations. This paper reports the design policy, specific mechanisms and system configurations, and the results of basic experiments using the proposed parallel gripper with an extension nail mechanism.

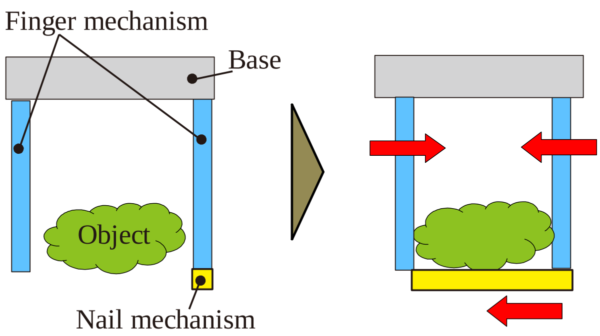


Figure 1. Parallel gripper development concept.

2 DEVELOPMENT CONCEPT

The development concept of the parallel gripper in this paper is to achieve stable grasping operations by using an extension nail mechanism mounted on one fingertip of the parallel gripper in accordance with the flexibility of the object. The development concept of the extension nail mechanism is to develop a mechanism configuration that achieves both miniaturization and large expansion/contraction spans with the nail part smoothly sliding underneath objects. The performance and design requirements were examined in consideration of these development concepts and the installation environment, namely, a logistics site.

2.1 Handled objects

We examined and categorized the articles to be handled, assuming a distribution warehouse as the robot application environment. Based on this classification, we developed a parallel gripper that can handle two types of commonly distributed objects:

- Rigid cardboard boxes (H 90 × W 200 × D140 mm; about 0.1 kg)

- Long articles packed in flexible cushioning material (About W 70 × D 230 mm; about 0.1 kg)

Items with these shape features were placed individually on a flat surface.

2.2 Design requirements

To investigate the performance required for a parallel gripper to grasp the assumed objects, we established the following design requirements.

- As a grasping strategy, the parallel gripper should approach the object from above to grip and lift the object.
- Based on the size of the target cardboard box (D 140 mm), the maximum opening width of the parallel gripper was set to at least 140 mm. The dimensions of the parallel gripper were approximately H 300 × W 300 × D 300 mm.
- The maximum payload of the robot arm (TV800; Shibaura Machine Co., Ltd.), on which the parallel gripper was attached, is 5.0 kg. Therefore, the total mass of the parallel gripper should not exceed 4.9 kg.
- We used current-controllable DC motors as actuators. One DC motor opens and closes the parallel gripper, and another extends and retracts the nail mechanism. The finger part with the extension nail mechanism is modularized so that the entire finger part can be quickly replaced in the event of failure. Furthermore, multiple modularized fingers are arranged on the parallel gripper in accordance with the size of the object to be handled.
- A permanent magnet is attached to the opposing fingertip so that the extension nail mechanism can be magnetically connected to the opposing fingertip without electric power. An iron member is used as part of the nail portion.
- The assumed mass W of the object to be handled is 0.1 kg. For the nail to slide underneath the object, it is necessary to lift the object with a force of at least 1 N, a value obtained by multiplying the assumed mass W by gravitational acceleration. The pressing force of the nail portion must therefore be at least 1 N.

2.3 Examination of extension nail mechanism

Figures 2 and 3 show schematic diagrams of the proposed extension nail mechanism and parallel gripper, respectively. We investigated configurations of the extension nail mechanism allowing the nail portion to smoothly slide underneath the object to transfer it onto the nail. The proposed extension nail mechanism comprises a stainless steel belt, two transport belts, a triangular nail, a belt drive, and winding units for each belt. Stainless steel belts were adopted for their thinness and strength. A triangular nail is connected to one end of the stainless steel belt, with the other end wound around the belt-winding unit. The first transport belt is situated just above the upper surface of the stainless steel belt, one end of which is folded back by the first nail roller for separation from the upper surface of the stainless steel belt and fixed to the support member. The other end is wound around the first transport-belt–winding unit. The second transport belt is placed just below the lower surface of the stainless steel belt and is folded back by the second nail roller so that one end is separated from the lower surface of the stainless steel belt. The other end is wound around the second transport-belt–winding unit. In each belt-winding unit, torque always acts in the direction the belt is wound by an elastic member such as a spring. Winding and arranging each belt improves its storability. The first direction-change roller changes the path of the first transport belt in an arbitrary direction, whereas the second changes the path of the second transport belt. The gap between the direction-change part changes the route of the stainless steel belt in an arbitrary direction. The belt-driving unit sandwiches the stainless steel belt between the drive roller and the passive roller and sends the belt out by rotating the drive roller. The triangular nail is moved forward or backward by operation of the belt-driving unit. At this time, the first transport belt winds around the first nail roller and the second transport belt winds around the second nail roller, moving in conjunction with the stainless steel belt.

