An End-Effector with Winding and Scooping Functions for Handling Thin and Long Fabric Sheet

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***Abstract*–In this study, we propose a novel end-effector for grasping and sorting operations on various parts of garments on a cutting machine in a factory. Furthermore, we propose a method for grasping a whole fabric by folding it back and forth into a smaller size, reducing the space required for packing and sorting various parts of multiple fabrics, reducing the height motion requirements of the robot, and increasing the ability to handle multiple types of clothing simultaneously. Then, we evaluated the proposed end-effector and the motion trajectory at a factory using real T-shirt parts of various materials, and confirmed the feasibility of the proposed end-effector and method for use in factories.**

***Index Terms*–Cloth manipulation, robot hand, Zigzag folding**

I. INTRODUCTION

Clothes are indispensable for people to live a social life. 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 a fabric part, and delivering it to a desired working space. Such a process is performed multiple times in the sequence of fabric assembly. Therefore, there is no doubt that it is important for the manufacture of fabric products.

When producing muscle or polo shirts, the fabric parts handled in the above process are thin fabric materials cut into predetermined shapes. Such fabric materials are highly flexible and easily deformable. Therefore, a certain skill is required when picking up only one piece. The automation of the task of picking up these fabric parts remain difficult and is performed by hand. Conversely, if this task can be automated and combined with the automation of the feed part of the sewing machine, it is believed that the overall automation rate of the sewing process can be significantly increased. This is expected to have a significant effect as a measure to cope with labor shortages. For some small factories, they always need to sort and pack many kinds of clothes simultaneously in a small working space. If the space required for placing fabric parts can be reduced while completing automation, more kinds of clothes can be handled simultaneously, and the work efficiency will be improved greatly.

The purpose of this study is to automate the task of pick-and-place of fabric parts, particularly thin, and large fabric materials commonly used in clothing such as muscle and polo shirts. Specifically, we focus on the task of picking up apieces of fabric material cut by a cutting machine and stacking them one by one. In this study, we describe the end-effector required to achieve this. The authors have previously devised a method for winding up a cotton fabric by pressing a brush with bristles onto the edge of the fabric and then rotating the cylindrical brush and confirmed its effectiveness through actual experiments [1]. Furthermore, the authors have developed an end-effector that not only retains its original function but can also carry the fabric rubber by pinching and grasping [2]. This study is a successor to these previous studies. While the previous studies have only targeted small fabric parts, some actual fabric parts are too large to be lifted by simply winding them up. One such example is the long fabric material shown in Fig. 1. Therefore, in this study, we construct a new end-effector that combines the function of winding up thin and light fabric with the function of scooping it up, while maintaining a small size comparable to a human fist. Furthermore, by combining the characteristics of the end-effector with the movement of a manipulator, we can lift, and transport the fabric material completely by folding it into a zigzag shape, as depicted on the right side of Fig. 1. This is a useful method for transporting fabric parts from one table to another, even with a robot that has a small range of vertical movement.

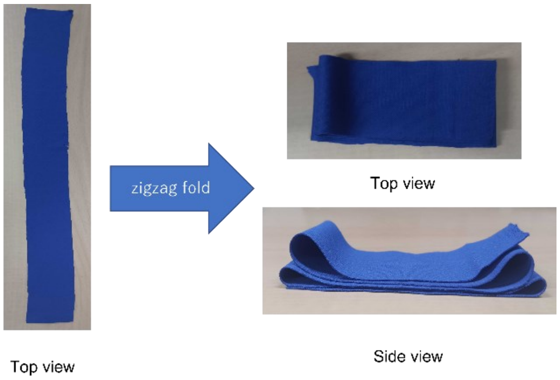


Fig. 1 Zigzag fold a thin and long fabric sheet.

The contributions of this study were as follows:

- We proposed a method for transporting thin, long fabric parts by folding them in a zigzag pattern and developed a small mechanism for achieving it.

