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# A Versatile End-Effector for Pick-and-Release of Fabric Parts

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*Abstract*— **A novel robotic end-effector is introduced for pick-and-release of several fabric parts used for producing underwear. One of the main operations in a factory for sewing cloth products is to pick up fabric parts, provide them to a sewing machine, and sew them together. In the case of underwear, thin cotton cloth is the target of manipulation. Since such cloth parts are placed in a stacked state, they tend to stick to each other, and a certain skill or technical acuity is required for picking up actions. Therefore, this work is typically mostly done manually at present. One purpose of this study is to automate such manipulation, so a mechanism is introduced to pick up only the top piece of cotton fabric from a stack. An essential part of the mechanism is an attached cylindrical brush with a removal cloth on its surface. The cylindrical brush is placed on the cotton fabric and is then rotated to roll up only the top piece of cotton fabric. This mechanism makes it possible to release the fabric by rotating the brush in the reverse direction. In addition, two sets of the cylindrical brushes are installed to face each other to enable pinching. This mechanism enables pick-and-release for various cloth parts, such as woven rubber pieces and piped cloth hems. Finally, a composite end-effector equipping these gripping functions is manufactured, and evaluation experiments are conducted using actual fabric parts.**

## I. Introduction

Clothes are indispensable for people's social lives. Therefore, cloth products are manufactured in large quantities every day in factories. One of the main steps in the manufacturing process is the work of picking up stacked fabric parts, providing them to the sewing machine, and sewing them into an assembled fabric part. This kind of work occurs multiple times in the sequence of fabric assembly.

When manufacturing underwear, a typical cloth part handled in the above work is a thin piece of cotton fabric cut into a predetermined shape. If a large number of cotton fabrics are stacked, pieces of cloth that overlaps tend to adhere. Therefore, it takes a certain skill or technical acuity to pick up only the top one. One of the other cloth parts is woven rubber. Woven rubber exhibits hardness anisotropy in and strong repulsive force, so slippage tends to occur during picking. Therefore, it remains difficult to automate the work of picking up these cloth parts, leaving such work to be done essentially manually. Therefore, if these operations can be automated, then the automation rate of the entire sewing operation can be greatly improved by combining with the automation of positional adjustment while sewing. These advances are expected to be very effective as countermeasures against labor shortages.

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Figure 1. Picking up the top of fabric sheets

The purpose of this study is to automate the work of pick-and-release of cloth parts. The work consists of picking up stacked cloth parts one by one, taking each one to a new location, and then releasing it. Fabric part materials of interest here are cotton fabric and woven rubber. This paper describes the development of an end-effector to achieve the work above.

The authors have developed an end-effector for picking up the top piece from a stack of cotton fabric pieces [1]. They confirmed that the cotton fabric could be rolled up by pressing a ciliated brush against the edge of the fabric and then rotating the brush. After that, the authors examined several types of brushes for improving the success rate for both pick up and release, finding the use of a remover cloth effective [2]. This study follows up on that one by proposing a versatile end-effector that improves the ability to roll up cotton fabric while also coping with woven rubber. In addition, the proposed end-effector is equipped with a transmitted light source by which to judge the number of held fabric parts, i.e., to determine whether or not the desired fabric part was picked up. A pick-and-release experiment using actual fabric parts was performed using the proposed end-effector. The authors also conducted a verification experiment on the work of picking up a part of the finished cloth product using the same hardware. These experiments show the versatility of the proposed end-effector in garment factories.

The main contributions of this work are as follows:

- The authors devised and actually produced a compact mechanism that can perform both roll up and pinching operations.
- The authors found out the movement of the end-effector to enable proper pick up in response to flexibility characteristics of each fabric part.
- The authors conducted pick-and-release verification experiments for different types of fabric parts and cloth products, and evaluated their performance.

The structure of this paper is as follows. In the next section, we introduce related work. In Section III, we explain issues on the pick-and-release task and our approach. In Section IV, we introduce our end-effector and its functions in detail. Experimental results are reported in Section V, and we conclude this paper in Section VI.

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## II. Related Work

### A. Picking up Fabric Parts

One approach for picking up cloth items from a stacked state is the use of dedicated robotic end-effectors. End-effector research and development has been ongoing for many years [3–6]. Schulz [7] introduced several types of grippers for garment picking. One, the "Needle" gripper, aims to entangle the fabric by card clothing. The "Bonding" gripper picks up a sheet of cloth by exposing an adhesive tape, while the "Freezing" gripper adheres to a target sheet by supplying water that freezes and bonds onto the fabric. These methods and others may damage the fabric or temporarily stain it. Ono et al. [8] proposed a robot hand to pick up a piece of cloth. The number of stacked items was assessed using measurements from a sensor in the tip of the hand. The hand was then inserted into the stack so as to grasp a given number of items. Nagata et al. [9] proposed a towel-picking method using touch sensors. Both approaches have contributed to the development of increased robot dexterity. Petrik et al. [10] demonstrated a gripper prototype to handle limp materials. The gripper was manufactured in consideration of grasping force, mechanical flexibility, and sufficient dexterity for tactile exploration. The aforementioned end-effectors are suitable for picking up a desired cloth part dexterously, but even these end-effectors have difficulty gripping only the targeted part when thin fabrics are densely stacked.