As the nail extends, it slides underneath the object's bottom surface and the mounting surface, and the object is transferred onto the first transport belt as the nail advances. When the target object is transferred to the first transport belt, the surface of the first transport belt, which is in contact with the bottom surface of the target object, comes out bit by bit so as to sink into the bottom surface of the target object. The first transport belt thus smoothly slides underneath the object, reducing the likelihood of damaging the object, even in the case of flexible objects. Similarly, the surface of the second transport belt, which is in contact with the mounting surface, also comes out bit by bit so as to gradually make contact with the mounting surfaces. The second transport belt thus moves smoothly on the mounting surface. Through the operation of the first and second transport belts, the nail portion executes a smooth reciprocating motion.

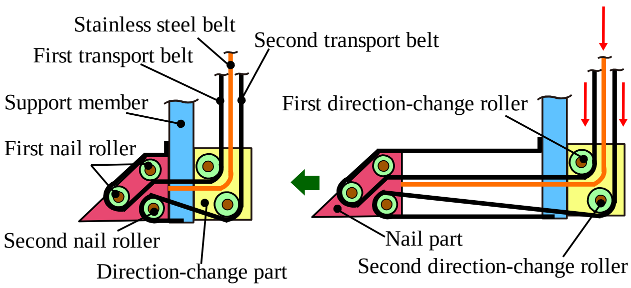


Figure 2. Schematic diagram of the proposed extension nail mechanism.

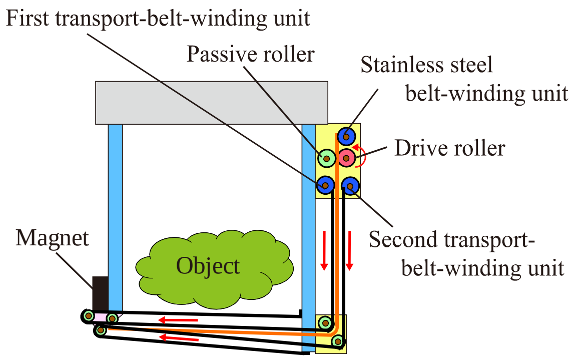


Figure 3. Schematic diagram of the proposed parallel gripper.

3 OVERVIEW OF DEVELOPED PARALLEL GRIPPER

This section describes the structure of the parallel gripper developed based on the concepts presented in Section 2.

3.1 *Overall configuration*

Figure 4 shows the developed parallel gripper. Its overall dimensions are H 300 × W 220 × D 320 mm and its mass is about 4.0 kg. The open/close range of the parallel gripper is 40–230 mm, and the open/close amount is 190 mm. The developed parallel gripper comprises a base unit, a movable base unit, an open/close drive unit, a finger unit with an extension nail mechanism, and a finger unit with a magnetic fingertip. To grasp a long flexible object, two fingers with a modularized extension nail mechanism were attached to the movable base. To make opposable fingers, two fingers with magnetic fingertips were attached to the base and connected with an acrylic plate. Because the side face of the object is supported by the acrylic plate, the nails easily slide underneath the object. The open/close drive unit fixed to the base unit is connected to a small DC motor (4.5 W; reduction ratio 29:1) and a trapezoidal screw (lead 1 mm) by coupling. The movable base moves linearly with the rotation of the trapezoidal screw, thereby adjusting the distance between the opposing fingers. Three DC motors are used, one for the open/close drive unit and one for each extension nail mechanism. As Fig. 5 shows, the extended nail mechanism magnetically connects to the opposing fingertip. A neodymium magnet (force 49 N; size ϕ20 × 4 mm) is attached to the opposing fingertip.

