An End-Effector for Pinch and Slide Unfolding Using a Protruding Passive Rotation Mechanism

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***Abstract*–In this study, we focus on pinch and slide unfolding, an effective method for unfolding clothes. However, pinch and slide unfolding exhibits its drawbacks. For instance, when a cloth is unfolded, gravity pulls it downward, causing the cloth to fall through the gap between the fingers. Hence, this paper proposes a novel end-effector used for cloth manipulation to improve the success rate of unfolding. Our approach demonstrates two main characteristics: (1) By devising an appropriate finger shape and gripping motion, the hem of clothes can be prevented from being pinched in a bent state; (2) A protrusion is attached to the finger pad that can be passively rotated by a bearing, enabling continuous capturing of minute irregularities on the hem of clothes during pinch and slide unfolding. The proposed end-effector was constructed and attached to a robot arm. The end-effector's effectiveness was confirmed through experiments of unfolding squared cloth sheets.**

Index Terms–Cloth manipulation, pinch and slide unfolding, robot hand, protruding rotation mechanism

I. Introduction

Manipulating cloth products using an automated machine is a challenging task. For example, consider the task of casually folding a cloth product placed on a table into a desired shape. Observing the procedure when humans perform this task, in general, instead of achieving the target state directly from the placed state, the cloth product is first lifted and unfolded. By including such an unfolding procedure, it is relatively easy to transition from the initial crumpled shape to a known shape. That is, once the unfolding state has been achieved, the target state can be prepared by performing routine folding procedures. On this basis, unfolding a cloth is an important step for establishing a working outlook in the manipulation of cloth products.

This study proposes an end-effector that facilitates the unfolding manipulation of cloth products. We adopt pinch and slide unfolding [1] [2] as the manipulation method and investigate the hardware design and motion method of the proposed end-effector, which can increase the success rate of unfolding. Here, the assumption exists that two end-effectors exist for pinch and slide unfolding. Figure 1 shows the manipulation flow. First, use one end-effector to grab one corner of the target cloth product, and then, use the other end-effector to grab a part near the corner. After that, the latter end-effector is moved to the hem, so that the cloth does not slip off the finger. Due to this manipulation, the cloth product will be unfolded between the two end-effectors.

Fig. 1 Pinch and slide unfolding [2]

As another method, cloth unfolding can also be achieved by the following procedure. One end-effector is used to grab and hang a cloth product, a camera or the like is used to measure the cloth surface, a gripping point is found on the cloth, and the other end-effector is used to grab that part and unfold the cloth product [3] [4]. However, since cloth products can take various shapes, this method requires advanced state estimation, which may take a significant amount of processing time. Conversely, in pinch and slide unfolding, the unfolding process can start by gripping any point near where one end-effector has already been gripped. This is a simple task for a human; it can be performed without further visual inspection of the gripping position.

However, pinch and slide unfolding exhibits its drawbacks. One of them is the gravity force acting on the cloth. The gravity force pulls the cloth downward during pinch and slide unfolding; thus, the cloth may fall through the gap between the fingers. In other words, during pinch and slide action, the gripping force of the end-effector is adjusted to slide on the cloth, so the cloth will inevitably slide downward because of gravity. However, if the cloth can be manipulated in a way that avoids this phenomenon as much as possible, the usefulness of pinch and slide unfolding will increase. Therefore, in this study, we propose a novel end-effector that can improve the success rate of cloth unfolding.

The contributions of this paper are as follows:

- By devising the finger shape and gripping motion, the hem of the cloth can be prevented from being pinched in a bent state.
- A protrusion is attached to the finger pad, and the protrusion can be passively rotated by a bearing. This enables continuous capturing of minute irregularities on the hem of the cloth during pinch and slide unfolding.
- The proposed end-effector was constructed and attached to a robot arm. Then, its effectiveness was confirmed through experiments.

The structure of this paper is as follows. We present related work in the next section. Section III explains the related issues and our approach. Section IV introduces the proposed end-effector in detail. Section V describes this study's mechanism under various conditions for performance verification and the experimental results of pinch and slide unfolding using an actual robot. Finally, we summarize this study in Section VI.