- We formulated the proper folding method and used it to generate the end-effector's trajectory.
- We successfully picked up long cloth fabrics using the robot hand we constructed. We also conducted experiments on fabric parts used in polo shirt production to demonstrate the effectiveness of the proposed end-effector.

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 introduce the motion trajectory of zigzag folding. Section VI presents the experimental results of zigzag folding using an actual robot. Section VII presents the experimental results of pick-and-place experiments conducted in a factory using the proposed end-effector. Finally, we summarize the study in Section VIII.

II. RELATED WORK

Thus far, the manipulation of cloth products has been realized using automated machines. Nagata et al. [3] proposed a towel-picking method using touch sensors. Petrik et al. [4] demonstrated a gripper prototype for handling limp materials. The gripper was manufactured according to the considerations of grasping force, mechanical flexibility, and sufficient dexterity for tactile exploration. Le et al. [5] developed an end-effector for grasping between the gaps of fabrics by inserting fingers. Contact sensors and stereo cameras with light-intensity differences are embedded in the tip of the end-effector. These end-effectors are intended for manipulating fabric products such as towels, and grasping thin fabric parts with them, as expected in this study, are difficult.

In a sewing factory site, one approach for picking fabric items is the use of dedicated robotic end-effectors. Therefore, various research and developments have been ongoing [6-9]. Schulz [10] introduced several types of grippers for garment picking. One is the “Needle” gripper that aims to entangle the fabric by card clothing. Others are the “Bonding” gripper for picking up a sheet of fabric by sticking out adhesive tape, the “Freezing” gripper for adhering to a target sheet by freezing and bonds after giving water, and so on. These methods may damage the fabric or temporarily stain it. A method for transporting large fabric parts using adhesion has also been proposed. Ku et al. [11] implemented a mechanism that hooks fabrics with a small pointed end and then clamps them by referring to the attachment mechanism of the lamprey. He et al. [12] have recently constructed an electroadhesion gripper. However, it is considered difficult to lift only the intended fabric part in a densely packed fabric environment due to the device's large size and high-power consumption. Ono et al. [13] proposed a robot hand for picking up a piece of fabric. The number of stacked items was assessed using measurements from a sensor in the tip of the end-effector.

One effective idea for picking up fabric is to pull up a part of the fabric using rollers. Kabaya et al. [14] developed a mechanism for pinching 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. Shibata et al. [15] proposed an end-effector with roller equipped with a piezoelectric sensor. It was used to flip the pages of a booklet and assess whether a page was flipped. Manabe et al. [16] targeted the fabric of Y-shirt, and demonstrated a device for picking up the fabric by rolling it up using two rollers with rubber on the surface. Yamazaki et al. [17] proposed a versatile end-effector for pick-and-place fabric parts. A roller with a remover fabric wrapped was used to pick up cotton sheets. Meanwhile, two opposing rollers were used to pick up the fabric rubber.

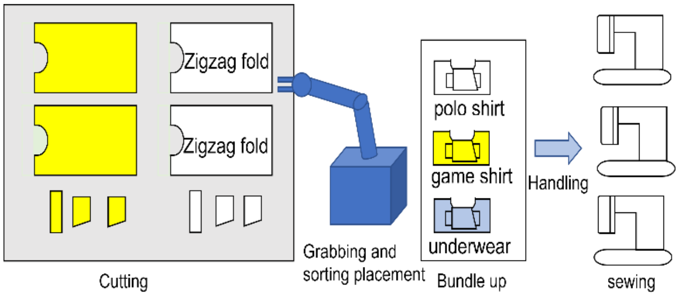


Fig. 2 A flow of fabrication process for small-lot, high-variety production sites.

As mentioned above, various end-effectors have been developed. However, while the lifting and placing of fabrics have been evaluated, there seems to be no research from the perspective of transporting long fabric parts. However, in sewing factories, it is necessary to transport fabric parts of various shapes, and in some cases, each fabric part must be compactly stored in the end-effector regardless of its size. In this study, we propose a method that can handle such cases by utilizing existing mechanisms.