Figure 6 shows a schematic of the drive control system used in the experiment. In this system, voltage corresponding to the target speed is output to the motor driver, and the DC motor is driven by passing a current through it. Control is performed by detecting the speed, inputting it to the counter board, and feeding it back. A displacement sensor is used to detect when the elongated nail reaches the tip of the opposing finger.

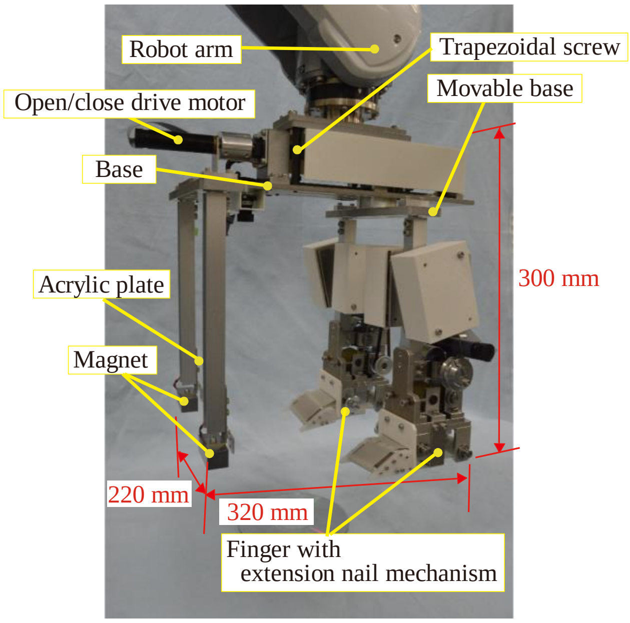


Figure 4. Appearance of the developed parallel gripper.

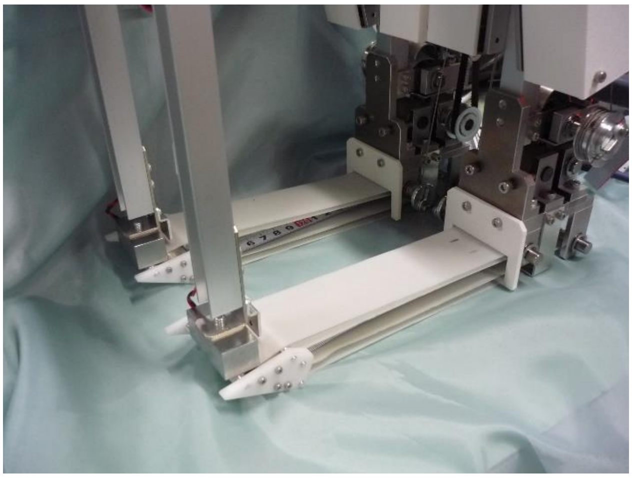


Figure 5. Magnetic coupling of the fingertips.