II. Related work

A. Cloth Manipulation Using General-Purpose Hand

So far, the manipulation of cloth products has been realized using automated machines, including general-purpose robot hands. Maitin–Shepard et al. [5] folded multiple towels using a two-finger hand equipped with a pressure distribution sensor and a 3-axis accelerometer. Monsó et al. [6] proposed a planning method for picking up one cloth product from a pile of cloth products randomly stacked. A Barret Hand with three fingers was used in their method. Twardon et al. [7] proposed a topological expression in anticipation of application to work such as sleeved clothes and showed the detection of the opening of clothing. In their verification experiment, multi-finger hands (Shadow Dexterous Hands) were used to grip the clothes. Demura et al. [9] proposed a method for lifting cloth products folded and stacked on a table without collapsing their shape. The manipulation was performed using a single-arm manipulator equipped with a two-finger hand.

From the investigation above, we notice that conventional studies focused on grasping the desired cloth, but manipulations such as moving the robot hand while sliding on the target cloth have not been thoroughly investigated. This may be due to the lack of hardware potential in the case of two-finger hands. Alternatively, the dexterity of a multi-finger hand has not been fully utilized.

B. Specific End-effectors

End-effectors for cloth manipulations are available. The finger structure that can be inserted beneath the cloth is one point of emphasis. The CloPeMa project in Europe achieved many breakthroughs in fabric manipulation, including the two-fingered hand used by Doumanoglou et al. [11] to fold fabric products. This hand was proposed by Le et al. [12] and demonstrates a structure that allows the hand to be inserted into the gap between clothes for gripping. From another viewpoint, Kabaya et al. [10] constructed a two-finger robot hand with a rotation mechanism at the fingertips to pick up randomly placed cloth products. The rotation mechanism is also used in our study, but the expected effect is different from that in Kabaya's work.

These end-effectors facilitate basic movements such as picking up a cloth. Conversely, whether the hand configuration is appropriate for manipulations such as pinch and slide unfolding is unclear. Conversely, Donaire et al. [13] proposed an end-effector. One of its features is that a cam mechanism is built into the finger pad so that the friction between the cloth and finger can be adjusted. They demonstrated the proposed hand's high versatility in cloth manipulation by pinching a cloth product, sliding the finger while pinching it, and folding the cloth product. However, because the mechanism is inserted in the fingertips, the hand became large and heavy.

III. Issues and Approach

A. Issues of Pinch and Slide Unfolding

The assumption exists that a rectangular cloth is randomly placed on a table. The pinch and slide unfolding process in this study begins with the corners of the target cloth already picked and lifted. In other words, the cloth is hung, with the corner as the uppermost end. The hem of the cloth, which can serve as a manipulation target for pinch and slide action, exhibits different shapes from trial to trial. The unfolding manipulation is performed as follows, with an end-effector sliding onto the hem. Here two end-effectors are considered, which are called a right hand and a left hand, respectively. The right hand represents the proposed end-effector.

1. (Left hand) As a preparation, grab the corners of the cloth and lift it up
2. (Right hand) Move to the vicinity of the left hand
3. (Right hand) Correct the undesirable hem shape using the end-effector's structure and motion
4. (Right hand) Grasp the cloth
5. (Right hand) Unfold the cloth by pinch and slide action

In our approach, the first step is the initial state on pinch and slide unfolding, and some points to note exist. In general, the cloth material hangs down because of its weight, and the opposite corner against the gripped corner is placed on the lowermost end. As a result, cloth hems may be significantly bent to face the center of the cloth. If the unfolding manipulation begins from such a state, the unfolding may fail because the bending cannot be resolved during the pinch and slide action.

In addition, a possibility exists that the cloth will fall off from the end-effector during pinch and slide unfolding. Such a situation should be prevented as well. On this basis, two main requirements are found for using the end-effector.