III. ISSUES AND APPROACH

A. Issues

The fabric parts targeted in this study are fabrics used for manufacturing polo shirts, game shirts, underwear, and other similar clothing items. These fabrics are composed of several materials such as cotton and polyester and generally have the characteristics of being thin and lightweight.

We focused on stacking fabric pieces cut by a cutting machine to their designated locations. It is assumed that such a process occurs in a scenario of small-scale production of various types of fabric products. Figure 2 depicts the specific flow. After obtaining the fabric pieces necessary to produce a certain fabric product through cutting, these pieces are organized by product. The organized pieces are then transported as a bundle to the sewing workstations to continue the sewing process. This process prevents part mismatches between products. Conversely, since fabric pieces of various sizes and shapes need to be organized in one place, different movements are required for each part in the pick-and-place operation when automating. In addition, it is desirable to transport even large fabric pieces without dragging them, which requires special considerations.

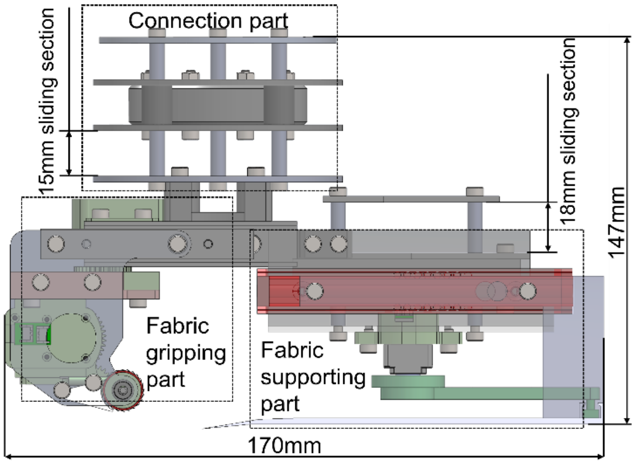


Fig. 3 Proposed end-effector.

Based on the above assumptions, the issues of this study can be summarized as follows:

1. The ability to pick up fabric parts of various sizes even if their edges are in close contact with the remaining fabric on the cutting table.
2. When picking up the parts, the structure should be less likely to fail during transport, even for long or large pieces of fabric.
3. The ability to transport long or large pieces of fabric without dragging them, without requiring the robot arm to have a large range of motion in the vertical direction.

In addition, it is necessary to consider as much as possible to make the end-effector lightweight and small, and to minimize the initial introduction and operating costs.

B. *Our Approach*

The following is a response to the issues presented in the previous subsection. The numbers 1–3 below correspond to those issues in the previous subsection.

1. Adopt a winding mechanism as in [17], to pick up fabric parts by contacting the edge of a target fabric part, which can pick up only the fabric part even when the distance between the target fabric part and the surrounding fabric is minute.
2. Attach a horizontally movable board to the end-effector. After lifting the edge of the fabric part by winding, the board can slide underneath to enable contact with the fabric part over a large area.
3. Combine the motion of the board to lift the fabric part and the movement of the end-effector, and fold the fabric part into a zigzag shape. Then, by scooping up the folded fabric part with the board, it can be transported without being dragged.

We describe the specific structure and manipulation strategy of the end-effector in the next section.

IV. PROPOSED END-EFFECTOR

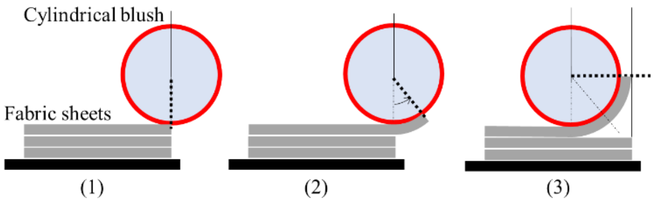


Fig. 4 A motion to wind up the edge of cloth fabric. (1) Contact to the top of fabric sheet, (2) by rotating the brush on the spot to slight grasp the fabric sheet, and (3) rotating and horizontally moving (wind up while rolling).