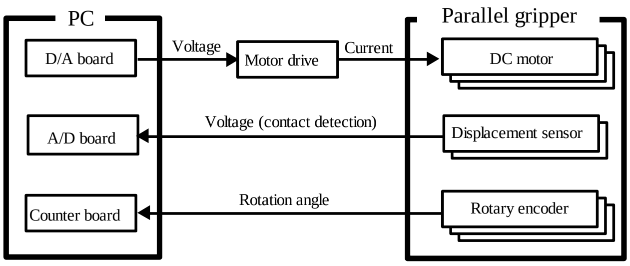
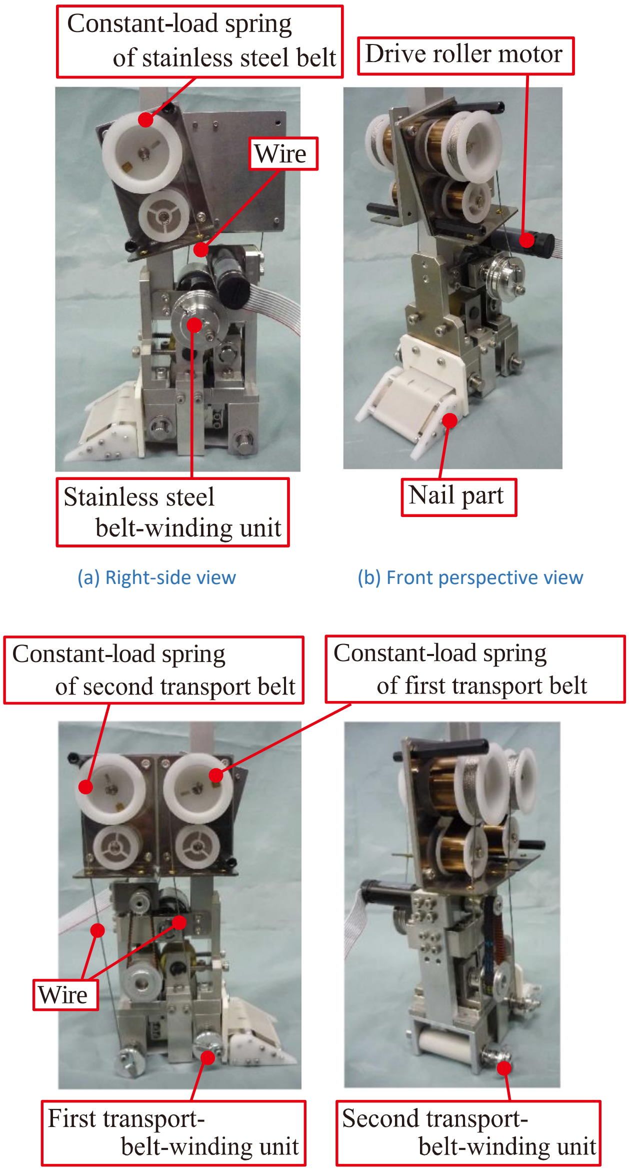


Figure 6. Drive control system.

3.2 *Structure of the extension nail mechanism*

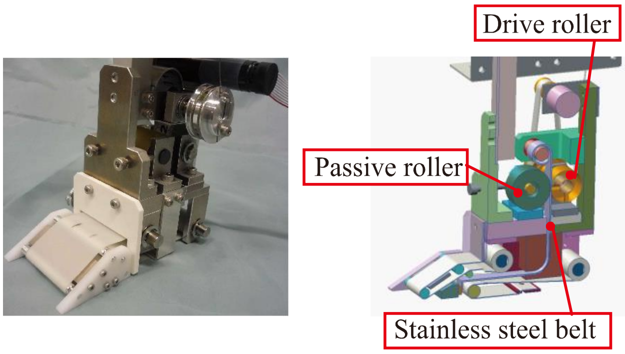
Figures 7–9 show images of the developed extension nail mechanism. The finger with the extension nail mechanism measures H 220 × D 115× W 110 mm with the nail contracted and has a total mass of about 1.1 kg. The stroke of the nail mechanism is 180 mm. For expansion and contraction, the winding unit of each belt combines a wire pull-out constant-load spring (1.96 N) and a passive rotating part. Three pull-out constant-load springs wind up the stainless steel belt, the first transport belt, and the second transport belt. The stainless steel belt, which is sandwiched between the drive roller and the passive roller, is sent out by rotation of the drive roller, thereby extending the nail portion. A small DC motor (4.5 W; reduction ratio 370:1) is connected to the drive roller via a timing belt. The first transport belt has a path that covers the nail surface such that the nail can smoothly slide underneath the object. The transport-belt material is high-strength silicone rubber (tear strength 32 N/mm). The inclination angle of the nail part is 30°.



(a) Right-side view (b) Front perspective view

(c) Left-side view (d) Rear perspective view

Figure 7. Appearance of the extension nail mechanism.



(a) Appearance (b) Internal structure

Figure 8. Nail mechanism structure.