One effective concept for picking up fabric is to pull up a part of the fabric using rollers. Kabaya et al. [11] developed a mechanism to pinch a piece of fabric by rotating two rollers facing each other. Its performance was verified through experiments using relatively thick fabrics such as towels and felts. This concept has subsequently been used to manipulate thinner and lighter materials. Shibata et al. [12] proposed an end-effector with a roller equipped with a piezoelectric sensor. This device was used to flip pages of a booklet and assess whether a page successfully flipped. Manabe et al. [13] targeted Y-shirt fabric, demonstrating a pick up device that rolled up the fabric using two rollers with rubberized surfaces. However, cotton sheets, which are among the targets in the present study, are more flexible than Y-shirt fabric and tend to adhere together. Therefore, it would be difficult to pick up individual cotton sheets with such an approach. For the same reason, it is difficult to use a conventional robot hand for the purpose of handling cotton cloth. Therefore, a new method is required.

### B. Cloth Manipulation by Autonomous Robots

Cloth manipulation by autonomous robots has been a standing topic in the field of Intelligent Robotics [14] [15]. As the picking up of cloth is the first step in manipulation, this subtask has been addressed in many lines of cloth manipulation study. Willimon et al. [16] addressed the task of selecting a single grasp point for lifting up a cloth item from arbitrary messy shape configurations. Yuba et al. [17] introduced a pinch-and-slide motion to unroll a cloth item, and detecting a corner part of the cloth as a first grasping point. Ramisa et al. [18] proposed a method for detecting characteristic parts such as collars and cuffs in images of shirts and other clothing items in arbitrary shape configurations. Yamazaki [19] proposed a method for simultaneous detection of multiple grasp points on cloth items in arbitrary shape configurations. Doumanoglou et al. [20] proposed a method for spreading out unknown cloth items presented in arbitrary shape configurations. They used Hough forests to determine grasp point detection. There are many other studies related to gripping on cloth manipulation, including review papers of such studies [21]. Recently, there have been proposals to increase the transparency of research results by setting standard tasks and organizing manipulation difficulty levels [22].

As these results illustrate, many studies have demonstrated success in picking up cloth items. However, these methods assume settings in which the cloth can be properly grasped by merely extending the hands to approximately detected grasp points. In the present case, however, dexterous picking of densely stacked items is targeted. The success or failure of the manipulation is dominated by the fact that the cloth to be operated is lightweight and easy to stick each other. This is a property not found in cloth, which is used in many studies mentioned above.

## III. Issues And Proposed Approach

### A. Issues

As mentioned in section I, the target cloth parts are cotton fabric and woven rubber. Among the materials that make up underwear, these two differ most dramatically in physical properties. For example, cotton fabric has the property of being thin, light, soft, and rich in fibers. As a result, when cotton fabric pieces are stacked, they tend to adhere to each other, and when the top piece of fabric is lifted, the piece of fabric below is also lifted. On the other hand, woven rubber is a thin, elastic cloth part. Unlike cotton fabric, woven rubber parts do not adhere to each other, but the surface is relatively smooth and elastic, so parts easily slip off the stack.

Here, cloth parts cut into a predetermined shape are assumed to be stacked on a horizontal table. In the stacked state, some successive fabric pieces' edges are neatly aligned, having been cut immediately prior. In other cases, successive fabric pieces' edges are displaced by up to several millimeters as a result of being restacked after an additional processing step. Under such circumstances, the work targeted in this study is to pick up, transport, and release the aforementioned types of cloth parts one by one. For this purpose, it is necessary to consider both the mechanism and the operation method for stably picking up a single piece. In addition, a functionality to detect pick up failures is required.

### B. Proposed Approach

As mentioned in Section II, end-effectors for picking up a single piece from the stacked cloth parts have been proposed before. Some of these end-effectors are suitable for the purpose of picking up a single cloth part, such as the "Freezing" method. However, such a method would take time for a series of manipulations and would make the device expensive and heavy in weight. On the other hand, the method of piercing and hooking the cloth with a needle or the like should be avoided because it might damage the cloth parts, and the needle may be end up mixed in with the cloth product.

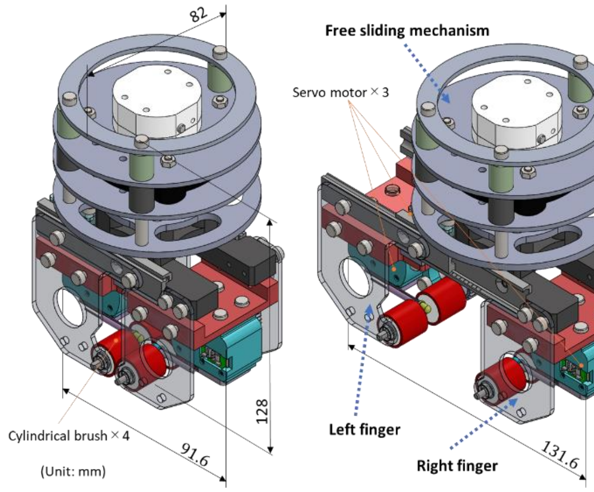


Figure 2. Overview of the proposed end-effector

In addition, since the authors assume that the end-effectors will be used in a factory, the compactness of the equipment should be considered. In order to pick up a single cloth part from a reusable shipping carton and provide it to the sewing machine, it is desirable that the device be small. Furthermore, if it is possible to handle multiple types of cloth parts required in the manufacture of underwear without replacing or duplicating the hardware, such a capability can contribute to the compactification of the production line, allowing both low-volume and high-mix production.

