A Pair of End-Effectors for Unfold-to-Fold a Fabric by Dual-Arm Manipulation*

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***Abstract*— This paper describes a pair of end-effectors for doing a unified fabric manipulation task termed unfold-to-fold. For the unfolding action, a pinch-and-slide motion have been employed, and the mechanical structure and motion method of the robot end-effectors have been studied to increase the success rate of this motion. However, there are several factors that can cause the work to fail. One of them is the gravity applied to the fabric itself. During the unfolding, the fabric may be pulled downward and falls through the gap between the fingers. If cloth manipulation can be performed in a way that avoids this accident as much as possible, the usefulness of pinch-and-slide unfolding will increase. In this study, we propose a novel end-effector that can improve the success rate of the unfolding. We also make it possible to fold the fabric in two while lifting it up with the other novel end-effector, thereby streamlining the folding manipulation. We confirmed the effectiveness of the proposed end-effectors by conducting an experiment with several fabrics of different thicknesses and weights.**

I. Introduction

Making fabric manipulation possible with automatic machines is a challenging issue. For example, consider the task of folding a fabric product placed randomly on a table into a desired target shape. Observation of the human procedure for this task reveals that, in general, the target shape is not achieved directly from the crumpled state, but rather, the cloth is first lifted and opened, that is "unfolded". This unfolding process has the effect of transitioning the fabric from its initial disordered shape to a known shape. This allows the fabric to be folded by following a routine procedure. This indicates that unfolding a fabric once and then folding it is an effective strategy for manipulating fabric products.

The purpose of this study is to construct end-effectors that facilitate the folding of fabrics. The general procedure of folding is as described above, with the assumption that the unfolding manipulation is performed before folding. For the unfolding action, a pinch-and-slide motion [1, 2] is employed, and the mechanical structure and motion method of the robot end-effectors are studied to increase the success rate of this motion. The pinch-and-slide motion is an unfolding method that assumes the existence of two end-effectors. The flow is shown in Fig. 1. First, one end-effector grasps a corner of the fabric, and the other end-effector grasps the nearby area. Then, the latter end-effector is moved so that it slides on the hem of the fabric so that the fingers do not leave the fabric. The fabric is then unfolded between the two end-effectors. After that, it moves to folding phase, aiming to fold the fabric properly.

Many other methods of unfolding fabric have been proposed in previous studies. One method is to grasp the fabric

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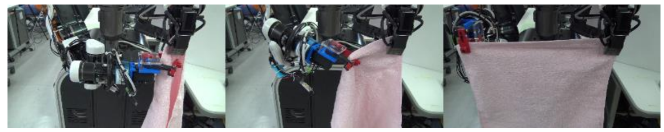

Fig. 1 Unfold-to-Fold task with pinch-and-slide unfolding [5]

with one end-effector and hang it, measure the fabric with a camera or other device, find another grasping point, and grasp it with the other end-effector and then unfold it [3, 4]. Since fabric can take various shapes, this method requires a high level of state estimation, and therefore, in some cases, a lot of processing time. On the other hand, pinch-and-slide unfolding can start when one end-effector grasp a nearby location where the other end-effector has already grasped. For human being, this is an easy manipulation way that can perform without having to keep looking at the grasping part. However, there are several factors that can cause the work to fail in pinch-and-slide unfolding. One of them is the gravity applied to the fabric itself. During the unfolding, the fabric may be pulled downward and falls through the gap between the fingers. In the pinch-and-slide process, the end-effector's grasping force is adjusted enough to allow the fabric to slide, so it is inevitable that the cloth slips downward due to gravity. However, if cloth manipulation can be performed in a way that avoids this accident as much as possible, the usefulness of pinch-and-slide unfolding will increase. In this study, we propose a novel end-effector that can improve the success rate of the unfolding.

By the way, in all of the aforementioned methods, it is customary to place the fabric on a table after unfolding, and then fold it by holding the corners with both hands. In this study, we introduce a new method in this regard. In other words, we make it possible to fold the fabric in two while lifting it up with both hands, thereby streamlining the folding manipulation.