A. *Structural Overview*

A schematic of the proposed end-effector is depicted in Fig. 3. The mechanism is composed of three parts. The first part is a cylindrical brush located on the left side, which is designed to grasp the fabric. The second part is located on the upper portion of the mechanism and serves to connect the robotic arm with the end-effector. Finally, the third part is a flat board located on the right side, which is responsible for holding and scooping the fabric sheet.

To stably pick up a sheet of fabric, it is desirable to contact the target fabric with the same force each time. Therefore, a method is adopted that uses the weight of the end-effector to apply a contact force. As depicted in Fig. 3, three shafts, which are directly connected to the wrist of robots, 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 fabric part, the end-effector's weight of $0.257g$ [N] (g: gravitational acceleration) is applied to the fabric part as a constant load. This passive movement range was set to 15 mm. As the proposed end-effector has a compact mechanism and is lightweight, this contact force can be realized solely by its weight.

In the following sections, we explain each important part in order. Furthermore, we provide a detailed explanation of the proposed end-effector for zigzag folding in Section V.

B. *Winding with a Cylindrical Brush*

A motor-driven cylindrical roller of radius 7 mm is attached to one end of proposed the end-effector. A remover fabric, typically used to remove dust from clothing, is attached to the surface of the cylinder. The remover fabric is polyolefin cilia of the following dimensions densely occupy the fabric area: length 1–3 mm; diameter less than 0.1 mm, and inclination 1–5°.

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

The idea of using this brush was proposed in [1], with a verification experiment with cotton fabric conducted and its

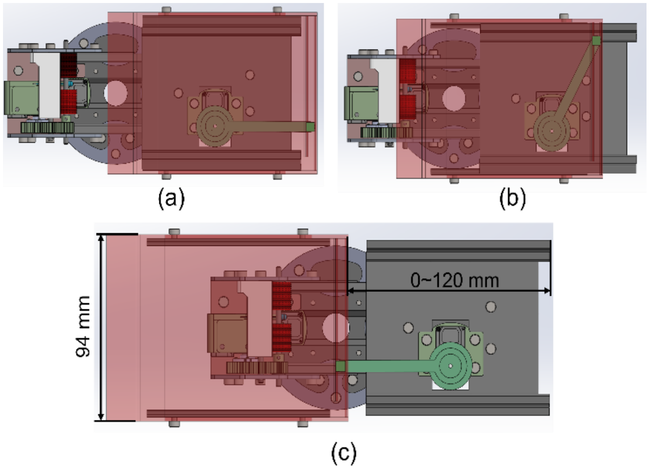


Fig. 5 The motion of the expanding flat board.

effectiveness described. Conversely, this study targets not only cotton fabric but also other fabric types. According to prior considerations, it was possible to pick up other fabric types using the same method. In [17], two brushes were installed facing each other and used for pinch gripping, whereas, in this study, the main purpose of this part is to roll up the fabric, and the flat board on the other finger plays the role of scooping the fabric up.

C. *Scooping up with a Flat Board*

The flat board shown in the right part of Fig. 3 primarily plays the following two roles: (1) a supporting role under the fabric to prevent the fabric from dropping while conveying fabric parts; (2) folding back and forth to make the original fabric which is too big to be fully grasped smaller. The latter is deeply discussed in the next section.

When the cylindrical brush lifts the edge of a fabric sheet slightly, the flat board is inserted under the fabric to support the fabric throughout the movement. For the operating principle of the flat board, the flat board can move horizontally using the rotating bar, as depicted in Fig. 5. As the rotation radius of the rotating bar is 60 mm, the relationship between the rotation angle θ and the horizontal movement distance is $60(1 - \cos\theta)$ mm, and the movement range of the flat board is 0–120 mm. This allows it to grip various parts of various types of cloth sizes while maintaining a lightweight mechanism.