Taking the above into consideration, the basic policy for constructing an end-effector is as follows.

1. Do not damage the cloth parts or allow liquids or glue to adhere to them. Do not apply excessive force to the parts.
2. Keep the size of the device small enough to avoid interfering with the supply of cloth parts to the sewing machine. Furthermore, the robot arm should not move unnecessarily in the pick up operation. For example, if the end-effector is brought into contact with a cloth part, most of the gripping can be applied by movement inside the end-effector.
3. The mechanism must be able to stably pick up and release both cotton fabric and woven rubber.
4. The mechanism must be suitable for repetitive work. In other words, even if many pieces of cloth parts are stacked, the mechanism must continuously pick up only the top cloth part without significantly affecting the state of remaining cloth parts.

## IV. The End-effector

### A. Appearance and Features

Figure 2 shows the appearance of the designed end-effector. This end-effector can be roughly divided into three regions: left finger, right finger, and free sliding mechanism. The attachment to the robotic manipulator is performed on the upper surface of the free sliding mechanism. A cylindrical brush is attached to the tip of each finger and is used to pick up cloth parts by rolling them up and sandwiching them. In this end-effector, three actuators are built in. Two of the actuators have the role of rotating the cylindrical brushes on the left and right fingers. The remaining actuator has the role of horizontally moving the left finger in response to the gear rack mechanism. All actuators are S204MD servo motor manufactured by FUTABA Inc. (torque: $2.1\mathrm{kgf}\cdot\mathrm{cm}$, maximum angular velocity: 0.12 sec/60deg, weight 12g, dimensions: $27.9 \times 16.0 \times 23.9$mm, power supply voltage: 5.0V). In the operation of this motor, the target angle is converted into a PWM signal and input.

The characteristics of this end-effector is as follows. Each item corresponds to the equivalently numbered item described as basic policy in section III-B.

1. In the pick-and-release work, the part that comes into direct contact with cloth parts is the lateral face of the cylindrical part. A remover cloth is attached to this surface, making it possible to hold cotton fabric by rolling up. On the other hand, in the case of woven rubber, the remover cloth acts as a non-slip material, making it possible to pull up the edge of the woven rubber. Grasping of the rubber is aided by minutely reducing the distance between the cylinders. By using these methods, it becomes possible to pick-and-release multiple types of cloth parts in a way that does not hurt any of them.
2. The end-effector is 82 mm in length, 91.6 to 131.6 mm in width, and 128 mm in height. This is almost the same size as an adult human fist, and is small enough not to get in the way even if it is installed near the sewing machine. The total mass is 335 g. Of this mass, the mass below the free sliding mechanism shown in Fig. 2 constitutes one of the parameters for stable pick-and-release of cotton fabric, as will be described in section IV-D.
3. Two sets of cylindrical brushes are placed facing each other, and as described in item 1, the holding method is properly selected depending on the type of cloth. As long as the cloth parts can be held by either of these, or as long as some other combination of rolling up and sandwiching works well, fabrics other than cotton and woven rubber can also be manipulation targets.
4. Adopt a holding method that moves only the top cloth part while holding down the entire stack of cloth parts. In the case of cotton fabric, the free slide mechanism plays an important role. In the case of woven rubber, the left and right rotatable brushes play an important role.

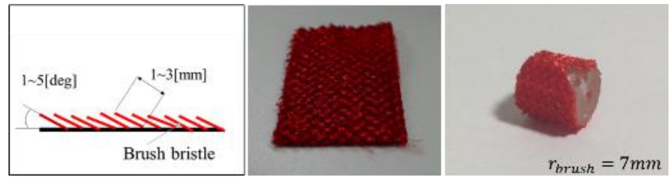


Figure 3. Remover cloth and cylindrical brush

### B. Cylindrical Brush

A motor-driven cylindrical roller of radius 7 mm, as shown in Fig. 3, is attached to the lower end of the end-effector. A remover cloth, often used to remove dust from clothing, is attached to the surface of the cylinder. The remover cloth's is Polyolefin cilia of the following dimensions densely occupy

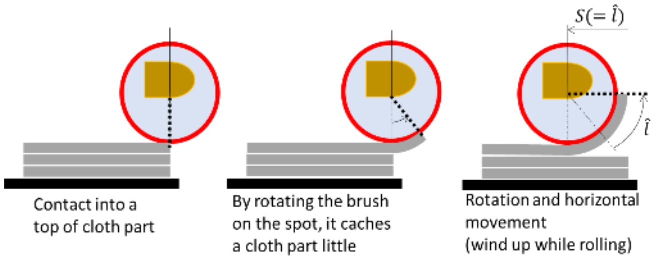


Figure 4. Rolling up procedure.