The contributions of this study is as follows:

- We improved an end-effector for pinch-and-slide unfolding [5] to solve the problem of the existing mechanism. The improved end-effector enables the unfolding of different thicknesses fabric.
- We focus on an unfolding-to-folding task. We developed an end-effector and a motion method to perform the task smoothly.
- We fabricated the proposed end-effectors, and confirmed its effectiveness by conducting an unfolding experiment with several fabrics of different thicknesses and weights, and the unfolding-to-folding task.

This paper is organized as follows. The next section introduces related work. Section III describes the problem settings and our approach, and Section IV details the end-effectors proposed in this study. In Section V, the mechanism is examined under several conditions to verify its performance, and the results of an experiment using a real robot to demonstrate the pinch-and-slide unfolding are reported. Finally, Section VI summarizes this study.

II. Related Work

A. *Cloth Manipulation Using General-Purpose Hand*

Automation of fabric manipulation has been realized in the past, often using general-purpose robotic hands. Maitin-Shepard et al. [6] used a two-finger hand equipped with a distributed pressure sensor and a three-axis accelerometer. First, a towel was unfolded on the table, then folded by grasping the corners with both hands. Monsó et al. [7] proposed a planning method for extracting a piece of fabric from a messy pile of fabrics, and verified the method with experiments on a real robot. Barret Hand, three-fingered dexterous hand, was used there. Cuén-Rochín et al. [8] used a method in which a fabric placed on a table in a wrinkled state is manipulated by pressing the fabric with the tip of one finger and sliding it on the table. Demura et al. [9] proposed a method of lifting fabrics folded and stacked on a table without losing their shape. A single arm manipulator with a two-fingered hand was used to perform the manipulation.

In reviewing the above, previous studies have succeeded in grasping fabrics, but have not examined in depth manipulation such as moving the hand while touching the fabric. Otherwise, it is assumed that the unfolded cloth is placed on a table and manipulated from there.

B. *Specific End-effectors*

There are also dedicated end-effectors that focus primarily on fabric manipulation. Kabaya et al. [10] constructed a two-fingered robot hand with a rotating mechanism at the fingertips to grab up randomly placed fabric products. Doumanoglou et al. [11] realized a task of unfolding fabric products. The hand used in this task was proposed by Le et al. [12]. It had a structure of inserting a fingertip between fabrics for grasping. Yamazaki et al. [13] constructed an end-effector with a structure that can both wind and pinch. They showed that the end-effector can pick up both thin, light, and easily stick to each other, such as cotton fabrics, and hard and slippery fabrics, such as fabric rubber.

These end-effectors make basic movements such as picking up fabric easier. On the other hand, it is not clear whether the hand configuration is appropriate for manipulations such as pinch-and-slide manipulation. On the other hand, there is an end-effector proposed by Donaire et al. [14]. One of its features is that a cam mechanism is incorporated in the fingerpad to adjust the friction between the cloth and the finger. The end-effector was shown to be highly versatile in the category of cloth manipulation, as it could pick up the cloth, slide the finger while picking up the cloth, and fold the cloth product. On the other hand, it was relatively large and heavy. This is because a motor is attached to the fingertip to adjust the frictional force of the gripping area. Heavy and large end-effectors require more power for robots and may limit its manipulation range. Therefore, the end-effector should be small and lightweight.

III. Issues and Approach

A. *Issues on Unfold-to-Fold Task*

The Unfold-to-Fold task in this study focus on the manipulation after the cloth is grasped, and it is assumed to start with a rectangular piece of fabric that is lifted by picking its corners. That is, the fabric is hung with the corner as the top hem and the hem of the fabric that will be used for the pinch-and-slide is a different shape for each trial.