(a) Ability to eliminate the bending of the hem during the unfolding manipulation

(b) Cloth does not slip off from the end-effector

B. Our Approach

As a countermeasure to the first requirement (a), we adopt the policy of sandwiching a cloth product by surface contact. Furthermore, we devise a combination of a special finger shape and end-effector movement to eliminate bending when the cloth has been grabbed. As a countermeasure to the second requirement (b), we attach a protrusion on the finger pad that captures minute irregularities on the cloth hem. However, capturing irregularities on the hem simply by using a protrusion is difficult. Nonetheless, one solution to this problem is to make the protrusion passive. Therefore, we mount the protrusion on a passively rotating disk. In the next sections, we introduce the concrete end-effector structure and motion strategy.

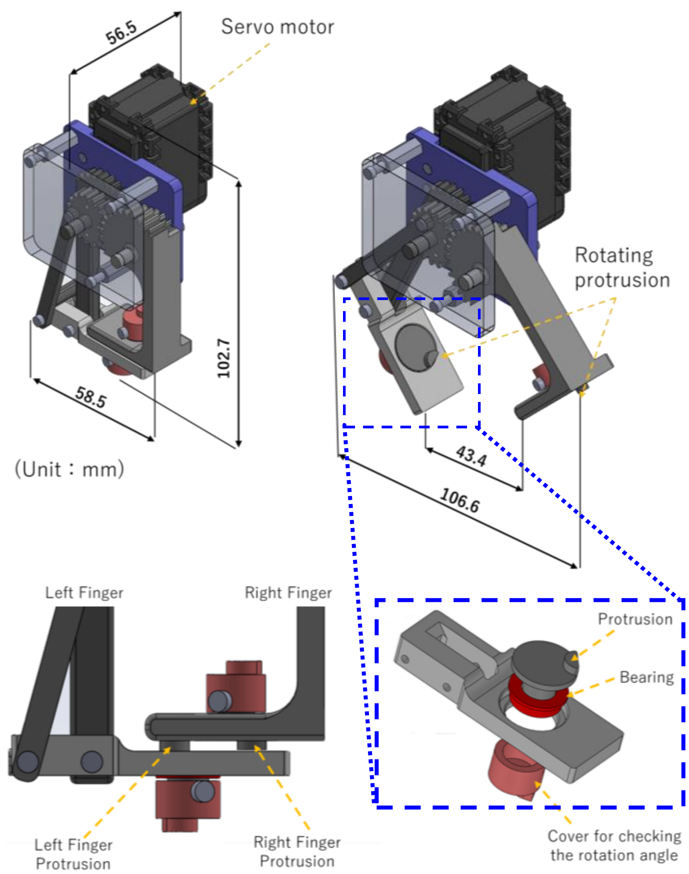


Fig. 2 The proposed end-effector

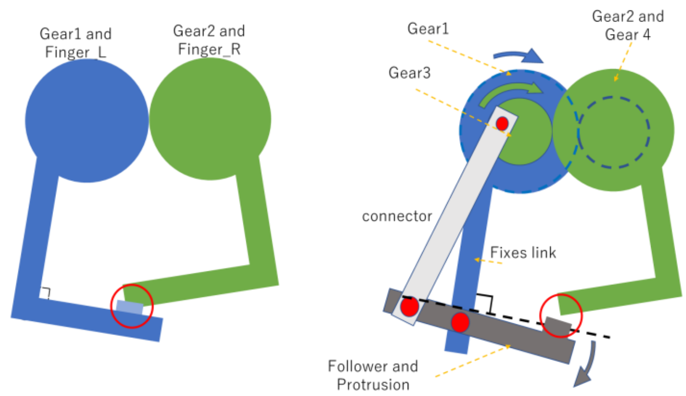


Fig. 3 The link structure to open the end-effector without interfere.

IV. Proposed End-Effector

A. Structural Overview

A schematic of the proposed end-effector is shown in the upper panels of Fig. 2. The cloth is sandwiched between two fingers, and the fingers are driven by a single servomotor. That is, the torque of the motor is transmitted from the motor shaft via gears to the two fingers.

The end-effector demonstrates two main features. This first feature is a protrusion attached to the pad of each finger. The protrusions exhibit a semicircular shape and are arranged so that they alternately face each other when the end-effector is closed, as shown in the lower left panel of Fig. 2. In addition, the protrusion is mounted on a disk in the bearing and can rotate freely. That is, when this protrusion makes contact with the cloth during pinch and slide unfolding, it rotates away from the cloth in response to the external force. The lower right panel of Fig. 2 depicts the rotational protrusion mechanism in detail. Since the rotation is passive, the success rate of the unfolding motion is increased by parrying the force accompanying the movement of the end-effector and the force received from the cloth.