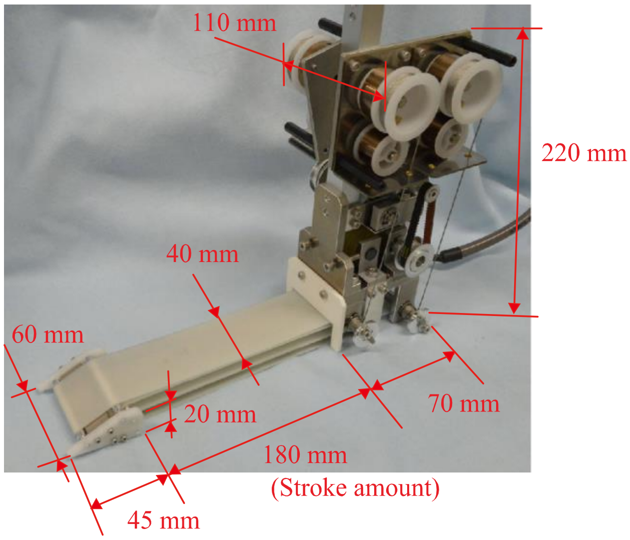


Figure 9. Dimensions of the finger with the nail extension mechanism.

3.3 *Inclination angle of the nail part*

We investigated the inclination angle of the nail that would allow it to smoothly slide underneath objects. Specifically, we considered the relation between the pressing force of the nail mechanism and the inclination angle of the nail.

Figure 10 is a schematic diagram showing the nail sliding underneath the object. Here, F [N] is the pressing force of the nail mechanism, ϑ is the nail inclination angle, R [N] is the surface pressure from the object to the nail surface, f_1 [N] is the frictional force between the nail's lower surface and the mounting surface, and f_2 [N] is the frictional force between the nail's upper surface and the object. Assuming that F is balanced with R, f_1, and f_2, the following equation is established.

$$F = f_1 + f_2 \cos\theta + R \sin\theta\,. \quad (1)$$

Furthermore, assuming that the friction coefficient between the nail's lower surface and the mounting surface is μ_1 and that the normal force is N_1 [N], the following expression holds for the friction force f_1 [N]:

$$\mathrm{f}_1 = \mu_1 \mathrm{N}_1\,. \quad (2)$$

Similarly, assuming that the friction coefficient between the nail's upper surface and the object is μ_2 and that the normal force is N_2 [N], the following equation holds for the friction force f_2 [N]:

$$\mathrm{f}_2 = \mu_2 \mathrm{N}_2\,. \quad (3)$$

From Eqs. (2) and (3), Eq. (1) becomes

$$F = \mu_1 N_1 + \mu_2 N_2 \cos\theta + R \sin\theta\,. \quad (4)$$

Assuming that friction coefficients μ_1 and μ_2 are extremely small due to the transport belt covering the nail mechanism, the following equation is established.

$$F \cong R \sin\theta\,. \quad (5)$$

Assuming the surface pressure R is a constant value independent of the nail inclination angle ϑ, the pressing force F of the nail mechanism decreases with smaller ϑ. In consideration of nail mechanism durability and Eq. (5), we set ϑ to 30°.

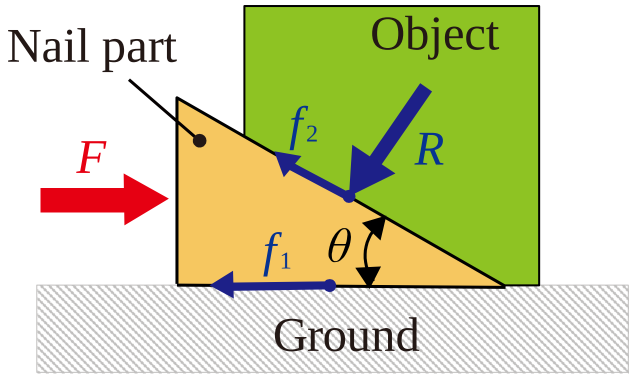


Figure 10. Schematic diagram of the nail sliding operation.