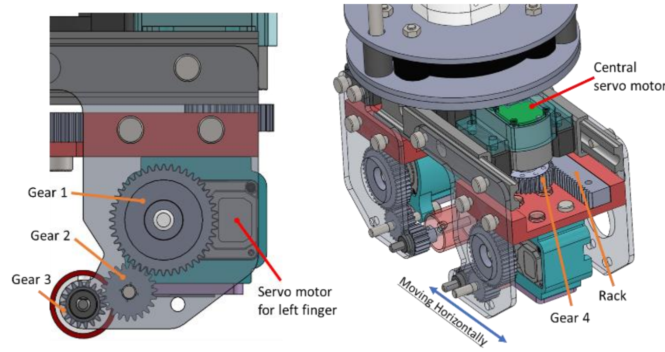


Figure 5. Left finger part. Left panel shows gear placement and right panel shows rack structure.

the cloth area: length 1 to 3 mm, diameter less than 0.1 mm, and inclination 1 to 5°.

As shown in Fig. 4, in the proposed end-effector, a cotton fabric piece is gradually adhered to the surface of the cylindrical brush by moving the brush so as to roll it on the cotton fabric. The reason for choosing removal cloth as the surface material is that it has the following characteristics: the short bristles on the surface of the remover cloth catch in the cotton fabric, generating a weak adhesive force. By adhering over a large area on the cylindrical surface, the cotton fabric can be lifted without slipping off.

Before selecting removal cloth, the authors also considered using needle cloth or sandpaper [1]. Compared to these, the bristles of the removal cloth are not deeply inserted into the cotton fabrics, so the phenomenon of rolling up multiple fabrics at once can be suppressed avoiding damage. In addition, when the cylindrical brush is rotated in the direction opposite that of pick up, the cotton fabric naturally peels off due to gravitational force, so the release operation can be easily performed.

On the other hand, for hard and elastic cloth parts such as woven rubber, the cylindrical brushes facing each other are rotated in the reverse direction. This is a motion for pulling the cloth part into the middle position of the facing cylinders, for the purpose of pinching. Here the removal cloth plays a non-slip role.

### C. *Fingers*

A) Left finger part

The left finger is the part located on the left side of the overall image of end-effector shown in Fig. 2. There are two main mechanisms in this area. The first is a mechanism that rotates the cylindrical brush. Motor torque is transmitted from the servomotor to the brush via three gears (Fig. 5, left). Here, the gears attached to the motor shaft are called Gear 1, Gear 2, and Gear 3. The pitch circle diameters (PD) are 22, 11, and 9 mm, respectively, and the angle $SM_{L\_\alpha}$ [rad] for rotating the brush by $b_{L\_\alpha}$ rad is calculated as

$$SM_{L\_\alpha} = \frac{Gear3_{PD}}{Gear1_{PD}} \cdot b_{L\_\alpha}. \tag{1}$$

The second mechanism is a gear rack mechanism for operating the entire left finger in the horizontal plane (Fig. 5, right). A fourth gear, known as Gear 4, is implemented, with a pitch circle diameter of 18 mm. The motor angle $SM_{M\_\alpha}$ [rad] for moving the left finger by $S$ mm can be calculated as

$$SM_{M\_\alpha} = S/(Gear4_{PD}/2). \tag{2}$$

The synchronization of these two mechanisms realizes the horizontal movement of the left finger that accompanies the rotation of the brush, which is indispensable for the rolling up operation. In this operation, when the target angle $b_{L\_\alpha}$ [rad] of the brush is input, the central motor and the motor for the left finger start to move at the same time. The circumference $\hat{l}$ of the brush is calculated as

$$\hat{l} = r_{brush} \cdot b_{L\_\alpha}. \tag{3}$$

As the length $S$ is the same as $\hat{l}$, the command to the central motor is calculated as

$$SM_{M\_\alpha} = (r_{brush} \cdot b_{L\_\alpha})/(gear4_{PD}/2). \tag{4}$$

B) Right finger part

Like the left finger, the right finger has a cylindrical brush that can be actively rotated at the tip of the finger. The gear configuration is similar to that of the left finger but without the horizontal movement mechanism. This finger part is not used when handling cotton fabric, but when picking up woven rubber, an edge of the cloth part is pulled up by rotating it in the direction opposite that of the left cylindrical brush. Afterward, the cloth part is sandwiched between the fingers.

### D. *Sliding Mechanism*

In order to stably pick up a single piece from the stacked cloth parts, it is desirable to contact the target cloth parts with the same force each time. However, the height of the cloth parts can vary depending on the number of stacks and other factors. In particular, cotton underwear fabric is a soft material with a thickness of less than 1 mm. It is difficult to actively control the contact force to manipulate such objects.