The Unfold-to-Fold task is performed with one end-effector picking the fabric and another end-effector in the following steps. Here, we use the words left hand and the right hand. The right hand is the end-effector for pinch-and-slide unfolding, and is mainly used in Unfolding. The left hand is mainly used for Folding.

1. (Left hand): As a preparation, grasp a corner of the fabric and hung it,
2. (Right hand): Move the hand nearby the left hand, and touch near an hem of the fabric,
3. (Right hand): Pinch-and-slide unfolding,
4. (Left hand): Grasp an hem sticking out from the fingers of the right hand,
5. (Left & Right hand): Fold the fabric in two.

The second item is the first action for the pinch-and-slide unfolding, where the following points should be noted. In general, the fabric hangs down due to its own weight, and the corner opposite to the corner being grasped comes to the bottom side. As a result, the hem of the fabric that is the target of the sliding action may be folded so that it faces the center of the fabric. If the unfolding manipulation is started in this state, the fabric is pulled so that it is caught by the end-effector, and the unfolding cannot be performed properly.

In addition, the fabric may fall out of the end-effector during the pinch-and-slide manipulation. It is desirable to prevent this phenomenon as well. In other words, the two main requirements for the right-hand end-effector are as follows.

(a) Fabric folding can be eliminated during the unfolding manipulation,

(b) the fabric does not fall out of the end-effector.

After unfolding is accomplished, the fabric is folded in two. For this purpose, the following requirements are made of the left-hand end-effector.

(c) To grip the other corner of the fabric without releasing the corner already gripped.

If all (a)-(c) can be achieved stably, the Unfolding-to-Folding task can be realized while hanging in the air, leading to an efficient folding action.

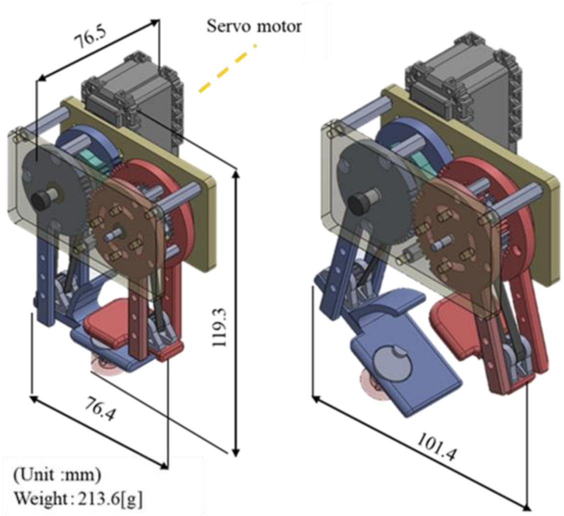

Fig. 2 The end-effector with pinch-and-slide unfolding as main purpose (PS-hand)

B. Our Approach

In a previous study, the authors proposed an end-effector for the right hand [5]. We describe the main points of this end-effector. As a countermeasure described as (a) in the previous subsection, we adopted a policy of clamping the fabric in a surface contact. The shape of the fingers and the movement of the end-effector were devised so that unnecessary folding would be removed when unfolding process proceeds. On the other hand, as a countermeasure to (b), a protrusion is attached to the fingerpad so that the hem of the fabric does not fall out from between the fingers. Since we noticed that it is difficult to keep catching the hem simply by providing protrusions, we added a passive rotation mechanism to the protrusions.

Experiments have confirmed that this policy works to a certain degree. However, there was room for improvement in the countermeasure for (a). In addition, the thickness of fabrics that can be handled is limited due to the restrictions of the mechanism, and there was a problem in terms of versatility. In this study, we propose a new mechanism and device to solve these problems.

On the other hand, the end-effector for the left hand is a new development target. In this study, a mechanism is devised based on the function of the fingers when a human being performs a similar folding manipulation. We will try to make it possible to grasp multiple corners with a small number of actuators, and to make the mechanism compact and lightweight.