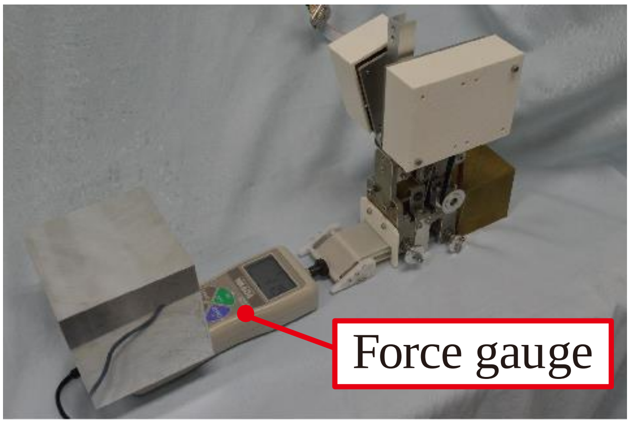


Figure 11. Measurement of the nail mechanism pressing force.

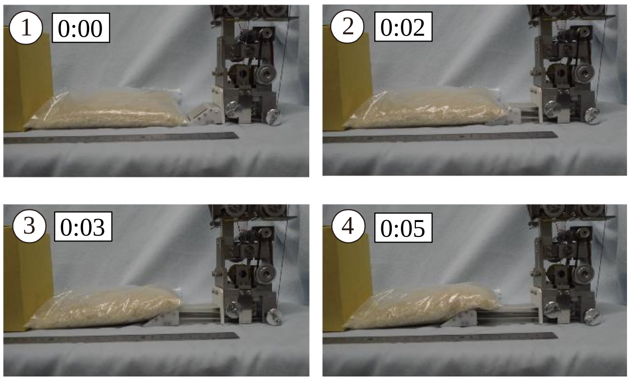


Figure 12. Evaluation of the nail mechanism sliding underneath a flexible object.

4 MECHANISM VERIFICATION

This section details the results of experiments using the developed parallel gripper, including the pressing force of the extension nail mechanism and the approaching action toward the bottom of a flexible object, the load resistance of the extended nail when magnetically connected to the opposing finger, and the grasping motion of the object. Previously, the position and orientation of the object were detected using an external sensor, but this time, to confirm the mechanism operation, information on the position and orientation of the object as well as the operation target values for each arm were given in advance, and the handling operations of the parallel gripper were performed based on this information.

4.1 Extension experiment of nail mechanism

As shown in Fig. 11, a weight was placed on a force gauge (DS2-500N; IMADA, Inc.) to immobilize it. Then, the force gauge was placed in contact with the tip of the nail mechanism, the nail mechanism was extended, and the pressing force was measured. The gauge showed that a maximum pressing force of 13 N was applied, confirming that the developed nail mechanism can generate the target force of 1 N or more.

As shown in Fig. 12, we verified the approach of the nail mechanism toward the bottom of the flexible object. A bag filled with about 0.6 kg of rice was used as the flexible object. In the experiments, the nail mechanism performed extension operations from the contracted state, and we visually confirmed whether the nail mechanism could slide underneath the flexible object. These experiments confirmed that the developed nail mechanism smoothly slides underneath the flexible object due to the arrangement of the transport belts on both sides of the stainless steel belt. The nail mechanism took about 5 s to reach the maximum extended state from the contracted state. We also confirmed that a winding structure combining a constant-load spring and passive rotating part during pawl retraction smoothly wound each transport belt. However, for the nail mechanism to smoothly slide underneath the bottom surface of the object, the bottom surface of the object needs to be somewhat round.

4.2 Evaluation of the load resistance of the extended nail mechanism

As shown in Fig. 13, we evaluated load resistance of the transport belt when the elongated nail mechanism was magnetically coupled to the opposing fingertip. The nail mechanism was in the maximum extended state. In experiments with the parallel gripper lifted by the robotic arm, a weight (about 1.8 kg) was placed on the center of the transport belt of the elongated nail mechanism, and we verified whether magnetic coupling of the nail mechanism could be maintained. Because the maximum payload of the robotic arm supporting the parallel gripper is 5 kg, we set the weight to 1.8 kg in consideration of the weight of the parallel gripper (4 kg). These experiments confirmed that even when a 1.8 kg weight was placed at the center of the transport belt, the magnetic fastening of the nail mechanism was not released, indicating that the load capacity was sufficient.