The second feature is the shape of the finger and its driving method. As previously mentioned and shown in the lower left panel of Fig. 2, two fingers alternately face each when the end-effector is closed. The main reason for using this finger shape is to allow surface contact between the finger and some areas of the fabric, as opposed to the contact between protrusions and the fabric. One of these effects will be discussed in detail in IV-C. However, one caveat is found here: when closing the end-effector, the protrusion and the tip of the finger will interfere with each other if the rotation angle is the same for both fingers. Therefore, in this study, this is avoided by adopting a speed-increasing mechanism and a link mechanism using two-stage gears. Details are provided in the next subsection.

B. Structure for Finger Opening and Closing

Figure 3 illustrates the situation of opening and closing the proposed end-effector. Simply opening and closing both fingers with one motor driving causes interference between the fingertip and the protrusion, as shown on the left side of the figure. Therefore, we devise a structure, as shown on the right side of the figure.

The following is the driving force for opening and closing the end-effector. Gear 1 is directly connected to the motor, and gear 1 and gear 2 are in mesh with each other. As a result, each finger fixed to gear 1 and gear 2, respectively, is rotated. At this time, to avoid the interference of the protrusion, the link mechanism shown on the right side of Figure 3 is adopted, allowing the finger to close without interference by swinging the fingertip.

The link mechanism should exhibit a rotational pair in addition to the reference stationary clause. Here, the link extending from gear 1 is a stationary node, and gear 3, arranged to overlap gear 1, is a rotational pair. Gear 3 is not fixed to gear 1 and is independent of gear 1’s rotation. In addition, since gear 1 is fixed to the stationary node, it cannot be a kinematic pair. Gear 3, a kinematic pair of rotations, needs to rotate more than gear 1. Thus, more motors could be added; however, in the proposed end-effector, the above-mentioned number of rotations for gear 1 is used. Specifically, by using a two-stage gear exhibiting gear 2 and gear 4, the rotation of gear 1 is accelerated and transmitted to gear 3. The gear ratio from gear 1 to gear 3 is 1: 2.25. This gear ratio was determined by trial and error. This difference in rotation angle enables the swinging motion of the fingertips and avoids interference.

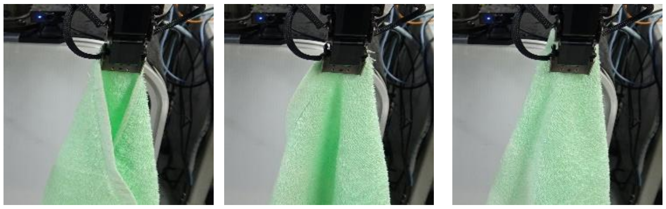


Fig.4 Possible bending pattern

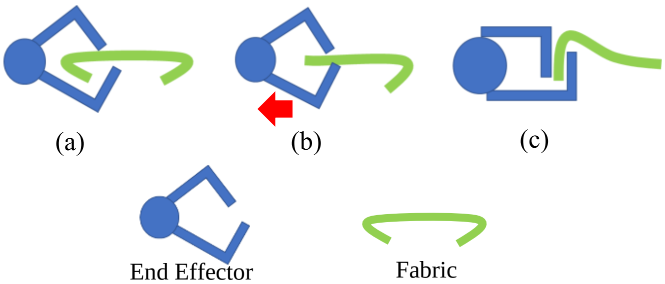


Fig.5 Bending state cancellation

C. *Preliminary Action to Cancel Hem Bending*

Figure 4 shows possible cloth shapes before pinch and slide unfolding. In almost cases, hems bend toward the center of the cloth. As mentioned in subsection III-A, one issue regarding pinch and slide unfolding is that the unfolding proceeds without being able to eliminate such bending. This situation can be avoided by employing the proposed finger shape. The motion procedure is as follows:

(a) Loosely close the fingers near the center of the cloth to allow the fingertips to touch the cloth.
(b) Move the fingertips while touching the cloth to eliminate the bending.
(c) When the cloth around the fingertips is unfolded, firmly close the fingers, sandwiching the cloth.