IV. Proposed End-Effectors

A. PS hand: Overview

First, an end-effector whose main purpose is pinch-and-slide unfolding is described. This is the hand on the side referred to as the right hand in the previous section, and will be referred to as the PS (pinch-and-slide) hand. The appearance of the PS hand is shown in Fig. 2. This end-effector is composed of two major parts: the pinching part and the part for eliminating unnecessary folding.

The pinching part is the most important part for pinch-and-slide unfolding. In the previous study, it was confirmed that a

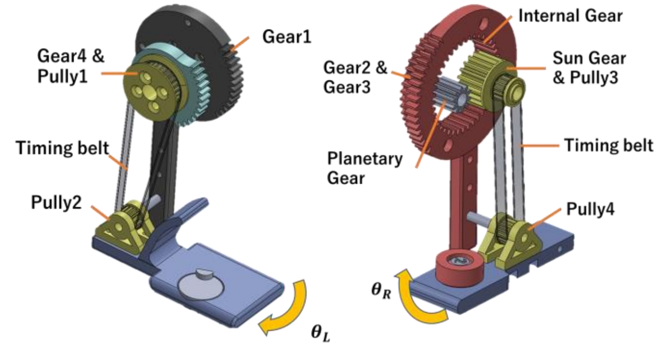

Fig. 3 Detail structure of each finger

TABLE 1 Teeth number of rotating parts

	z: gear and pully teeth
Gear1	50
Gear2	50
Gear3	60
Gear4	40
Internal Gear	40
Planetary Gear	10
Sun Gear	20
Pully1	28
Pully2	14
Pully3	14
Pully4	14

high success rate was achieved by placing a protrusion on each of two fingerpads. However, the fingers were parallel only when the end-effector was fully closed. In other words, the distance between the fingers when clamping the fabric was defined by the hardware. The PS hand, therefore, makes the fingers oscillate in opposite directions as the end-effector opens and closes. As long as the rotation angles of the oscillation are consistent, the two fingers always remain parallel, regardless of the degree to which the end effector is opened or closed. To achieve this oscillating motion, a planetary gear mechanism and a belt and pulley mechanism are combined. This enables the movement without the need for additional actuators.

B. PS hand: Detail of Finger Parts

The PS hand uses only one motor to perform the opening and closing of the left and right fingers by oscillating both fingers simultaneously. The direction of rotation is the most important factor to be considered for the oscillating motion. The left fingertip rotates so that it opens further as the hand open. In contrast, the fingertip of the right finger performs an oscillating motion so that it closes in relation to the hand's opening in order to maintain parallelism with the left finger.

Figure 3 shows a detailed view of each finger. The gear 4 of the left finger is independent of the gear 1, and is sped up relative to the gear 1 by meshing with the gear 3 on the right finger. The increased speed is transmitted to the fingertip by a belt to perform an oscillating motion. The right finger has a two-stage gear, a planetary gear mechanism, and a belt mechanism. Planetary gears are characterized by their ability to switch the speed transmission ratio and direction of rotation by selecting the fixed elements, and by the compact design of the device. In the proposed end-effector, the direction of the oscillating motion of the right fingertip and the transmission

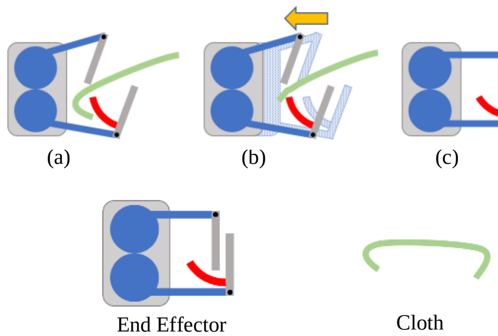

Fig. 4 Bending state cancellation

mechanism other than the planetary gear mechanism are selected to reverse the direction of rotation. The velocity transmission ratio $Ratio_{L/R}$ to the oscillating motion of the fingertip to the rotation angle of the motor is given by Eqs. (1) and (2), where z is the number of teeth. The gear ratio 2 is obtained by changing the number of teeth in each part as shown in Table 1.