In order to grip the fabric and insert the flat board under the fabric, we require a certain difference in height between the cylindrical brush and the flat board, but the cylindrical brush and the flat board have to touch the ground together when gripping the fabric. In order to solve this problem, we connect the flat board to the holder with three linear bushings through three shafts, so that the flat board is constrained to move up and down passively. The range of movement is set to 18mm.

To allow the flat board to smoothly insert and remove the fabric, the contact surface between the flat board and the fabric is polished smooth so that the frictional force between the flat board and the fabric is smaller than the frictional force between the fabric and the fabric, and the front edge of the board is tilted 5° to set the board to be easily inserted under the fabric.

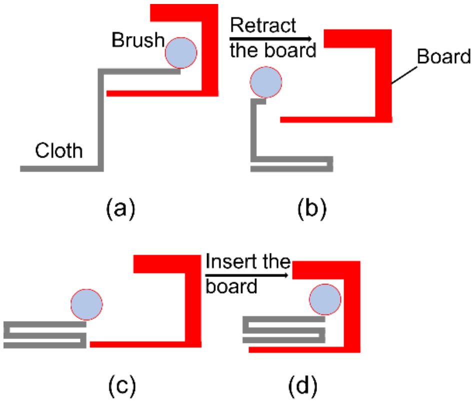


Fig. 6 The motion of the final zigzag folding.

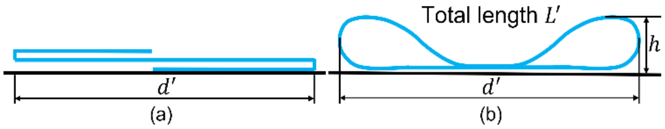


Fig. 7 Folded fabric shape. (a) and (b) shows ideal and actual, respectively.

V. ZIGZAG FOLDING STRATEGY

A. *Principle of Zigzag Folding*

The end-effector introduced in the previous section can stably handle the fabric from rolling to lifting because of its large contact area with the fabric. However, if the fabric part is too large to lift, it will have to be transported by dragging one end, which is undesirable.

Therefore, combining the characteristics of the end-effector and the motion of a manipulator, we propose a method for zigzag folding the fabric and then scooping up the entire fabric, as depicted in Fig. 6. During the zigzag folding process, the flat board needs to always be extended to support the fabric and prevent it from falling off during movement. However, before the final zigzag folding, the flat board that was previously extended needs to be retracted to insert it under the fabric and scoop up the whole fabric. After zigzag folding is completed, the flat board is inserted under the fabric to scoop it up completely. As a result, it is expected that after n times zigzag folding, the width of the fabric will be reduced to $1/(2n + 1)$ from the original length, enabling the fabric to be contained in the end-effector. This also has the advantage of significantly reducing the need for the robot's high range.

B. *Calculation of Motion Trajectory*

Under ideal conditions, the fabric will be folded perfectly, as depicted in Fig. 7(a); however, under actual conditions, using zigzag folding, the curved section will be drop-shaped as depicted in Fig. 7(b) [18]. Therefore, when folding the fabric, this gap must be taken into consideration when designing the motion trajectory of the end-effector. In this study, a method is proposed to achieve multiple equal-width folds of fabrics by combining linear motions. To accomplish this, it is necessary to calculate the difference between the

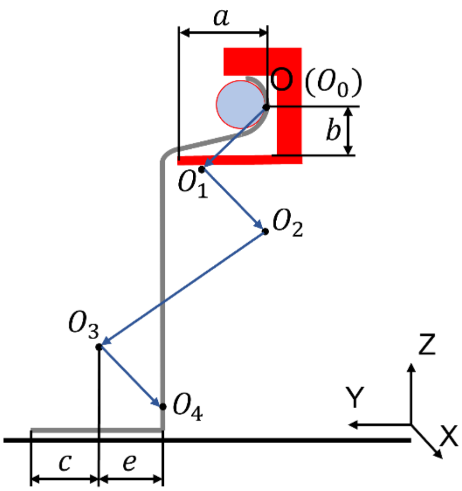


Fig. 8 The motion trajectory of using twice zigzag folding.

ideal and actual lengths of each curved section of the fabric first.