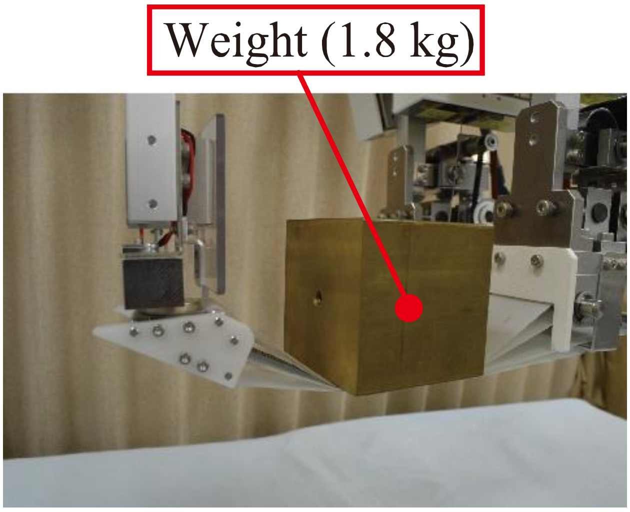


Figure 13. Load capacity evaluation of the extension nail mechanism.

4.3 Object grasping experiment

We performed a basic grasping motion experiment using the developed parallel gripper combined with a robotic arm. As described in Section 2.1, the rigid object was a cardboard box (H 90 × W 200 × D 140 mm; about 0.1 kg), and the flexible object was a long object (about W 70 × D 230 mm; about 0.1 kg) packed in cushioning material. In the experimental procedure, we first moved the parallel gripper to the position for grasping the target object by the robotic arm. Next, we adjusted the gap between the opposing fingers by operation of the open/close drive unit. Finally, the robotic arm picked up the target object.

Figure 14 shows how the rigid body was picked up. We confirmed that the nail mechanism can be more stably lifted by positioning it underneath the cardboard box during grasping. In Fig. 14, the transition time from the open state of the parallel gripper to lifting the object was about 15 s.

Figure 15 shows how the flexible object was picked up. During grasping, we confirmed that the extended nail mechanism slide underneath the flexible object, and that the extended nail mechanism magnetically connected to the opposing finger, allowing the flexible object to be lifted and transported. In Fig. 15, the transition time from the open state of the parallel gripper to lifting the object was about 48 s. It took this long because the extension operations for each nail mechanism were performed separately for verification of the mechanism.

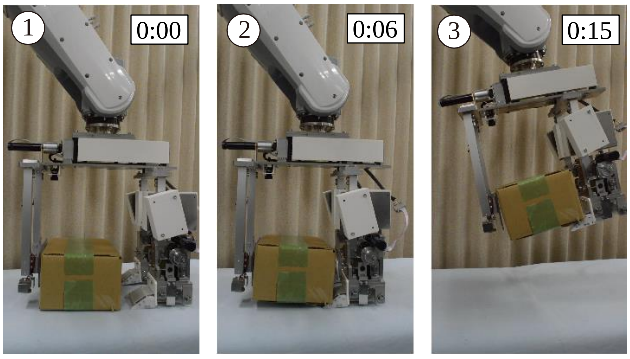


Figure 14. Experiments for grasping a rigid object.

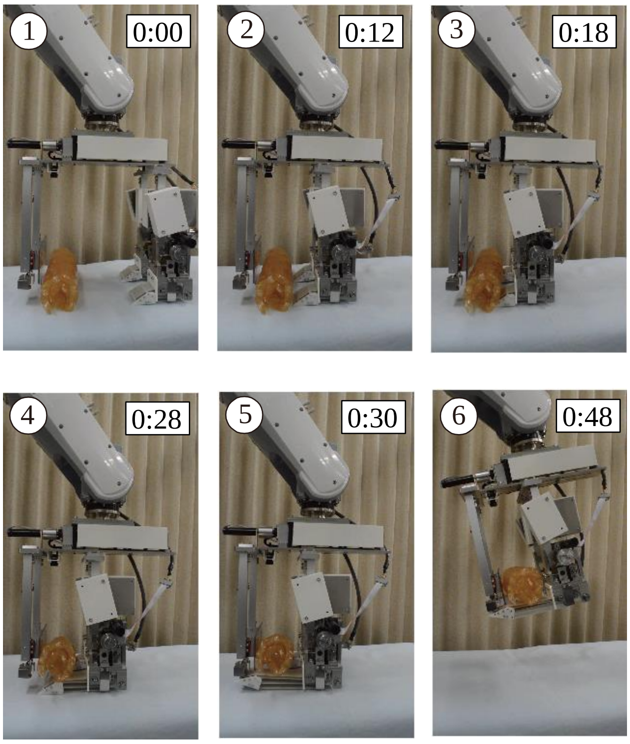


Figure 15. Experiments for grasping a flexible object.