$$Ratio_L = \left\{\frac{Z_{gear2}}{Z_{gear1}} \cdot \frac{Z_{gear3}}{Z_{gear4}} - 1\right\} \cdot \frac{Z_{pully1}}{Z_{pully2}} + 1 \quad (1)$$

$$Ratio_R = \left\{\frac{Z_{gear2}}{Z_{gear1}} \cdot \frac{Z_{InternalGear}}{Z_{SunGear}} + 1\right\} \cdot \frac{Z_{pully3}}{Z_{pully4}} - 1 \quad (2)$$

C. PS hand: Bending State Cancellation

The above mechanism makes it possible to hold fabric of various thicknesses with surfaces contact. On the other hand, some of the movements that could be achieved with the previous end-effector became difficult. Specifically, it became difficult to eliminate the unnecessary fold from the first suspended state of the fabric. This is because the robot arm needs a large range of motion in order to insert the fingertips of the PS hand between the folds of the fabric, whereas the previous end-effector was able to insert the fingertips between the folds of the fabric and hook them.

To solve this problem, an auxiliary finger is attached to the outer finger joint to eliminate unnecessary folds. Figure 4 shows the situation. The following manipulations are performed at (a)-(c) in the figure.

(a) Close the end-effector so that the tip of the end-effector touches the center of the fabric.
(b) The end-effector body is moved parallel during the tip of the end-effector in contact with the fabric hem to eliminate the fabric fold.
(c) The end-effector is closed when the fabric is no longer folded unnecessarily, and the fabric is clamped.

D. PS hand: Protruding Passive Rotation Mechanism

The most likely failure in pinch-and-slide unfolding is that the fabric falls out of the end-effector during the manipulation. Therefore, a protrusion is placed on the end-effector's finger. The protrusion catches a step of the hem of the fabric to prevent it from falling out of the end effector. However, the success rate of unfolding is not improved much by simply adding protrusions. This is because when the protrusions make contact with the hem during the pinch-and-slide unfolding, the force from the fabric hem can distort the fingers, causing the fabric to fall out through the gap.

To reduce this phenomenon, the protrusions are passively rotatable to provide a degree of freedom. This makes it possible to unfold while passing away the impulsive force, reducing the possibility of yielding gaps that could cause the fabric to slip down. Moreover, since the end-effector is expected to be attached to the robot's hand, it should be lightweight and compact. The above mechanism is more suitable for end-effectors because it is passive and does not require an actuator.

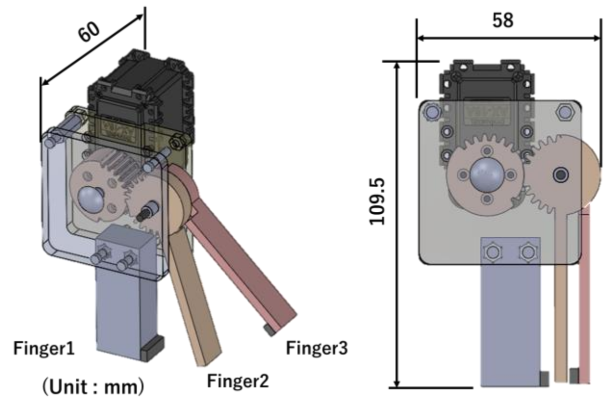

Fig. 5 The end-effector with (Corners holding) as main purpose (CH-hand)

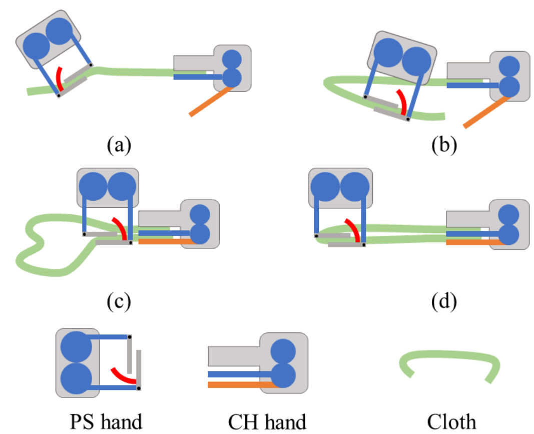

Fig. 6 The end-effector with (Corners holding) as main purpose (CH-hand)