Fig. 5 illustrates this procedure. This enables the grabbing of the cloth without undesired bending. Moreover, when the bending is small, step (a) can be skipped, and the manipulation is started from (b).

D. *Protruding Passive Rotation Mechanism*

Cloth falling out of the end-effector during manipulation is the most common failure in pinch and slide unfolding. Therefore, a protrusion is provided on the finger pad. This protrusion is caught on the step on the hem of the cloth to prevent it from falling off.

However, based on our prior investigation, simply adding a protrusion to the finger pad does not significantly improve the success rate of unfolding. When based on the behavior of the pinch and slide action, the following phenomenon was observed. In the first stage, when the cloth is gripped by the end-effector, the finger is not yet in contact with the cloth hem. After that, the pinch and slide action is applied, and the protrusion makes contact with the hem. At this moment, the force received from the hem of the cloth distorts the finger, creating a gap in the fingers, through which the cloth falls off. To mitigate this phenomenon, the maximum force that the protrusion receives from the cloth hem should be suppressed. Therefore, the protrusions can be passively rotated, so that unfolding can be performed while parrying the force and preventing the creation of gaps through which cloth slips off. As described in the experiment, pinch and slide unfolding can be stably performed regardless of the end-effector's direction. In addition, since end-effectors are generally attached to the tip of a robot arm, they should be lightweight and compact. The proposed mechanism does not use an actuator because of the passive rotation. Therefore, it is suitable for end-effectors.

Besides, the concept of incorporating a passive rotation mechanism into finger pads has been previously reported. Osawa et al. [14] achieved the unfolding manipulation of cloth products using two manipulators. In their study, a two-finger hand was used, and passively rotating parts were embedded in the finger to prevent unnecessary wrinkles when hanging clothes. In this study, we found that a similar mechanism can stabilize pinch and slide unfolding.

The shape of the protrusions should be considered. For instance, Shibata et al. [1] thoroughly investigated pinch and slide unfolding. They developed several types of fingertip shapes and verified them through experiments. Their results showed that the success rate was high when a half-rounded rectangular shape was used. Referring to their findings, we adopted the same protrusion shape in this study.

Table 1 Basic specifications of Dynamixel motor

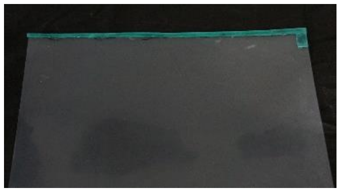
Stall torque	1.8N•m (at 12V, 2.2A)
Supply voltage	11.1V
Output axis operating range	0～300°
resolution	0.29° （10bit)

V. EXPERIMENTS

A. *Experiment Settings*

The proposed end-effector shown in Fig. 2 has been manufactured. Almost all parts of the end-effector were manufactured using a three-dimensional (3D) printer, except for fixtures such as screws and spacers. ABS (Acrylonitrile-Butadiene-Styrene) resin, which is a common material for 3D printers and demonstrates excellent mechanical properties such as impact resistance and rigidity, was used for modeling. A Dynamixel AX-18A manufactured by Best Technology Inc was the motor used. Table I lists the main specifications of the motor. The maximum opening width of the end-effector was 43.4 mm, and the total weight was 118.4 g.

(a) File folder1



(b) File folder2

(c) Fabric1

(d) Fabric2

Fig. 6 Target folder/cloth

Table II Folder/cloth status

	Size [mm^2]	Thickness [mm]	Thickness of edge [mm]	Weight [g]
File folder1	301×210	0.20	1.54	13.8
File folder2	301×215	0.20	1.66	13.8

(a) File folder status

	Size[mm^2]	Thickness[mm]	Weight[g]
Fabric1	344×348	2.32	36.4
Fabric2	898×282	0.43	28.4

(b) Fabric status

As a preliminary step to the experiment using cloth fabric, we tested the pinch and slide unfolding of a material harder than cloth. The objects used in the experiment were plastic file folder. The file folders were given an edge as shown in upper panels of Fig. 6. The thickness and size are shown in the upper part of Table II. Two adhesives were placed at the borders of the edges to create obstacles in the pinch and slide unfolding. The obstacles were approximately 2 mm in size and 1 mm in thickness. Two types of file folder were prepared and obstacles were differently arranged with them.