Assuming the width of the overlapping part of the fabric is d', the actual length of fabric required for n zigzag folds is L',and the height of the curved section is premeasured as h. Therefore, we can calculate the difference ϵ between the ideal and actual lengths of the fabric required for one zigzag folding using $(L' - 2nd')/n$, and therefore, the length difference of each curved section can be obtained as $\epsilon/2$. The subsequent step involves calculating the coordinates of each motion point along the motion trajectory of the end-effector.

In Fig. 8, the blue line represents the motion trajectory of twice zigzag folding, and the points $O_0 - O_4$ are connected in a straight line in sequence, and the starting point O_0 is coincided with the rightmost point O of the brush. Here, r represents the radius of the brush, a represents the horizontal distance between the forward edge of the board and point O, b represents the vertical distance between the surface of the board and the point O, e represents the length of the overlapping part of the fabric, and c represents the length of the remaining part. The full length L of the fabric can be obtained as $L' + c$ (In this case $L' = (2n + 1)e + n\epsilon$). With the above variables, the Y and Z coordinates of the starting point O_0 for zigzag folding can be obtained as follows:

$$O_0: (L - \pi r - c - e - a, L - c - e - \epsilon/2 - a + b) \tag{1}$$

When performing n zigzag folds, the end-effector moves in a straight line $2n$ time. The target coordinates for the i-th move can be calculated using the following equations, where i ranges from 0 to $2n - 2$:

$$\begin{aligned} O_{iy} &= L - \pi r - c - a - |\cos(i\pi/2)\, e| + |\sin(i\pi/2)\epsilon/2| \\ O_{iz} &= L - c - a + b - (i + 1)(e + \epsilon/2) \end{aligned} \tag{2}$$

To obtain the last two coordinates (the $(2n$-1)-th and $2n$-th in ascending order), the extended board must be retracted to insert it under the fabric and lift the whole fabric. The coordinates can be calculated using the following equation:

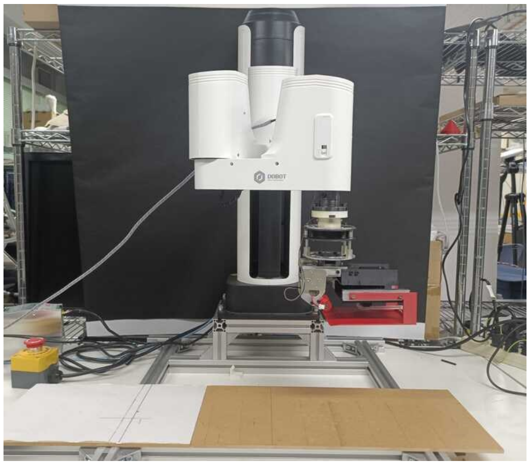


Fig. 9 Experimental settings.

$$\begin{aligned} O_{2n-1} &: (L - \pi r - c + \epsilon/2, e + \epsilon/2 + r + nh) \\ O_{2n} &: (L - \pi r - c - e, r + nh) \end{aligned} \tag{3}$$

VI. VERIFICATION EXPERIMENTS

A. *Experiment Settings*

For the validation of the proposed end-effector, a verification experiment was conducted using actual fabric parts. The end-effector was attached to Dobot M1, a light industrial robot with three joints, with a working range of ±90° for the main arm, ±130° for the small arm, and 5–250mm for the Z-axis. In the experiment, a wooden plate was laid flat on a table, and a fabric part was placed on top of it. The robot was instructed to pick up the fabric part and place it on the right side. Then, for rectangular fabric assemblies beyond the robot's Z-axis range, a zigzag folding trajectory was tested, as well as the ability of the end-effector to perform pick-and-place tasks on fabrics too large to be lifted. The experimental environment is depicted in Fig. 9.