E. CH-hand

Assuming that the fabric is unfolded, consider the subsequent action of folding it in half. In case of human being, he/she folds a fabric vertically and brings the corners that are currently held in each of the left and right hands to the same position. Then, one hand grips the two corners together. At this time, the hand is held dexterously by sliding the fingers on the fabric while holding the fabric so that it does not fall off, or by switching the fingers that are holding the fabric. In this study, instead of reproducing such dexterous finger movements, a simple mechanism and manipulation procedure are devised for aligning two corners. The end-effector for this purpose will be referred to as the CH (Corners Holding) hand. This is the hand on the side referred to as the left hand in the previous section.

(a) Fabric 1 (b) Fabric 2 (c) Fabric 3

Fig. 7 Experiment target

The appearance of the CH hand is shown in Fig. 5. the CH hand has three fingers and can grasp twice. Figure 6 shows how to manipulate the fabric in combination with the PS hand. As shown in (a), in the first grasp, the corners of the fabric are pinched by finger 1 and finger 2. Then, as shown in (b), the corner on the PS hand side is moved between fingers 2 and 3, and the two corners are grasped simultaneously as shown in (c). At this point, one finger of the PS hand is inside the fabric and the other finger is outside the fabric. Therefore, as shown in (d), the distance between the PS hand and the CH hand can be reduced to about half the length of the fabric to realize a single folding motion of the fabric.

To achieve the grasping in (b), it is necessary to move finger 3 while maintaining the state of fingers 1 and 2. The proposed end-effector performs these movements with only one actuator. For this purpose, intermittent gears are used. Intermittent gears are gears with teeth on only one part of the gear, and can transmit rotation intermittently. In other words, it is possible to perform complex transmission, such as stopping rotation at an arbitrary time from a fixed point of rotation. The detailed structure of the fingers is as follows. Fingers 2 and 3 are supported by a single axis, but can rotate independently of each other. The gears are directly connected to the motor so that they engage with the gears at the base of each finger at the same time, thereby moving the two fingers. By using intermittent gears for finger 2, only finger 3 moves after finger 2 is fully closed. The maximum opening angle between fingers 2 and 3 is approximately 30 degrees. The number of teeth on each gear is all 25, and a tooth is provided on one part of the gear.

V. EXPERIMENTS

A. *Performace Evaluation of PS hand*

The PS hand was actually fabricated. Almost all parts were fabricated using a 3D printer, except for the fixtures such as screws and spacers. ABS (acrylonitrile butadiene styrene) resin, which is a common material for 3D printers and has excellent mechanical properties such as impact strength and rigidity, was used for modeling. In addition, parts requiring precise dimensions, such as pulleys, were fabricated by optical fabrication using clear resin. The motor was a Dynamixel AX-18A [15] manufactured by Best Technology. The total weight is 213.6 [g].

In order to evaluate the performance of the PS hand and to confirm whether it can solve the problems of the previous study, a pinch-and-slide unfolding was conducted using the previous end-effector and the PS hand. A dual-armed robot HIRO [16] manufactured by Kawada Robotics was used as the robot arm for the experiments. One end-effector (left hand) was equipped with an existing two-fingered hand, and the other end-effector (right hand) was equipped with PS hand.

TABLE 2 Fabric status

	Fabric 1	Fabric 2	Fabric 3
Material condition	Linen	Cotton	Pile
Size[mm^2]	456×690	1.35	47.0
Thickness[mm]	344×348	2.41	36.6
Weight[g]	490×720	2.80	123.4

TABLE 3 Result

	Fabric 1	Fabric 2	Fabric 3
Previous hand	90%	100%	40%
PS hand	80%	80%	80%

The amount of movement of the robot arm was pre-determined based on the size of the fabric. The success or failure of the experiment was judged as failure if the fabric was in the following state at the end of unfolding.