The bottom panels of Fig. 6 shows two squared cloth sheets used in the pinch and slide unfolding experiment. The bottom part of Table II lists the thickness and size of each sheet. Next, the thickness of the cloth sheets was measured using a constant pressure thickness measuring device. The target part of the sheet for pinch and slide unfolding was hemmed. Hemming is a processing method in which the edge of clothes is folded back and sewn to prevent the thread from fraying. Cloth 1, shown in Fig. 6, is a general hand towel made of 100% cotton, and the hem-processed edge is not very thick. Cloth 2 is a sufficiently thin cloth sheet (it is thin enough to show through on the other side), but its hem thickness is significantly thicker than that of the non-edge part.

A dual-arm robot HIRO manufactured by Kawada Robotics Co., Ltd. was used for the experiments. An existing two-finger hand was attached to one hand (left hand), and the proposed end-effector was attached to the other hand (right hand) of the robot. The extent of movement of the right arm was determined in advance according to the folder size and the cloth size. Pinch and slide unfolding was started as follows: a person picked up the cloth from its corner, which was randomly placed on a table, and then the robot's left hand held the cloth's corner. This meant that the initial shape of the cloth varied in each trial. After that, the robot gripped the cloth at another position by moving the right arm and closing the right end-effector near the already gripped position of the cloth. The width for sandwiching the cloth was 2 mm, and the height of the protrusions was 2 mm. The shape of the protrusion was a semi-cylinder, and its radius was 3 mm. These values were experimentally selected.

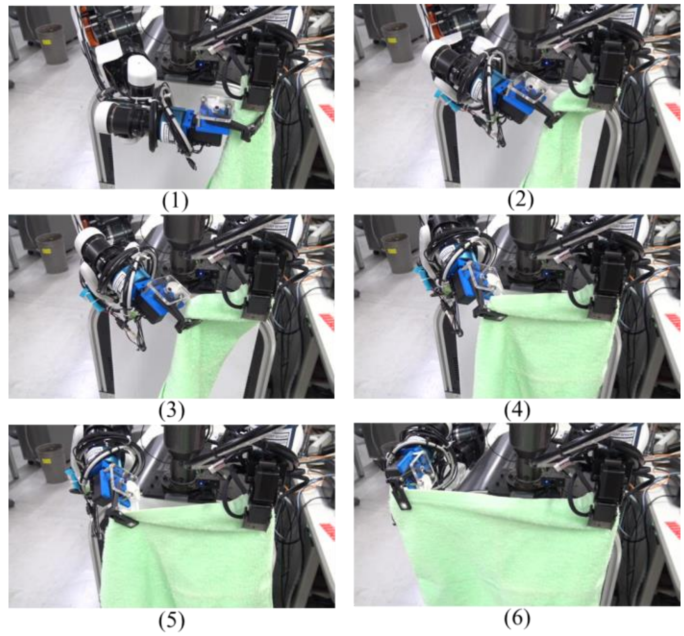


Fig. 7 Example of pinch and slide unfolding

Regarding the success/failure judgment of the experiment, if the cloth was in the following state at the end of unfolding, it was deemed a failure.

- The folder/cloth has fallen from the end-effector.
- The end-effector is not in contact with the hem of the folder/cloth-sheet.

B. *Experimental Results*

Figure 7 shows several images of when the unfolding task is successful. Here, the first gripping point is deeply located inside the cloth, but the position gradually moves close to the hem during unfolding. The protrusions safely captured the hem of the cloth midway through unfolding, and appropriate unfolding was achieved.