Therefore, a method is adopted of using the weight of the end-effector to applying contact force. As shown in Fig. 6, three shafts are attached to the end-effector. By passing them through a holder with three linear bushings, the structure is constrained to move up and down passively. As a result, when the cylindrical brushes come into contact with a cloth part, the end-effector's weight of $0.275g$ [N] ($g$: gravitational acceleration) is applied to the cloth part as a constant load. This passive movement range was set to 15 mm.

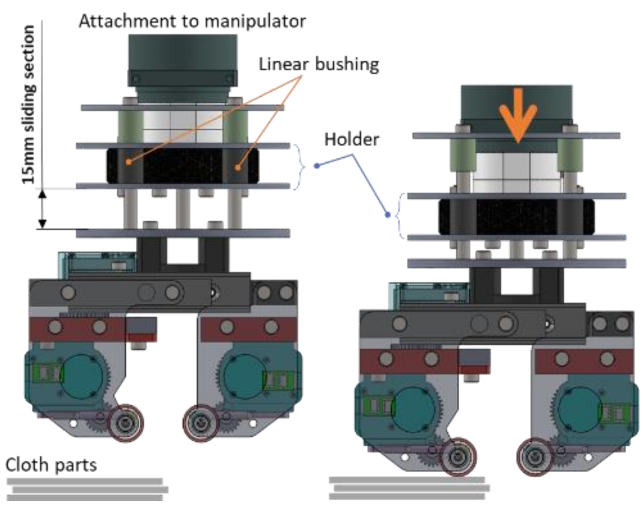


Figure 6. Free sliding mechanism.

The reason why the contact force to the cloth parts is set to the above value is due to experience in a previous study [2]. There, the authors investigated the appropriate contact force for pick-and-release. If the contact force is too strong, roll up is easy to accomplish, while release tends to fail because the adhesive force becomes too strong. Therefore, the authors investigated the contact force suitable for both roll up and release: about 3 N. Since the proposed end-effector has a compact mechanism and is lightweight, this contact force can be realized by its own weight alone.

## E. Part Counting Device

In the work of picking up cloth parts, cases arise in which even one piece cannot be picked up, or in which multiple pieces are picked up at once. Therefore, in addition to the components performing the main functions as explained in the previous subsections, a device is included for investigating pick up status. Specifically, the number of parts is determined by irradiating the rolled up cloth parts with a known intensity of infrared light and measuring the difference between that initial intensity and the intensity of light recorded after passing through any fabric picked up. The reason for choosing infrared light is to minimize the influences of ambient light and cloth color on variation in light transmission. As shown in Fig. 7, this mechanism is realized by an infrared LED with a diameter of 3 mm attached to the center of the right brush and an infrared phototransistor with a diameter of 3 mm attached to the center of the left brush. The resistance due to the amount of received light is expressed by the voltage $V_{IC}$ via AD conversion. The voltage $V_{IC}$ is calculated by dividing the voltage of the resistor $R_1$ by that of a fixed resistor $R_2$ (3.3 kΩ) changing depending on the amount of light received. The formula is as follows:

$$V_{IC} = \frac{1}{1 + \frac{R_1}{R_2}} V_{CC}. \tag{5}$$

When $R_1$ approaches 0, $V_{IC}$ becomes $V_{CC}$. When $R_1$ approaches ∞, $V_{IC}$ becomes 0.

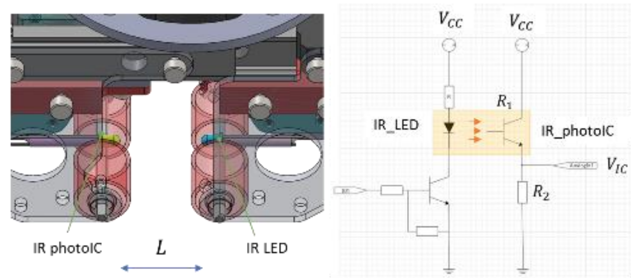


Figure 7. Part counting device.

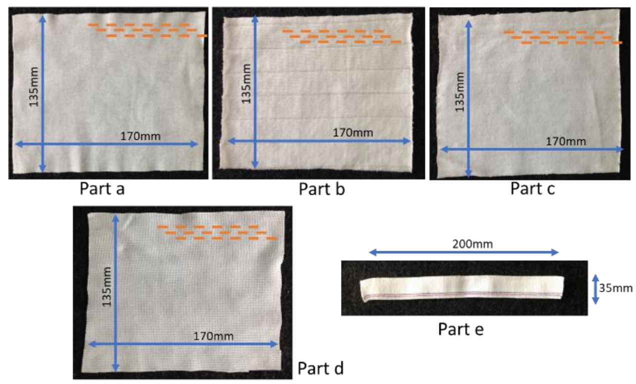


Figure 8. Examples of cloth parts. The orange dashed line indicates the fiber direction of the fabric.

# V. Experiments

## A. Experimental Settings

The proposed end-effector was attached to a 6-DoF manipulator (Manipulator-H manufactured by ROBOTIS Inc.), and the following items were evaluated by actual experiments.