- Fabric is falling off the end-effector,
- The end-effector is not in contact with the hem of the fabric.

Three types of fabrics shown in Fig. 7 were prepared for the experiment. Basic information of Fabric products is shown in Table 2. Fabric 1 is a loosely woven gauze fabric that is so thin that the other side can be seen through it. Fabric 2 is a 100% cotton hand towel, and Fabric 3 is a pile face towel. These cloths were selected for their different material condition, sizes, and weights. Ten experiments were conducted under each condition.

The experimental results are shown in Table 3. The previous end-effector showed a high success rate for Fabric 1 and Fabric 2. On the other hand, the success rate was only 40% for Fabric 3, which has a thickness of 2.80 mm. This is because the finger width of the end-effector in the previous study was 2 mm, and the end-effector could not be fully closed until the fingers were parallel. Thus, the fingers were not able to maintain parallelism during the pinch-and-slide process, and the fabric hem did not make good contact with the protrusions. In the PS hand, the result was 80% under all conditions. Compared to the previous end-effector, the success rate was lower for Fabric 1 and Fabric 2, but the rate was maintained for Fabric 3. This indicates that the hardware limitation, which was the purpose of the PS hand production and was an issue in the previous study, has been resolved.

There were two types of cases in which unfolding failed in the PS hand. The first was a case in which the fingertip was positioned far inside the fabric at the end of the unfolding manipulation. This means that the position of contact with the cloth should have moved closer to the hem as the sliding motion progresses, but this did not happen. It is considered that the force that grasps the fabric is too strong. A countermeasure to this problem is to adjust the current value of the motor by feeding back the force applied to the fabric. Another failure was a case in which the fabric fell off from the end-effector during the unfolding operation. The cause of this failure is assumed to be the backlash caused by the frequent use of gears such as two-stage gears and planetary gears in the end-effector. This is a disadvantage of having multiple gears. A possible countermeasure to this problem is to include a spring element around the shaft to reduce the effect of backlash.

B. *Unfolding-to-Folding*

The aforementioned PS hand and CH hand were used to perform unfolding and folding in a consistent manner. The work began with the CH hand grasping one of the corners of the fabric and hanging it down. First, a pinch-and-slide unfolding was performed, followed by a folding motion. In this process, it is necessary for the PS hand to pass the corner of the newly opened side to the CH hand and have it grasped in alignment with the corner that is already grasped. Therefore, the pinch-and-slide unfolding should not be performed until the corner is reached. Therefore, the unfolding was performed until just before the corner, so that the corner protrudes from the PS hand by several tens of millimeters. Then, the PS hand is moved to bring the protruding corner between fingers 2 and 3 of the CH hand, and then finger 3 is closed to achieve simultaneous grasping of the two locations. Then, by moving the robot arm so that the two hands are far from each other, the cloth is folded in two. Furthermore, by using a desk, the cloth was folded into four pieces. Figure 8 shows an example.

VI. Conclusion

In this paper, we propose two types of end-effectors for fabric folding. For the end-effector that performs a pinch-and-slide unfolding, we proposed an end-effector that maintains the functionality of the previous study while solving the problem by modifying the pinching method so that the surfaces that pinch the fabric are always parallel to each other. On the other hand, in order to perform folding, it is necessary to grasp another corner of the fabric while maintaining the grip on a fabric corner. Therefore, we constructed a new end-effector using intermittent gears that can transmit power intermittently. The actual folding work was performed using the fabricated end-effector. We confirmed that it is possible to fold a fabric multiple times by folding it once without using an external structure, and then folding it again using the desk.

Future plans include devising ways to increase the success rate, and also to propose an end-effector that can perform purposes other than folding.

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Fig. 8 Unfolding-to-fold experiment

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