To confirm the effectiveness of the proposed end-effector, the function of the passively rotating protrusion was evaluated. Specifically, several patterns regarding protrusions were created, including the presence or absence of passive rotation and the radius of protrusion shape. The success rate of pinch

Table III Effect of passive rotation mechanism

Tensile direction	Diagonally below	Horizontal	Diagonally above
File folder1	5/5	5/5	5/5
File folder2	5/5	5/5	5/5
Fabric1	8/10	10/10	10/10
Fabric2	9/10	9/10	9/10

(a) With passive rotation

Tensile direction	Diagonally below	Horizontal	Diagonally above
File folder1	5/5	5/5	5/5
File folder2	5/5	5/5	5/5
Fabric1	5/10	10/10	6/10
Fabric2	10/10	10/10	6/10

(b) Without passive rotation

and slide unfolding was investigated in each case. Each experiment is explained in detail below.

First, we verified the significance of passive protrusion rotation. The passive rotation mechanism was excluded, and the protrusion was fixed on the finger pad. Then, the finger pad was used to perform unfolding multiple times, and the results were compared to the results obtained when the passive rotation mechanism was considered. In this experiment, three direction types of the proposed end-effector were established: horizontal, 30° downward inclination, and 30° upward inclination.

Table III shows the results of 5 or 10 unfolding operations in each direction. No significant difference was obtained in the experiment with file folders. It was observed that the end-effector's fingers slightly distorted to avoid obstacles when non-rotating protrusions were used. On the other hand, with the passively rotating protrusions, the end-effector avoided the obstacle by rotating the protrusion. On the other hand, in the case of cloth, no significant difference was obtained in the unfolding in the horizontal direction. Overall, a high success rate of unfolding was obtained, proving the effectiveness of the protrusions. Similarly, in the inclined direction, with the passive rotation considered, the success rate was high. This result shows that the passive rotation during sliding makes successfully unfolding the cloth easier, even when the force applied from the cloth hem varies.

In addition, the success rate of unfolding based on the initial shape of the cloth was investigated. The three types of photographs shown in Fig. 4 show examples of the following shape states from the left: The hem is bent toward the front, no large bend exists, and the hem is bent toward the back. According to the results, with the passive rotation mechanism considered, the success rate in the first and third patterns is almost 100%. The second pattern exhibits a few failures. Conversely, without a passive rotation, overall, more failures occur.

Next, the effectiveness of the turning radius of the protrusions was investigated. Figure 8 shows a plan view of the protrusion. The turning radius varied between 3, 5, and 7 mm, and the experiment was conducted 10 times under each radius condition. The experimental results are shown in Table IV. In Cloth 1, the success rate increased as the turning radius increased. This is probably because when the radius of gyration is small, the rotational force cannot be obtained from the cloth and it does not follow the hem well. In contrast, in Cloth 2, no difference was found in the number of successes, even with a varying turning radius. Cloth 2 is thinner and lighter than Cloth 1, allowing it to slide and unfold, even if the rotating force was not applied. Therefore, a large turning radius is considered effective for unfolding heavy clothes such as Cloth 1.

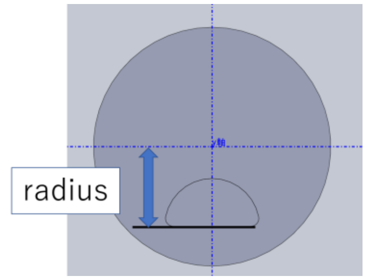


Fig. 8 Radius of gyration of protrusions

Table IV Effect of the radius of gyration

Radius of gyration	3mm	5mm	7mm
Fabric1	6/10	7/10	10/10
Fabric2	10/10	10/10	9/10

VI. Conclusions

In this paper, we proposed a novel end-effector for pinch and slide unfolding, which is a basic cloth manipulation process. Also, we proposed a rational finger shape and a gripping method to eliminate unnecessary cloth bending. In addition, to prevent the cloth from falling off the proposed end-effector during pinch and slide action, a passively rotating protrusion was attached to the fingers, and the protrusion's effectiveness was confirmed by an actual cloth unfolding task using a dual-arm robot.

In the future, we will devise ways to increase the success rate of unfolding and clarify the principle of pinch and slide action. In addition, we will improve the end-effector’s versatility.

Acknowledgment

This work was partially supported by KAKENHI and JST [Moonshot R&D][Grant Number JPMJMS2034].

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