- Performance in picking up a single piece from stacked cloth parts
- Performance in releasing the held cloth part
- Performance in counting the number of held cloth parts

In the experiment, a base with a piece of cotton fabric attached to a wooden board was prepared to prevent slipping, and the stack of cloth parts for the experiment was placed on it. The following five types of cloth parts were used in the experiments.

Part a) Milling: number of samples: 10;
dimensions: 135 × 170 mm; thickness: 0.5 mm; mass: 3.4 g; material: 100% cotton

Part b) Connected Jersey stitch: number of samples: 10;
dimensions: 135 × 170 mm, thickness: 0.6–0.7 mm; mass: 5.6 g; material: 100% wool (front side), 100% cotton (back side)

Part c) Connected Jersey stitch; number of samples: 10;
dimensions: 135 × 170 mm; thickness: 0.6 mm; mass: 3.8 g; material: 100% cotton

Part d) Ribbed: number of samples: 10; dimensions: 135 × 170 mm; thickness: 0.3 mm; mass: 2.2 g

Part e) Woven rubber: number of samples: 3;

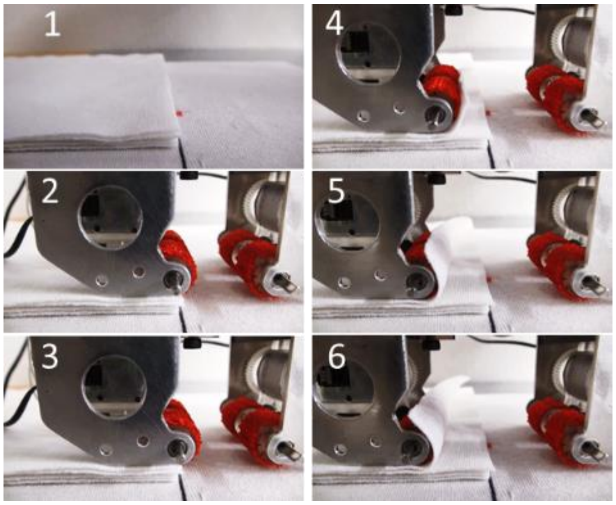

Figure 9. Picking up a cotton fabric by rolling up.

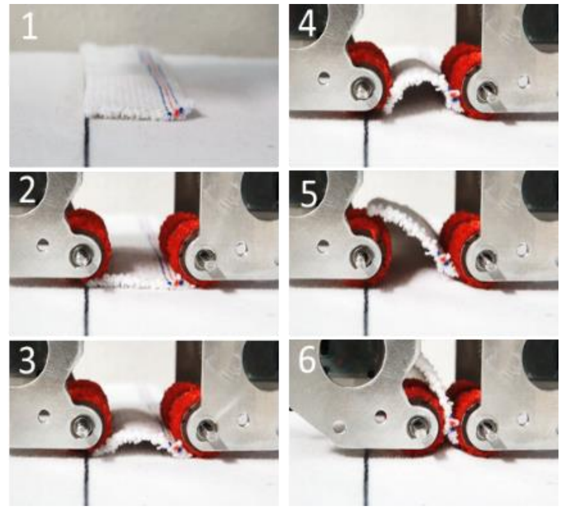

Figure 10. Picking up a woven rubber by pinching.

dimensions: $200 \times 30$ mm; thickness: 1.35 mm; mass: 4.8 g

Figure 8 shows the picture of the parts.

*B. Procedure for Picking Experiments by Rolling Up*

Fig. 9 shows an example of picking up a piece of cotton fabric. In the pick-and-release of this cloth part, roll up action was performed by the left finger alone. The motion procedure for this was as follows:

A) After opening the left finger, the manipulator was lowered vertically until its cylindrical brush touched the cotton cloth and the free slide mechanism functioned.
B) The cylindrical brush was rotated on the spot by $\theta_1$ = 24.5°.
C) By rotating the cylindrical brush and translating the entire finger at the same time, the cotton fabric was rolled up until the amount of rotation of the cylindrical brush reached $\theta_2$ = 150°. The angular velocity of the brush was 125.5 °/s.
D) After detecting the number of fabric layers, the same rolling motion as in C) was performed until it equaled $\theta_3$ = 200°.
E) The end-effector was lifted, and the success or failure of holding was checked. Afterward, the brush was rotated in the reverse direction to release the cotton fabric.

Each numerical value $\theta_1$, $\theta_2$, $\theta_3$ for the amount of rotation was determined empirically. Here, rotating on the spot as mentioned in B) plays an important role in this procedure. As already mentioned, a major problem is that the cotton fabric pieces easily adhere to each other. However, by adding this rotation action, the top cotton fabric, with which the cylindrical brush is in contact, is peeled away from the cotton cloth below it. The edge of the top cotton fabric can then be independently adhered to the cylindrical brush. After that, by combining translation with the rotation of the cylindrical brush, the second and subsequent cotton fabrics are rolled up so that they are not moved.

In addition, as one of the measures to stabilize the rolling up, the directions of the fabric fiber and the cylindrical brush axis are set perpendicular to each other. The reason for this is that cotton fabrics stretch less in the perpendicular direction than in the parallel direction.