B. *Fundamental Experiment of Picking up a Fabric Sheet*

A piece of rectangular fabric sheet, designed for sportswear with a size of 500×50 mm, was folded twice with a zigzag folding method with an overlap of 80 mm, and the length difference of its curved section $\epsilon/2$ was determined to be 6 mm through experimentation. By inputting these parameters into the coordinate equation in V-B, the coordinates of each motion point could be obtained to generate a complete motion trajectory. Then, the robot and the proposed end-effector were used to conduct the actual pick-and-place experiment.

C. *Zigzag Folding Experiment*

To verify the feasibility of the proposed folding trajectory described in V-B, experiments using three materials of fabric sheet were conducted. To evaluate the folding results, the overlap rate [%] was first defined. This calculates the ratio of the overlapping parts of the fabrics in the vertical direction. Based on the overlap rate, the success rate was judged when the rate was greater than 95%. The equation for the overlap rate is as follows:

$$\delta = (1 - l_c/l') \times 100, \tag{4}$$

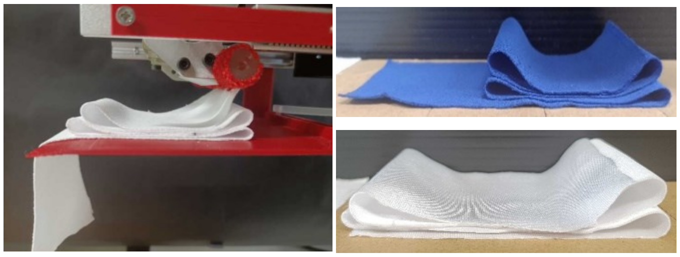


Fig. 10 Success case of zigzag folding.

TABLE I Experiments for verification trajectory

Type	Sportswear	Innerwear	Polo Shirt
Success rate	93%	95%	92%
Failed rate	7%	5%	8%
Total success rate	93.3%		

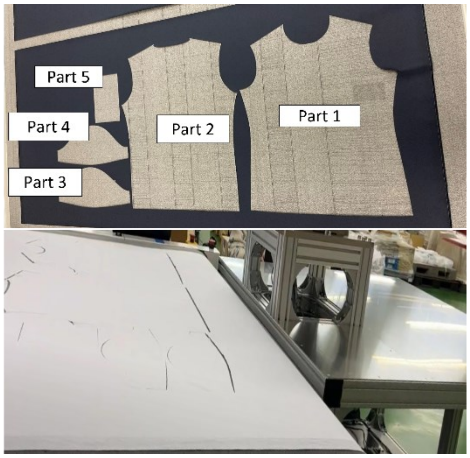


Fig. 11 Experimental settings in factory.

where l_c denotes the total length beyond or less than the overlapping area, and l' denotes the total length of the area. The following experiments will be performed on the motion trajectory.