4.4 Limitations of the system

We identified two main limitations of the system that need to be addressed in future research. One limitation is that the expansion and contraction operation times of the nail mechanism are long because it takes time to straighten the wound stainless steel belt. In addition, if the nail mechanism slides underneath the flexible object too quickly, the object might be damaged. Therefore, it is necessary to determine the appropriate movement speed of the nail mechanism in consideration of whether or not the object will be damaged.

The other limitation is that the nail mechanism may not be able to slide underneath the flexible object, as shown in Fig. 16. This occurs when the tip of the nail mechanism cannot enter the gap between the bottom of the object and the surface upon which the object lies. If the approach of the nail mechanism fails, the nail mechanism must be retracted again and the extension motion must be restarted. In the case shown in Fig. 16, it took about 13 s for the nail mechanism to resume the extension movement. Therefore, it is necessary to make the nail mechanism thinner for cases in which the gap between the surface and the object is small.

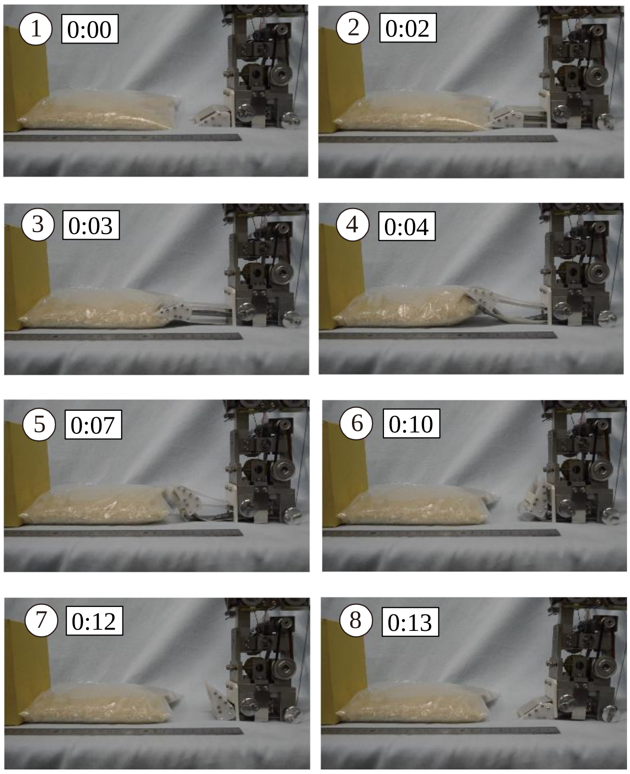


Figure 16. Example of the nail mechanism failing to slide underneath a flexible object.

5 CONCLUSION

Aiming to expand the range of applications for parallel grippers, we proposed an extension nail mechanism that can be mounted on one finger of a parallel gripper and described the verification of its mechanisms. In the proposed extension nail mechanism, the transport belts were arranged on either side of the extending nail part, allowing it to smoothly slide underneath the target object. To satisfy the design specifications for the extension nail mechanism (i.e., miniaturization and large expansion/contraction spans), each belt was elastically wound and arranged. With this configuration, we achieved a 180 mm expansion/contraction of the nail part. Because the elongated nail magnetically connected to the opposing fingertip, we confirmed that the extended nail could function even when supporting a weight of 1.8 kg. The developed parallel gripper grasps rigid cardboard boxes by adjusting the distance between the opposing finger mechanisms and grasps flexible objects by sliding an extension nail underneath them. A series of basic performance tests confirmed the utility of the developed parallel gripper.

In future research, we will investigate autonomous grasping operations by combining the developed parallel gripper with external sensors and a robotic arm, thereby promoting application of automated systems for logistics sites.

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