*C. Procedure for Picking Experiments by Holding*

Figure 10 shows an example of picking up a piece of woven rubber. The stacked woven rubber pieces were placed on the base so that the shafts of the cylindrical brushes were parallel to the long side of the woven rubber. The motion procedure was as follows:

A) The right finger was aligned and the left finger was opened so that the center of each brush was directly above a side edge of the woven rubber.
B) The manipulator was lowered vertically until both brushes touched the edges and the free slide mechanism functioned.
C) Both brushes were rotated by $\theta_1$ = 45° on the spot.
D) The left brush was rotated by an additional $\theta_2$ = 200°.
E) The left finger was closed, and the number of cloth parts was detected.
F) After lifting the end-effector, the left brush was opened, and the woven rubber was released.

The reason why motions C) to E) were used was as follows. A person who is picking up a thin piece of paper placed flat with index finger and thumb was observed, and the following motions were noted:

1. The tips of both fingers touched the paper.
2. Both fingers were rotated slightly to narrow the space between them. As a result, an upward convex bulge was produced on the paper.
3. The paper was grasped by narrowing the fingers further.

Items C) to E) above are imitations of these movements.

*D. Evaluation Method*

Five sets of experiments using the materials and parameter values listed in Sections V-B and C were performed for each cloth part. In one experiment, all the cloth samples for one cloth part were first stacked, then pick-and-release action was

Table I. Experimental Result

| | | Cloth parts | | | | |
|---|---|---|---|---|---|---|
| | | Part a | Part b | Part c | Part d | Part e |
| | No. of trials: N | 49 | 50 | 50 | 47 | 15 |
| | | | | | | |
| Pickup-and-release | (a) | 45 | 48 | 49 | 40 | 15 |
| | (b) | 3 | 2 | 1 | 0 | 0 |
| | (c) | 0 | 0 | 0 | 4 | 0 |
| | (d) | 1 | 0 | 0 | 3 | 0 |
| | (e) | 0 | 0 | 0 | 0 | 0 |
| | (f) | 0 | 0 | 0 | 0 | 0 |
| | | | | | | |
| | **Pickup success rate [%]** | **97.96** | **100.0** | **100.0** | **93.6** | **100.0** |
| | **Release success rate [%]** | **100.0** | **100.0** | **100.0** | **90.9** | **100.0** |
| | **Total success rate [%]** | **97.96** | **100.0** | **100.0** | **85.1** | **100.0** |
| | | | | | | |
| Part counting | No. of counting success | 45 | 47 | 50 | 40 | 15 |
| | | | | | | |
| | **Success rate [%]** | **91.0** | **94.0** | **100.0** | **85.1** | **100.0** |

repeated by the number of the samples. That is, there was a chance to 50 trials (10 sheets by 5 sets) for parts a) - d), and 15 trials (3 sheets by 5 sets) for part e). In evaluating the performance of the proposed end-effector, the following classifications were made based on the results of the work.

(a) Pickup was possible in good condition, and release was successful.
(b) Pickup was completed, but the holding condition of the cloth parts was insufficient (a case where a fabric sheet is partially peeled off from the brush and the edges of the fabric are bent.). However, release was successful.
(c) Pickup in good condition was successful, but release failed (a case where the cloth remains adhering to a part of the brush).
(d) Multiple cloth parts were picked up at the same time.
(e) Even one piece of parts cannot be picked up.
(f) Pickup was successful, but the cloth parts fell during transport.

For each trial, the results were classified as exactly one of the above. Afterward, the pickup success rate, release success rate, and total success rate were respectively calculated as

$$pickup\ success\ rate = \frac{\{(a)+(b)+(c)+(f)\}}{N},$$

$$release\ success\ rate = \frac{\{(a)+(b)\}}{\{(a)+(b)+(c)\}},$$

$$total\ success\ rate = \frac{\{(a)+(b)\}}{N}.$$

If n sheets ($n \leq 2$) were picked up at one time, only the number of extra sheets was subtracted from the total number of sheets.

In the evaluation of the number detection device, the number of parts actually picked up was compared with the number determined from the voltage value. If the number was the same, it was regarded as success; otherwise it was failure.

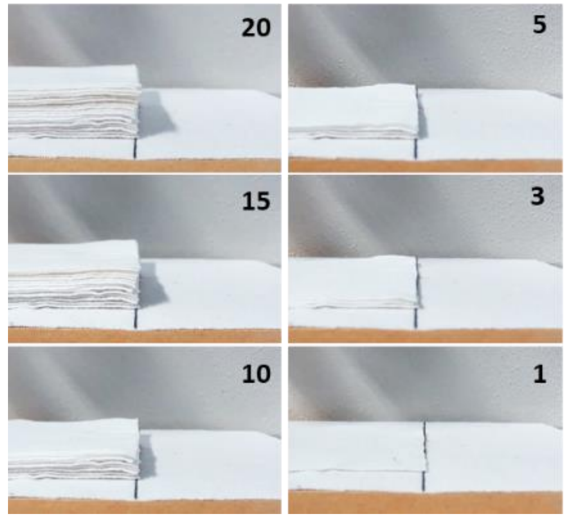


Figure 11. A result of continuous picking up experiment. Numbers depicted in upper right of each figure indicate the remaining number of cloth parts.

*E. Experimental Results*

The experimental results are summarized in Table I. In the pick-and-release column shown in the upper half, the results of trials are classified according to the criteria (a)–(f) described in section V-D, and the success rates were calculated. As can be seen from the table, good results were obtained for classifications a), b), and c). Meanwhile, the success rate for thin cotton fabric in classification d) was lower than for other cotton fabrics. Because this cotton fabric is thinner and lighter than others, it was easy for stacked cotton fabrics to adhere to each other. In the proposed end-effector, the region where the brush and the cotton fabric came into contact allowed good separation of the top piece of fabric from the remaining stack. However, when even one fiber of the cotton fabric was entangled at a position slightly away from the brush, the second and subsequent cotton cloths were also lifted. However, compared with those of a previous study [2], the success rates for both pickup and release were greatly improved. In particular, release saw a significant improvement of nearly 40%. As for classification e), no failure occurred as long as the cylindrical brush was brought into contact with the appropriate part. The time required for one pick-and-release manipulation was 25 seconds for parts a) -d) and 12 seconds for parts e).

Figure 11 shows the state of the cotton cloth stack left below once 20 cotton cloths had been picked up in order. The edges of the stacked cotton cloths were not found to deviate significantly from their initial positions. This is mainly because the action of bringing the brush into contact with the cotton fabric and then rotating it slightly for peeling was effective. Therefore, the proposed method was determined to be suitable for repetitive operation.

The lower part of Table 1 shows the results of sheet counting. Several failures occurred, four of which fell into classification (b) or (d). The reasons for these failures were that the edge of the cotton cloth was separated from the brush on the receiver side, or that there was a gap between the two cotton cloths. Figure 12 shows these situations. The space between

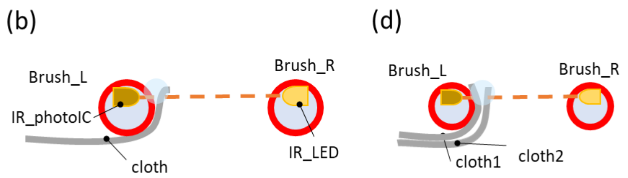

Figure 12. Factors of rolling work failure.

the cloths diffused the light, making it difficult to distinguish from the case in which many cotton cloths were picked up at once.

Figure 13 shows a trial of grasping a T-shirt placed on a table in order to investigate the possibility of future extension. For thick parts such as the neck, picking up like woven rubber was effective. On the other hand, for areas where the fabric is folded back, such as the waist (piped hem) and shoulders, it was effective to roll it up with one cylindrical brush and then pinch it, as with cotton fabric. From these results, if the material is a cotton cloth and the like, it is possible to grab various parts by using this end-effector.

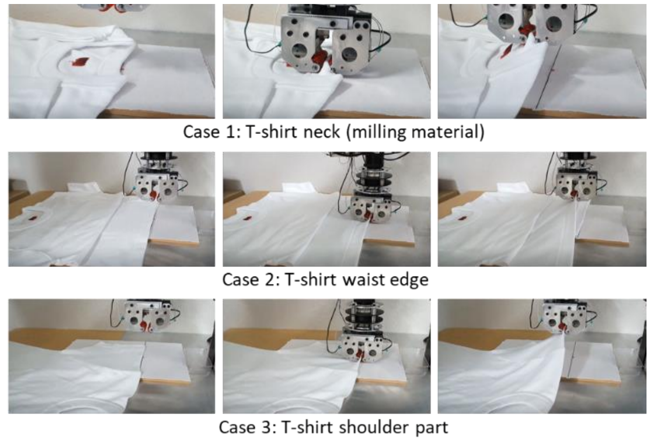

Figure 13. Result of picking up a part of T-shirt. In all the cases, the proposed end-effector and our grabbing procedure was available.

## VI. Conclusions

This paper described an end-effector for automating the work of picking up and transferring cloth parts. A structure was proposed that targets multiple types of cloth parts with different properties, such as cotton fabric and woven rubber. An operation method was proposed for picking and releasing each cloth part. In addition, a mechanism was incorporated for detecting how many cloth parts were picked up at once. The end-effector actually produced was about the size of an adult human fist and weighed about 300 g. In the pick-and-release experiment, the success rates for each of five cloth parts were 98% / 100% / 100% / 85% / 100%. These results confirmed that performance was good as a whole while leaving some room for improvement.

Currently, we are developing pick-and-place manipulation that place a cloth part on a table properly, in addition to improve the manipulation speed. This attempt might contribute to improving work efficiency, but it is a challenging theme because it is necessary to consider the dynamic characteristics of robots and cloth. In the future, the authors will also investigate the success rate when the number of stacked cloths is significantly increased. They will also evaluate the end-effectors for parts with shapes actually used for clothing.

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