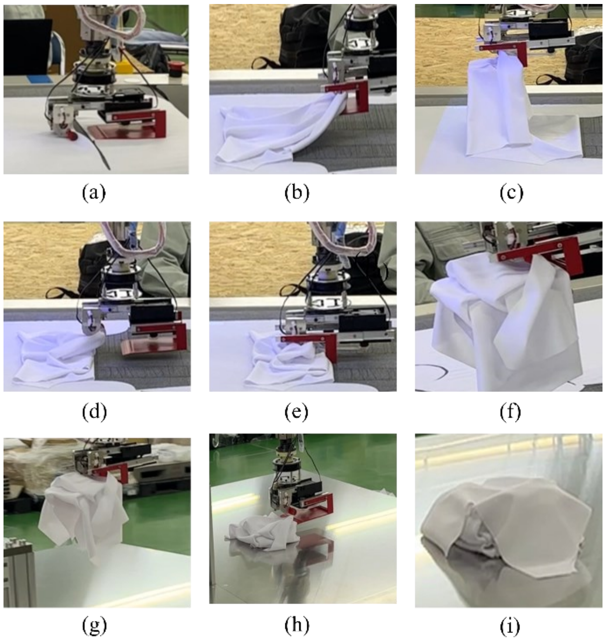
The fabrics used in the experiment are of three types, namely, sportswear, innerwear, and polo shirts, with each type having three sizes (400 x 50mm, 450 x 50mm, 500 x 50mm, respectively) prepared. The length difference in their curved sections $\epsilon/2$ was measured in advance and set to 6, 4, and 10 mm, respectively. Then, 50 pick-and-place experiments were conducted on each of these 9 objects, and the successful experimental cases are shown in Fig. 10.

The results are shown in Table I, indicated a total success rate of 93.3% for the zigzag folding experiment. Thus, the feasibility of the end-effector's motion trajectory can be verified.

VII. EXPERIMENTS IN SIMULATED FACTORY ENVIRONMENT

A. *Experimental Settings*

One application of the proposed end-effector is to stack fabric parts cut from a cutting machine at a specified location. To verify whether the end-effector works properly in the actual production process, a series of experiments were conducted in the factory to pick up every part of the T-shirts cut by the cutting machine and stack them on the table at the right.



(a) (b) (c)
(d) (e) (f)
(g) (h) (i)

Fig. 12 Pick-and-place experiment in factory.

TABLE II Evaluation results of each part of T-shirt

Part	Part 1	Part 2	Part 3	Part 4	Part 5
Holding success rate	94%	94%	100%	100%	97%
Removal success rate	100%	100%	100%	100%	100%
Release success rate	97%	96%	97%	97%	100%
Total success rate	90%	90%	97%	97%	97%

The end-effector was attached to IX-NNN10040 manufactured by IAI Inc. The positions of each part of the T-shirt and experimental environment are depicted in Fig. 11. Three types of fabric parts (sportswear, innerwear, and polo shirts) were selected as test pieces, and 10 experiments were conducted on each piece.

B. *Experimental Results*

In this experiment, the pick-and-place process was in ascending order of each part's label. Part 1 was folded twice using the zigzag folding method, as depicted in Figs. 12(a–d), to reduce it to 1/5 of its original size, and then, it was scooped up and placed on the table at the right, as depicted in Figs. 12(e–h). Next, Part 2 was placed on top of Part 1 using the same folding method, and the following parts were placed on top in turn without the need to use zigzag folding. The final experimental results are shown in Fig. 12(i).

The results are summarized in Table II, showing the definitions for each success rate: the holding success rate was the ratio of the number of successful holds to the total number of trials; the removal success rate was the ratio of the number of successful removals to the number of successful holds; the placement success rate was the ratio of the number of successful placements to the number of successful holds; the total success rate was the ratio of the number of successful placements to the total number of trials.

In this experiment, we conducted 20 experiments on each part of T-shirts of three different materials, and the results are shown in Table II. For the holding success rate, the end-effector failed to grip the large fabric (part1,2) because the gripping position was changed and the moving speed was too fast, while the small fabric (other parts) showed a relatively good holding ability. The removal success rate 100% showed the stability of this end-effector to removal the fabric. As for the release success rate, the main reason for failure was that the contact surface between the board and the fabric was not smooth enough, and there were many possibilities for improvement. In summary, the overall success rate was over 90%, indicating that the proposed end-effector has the potential for practical application in a factory setting, also, this end-effector still had room to improve the success rate.

VIII. CONCLUSIONS

In this study, we proposed a novel end-effector for grasping fabric parts and assembling them for packing before sending them to the sewer for sewing operations. In the proposed end-effector, we used a cylindrical brush to grasp the fabric and designed a flat board to scoop the whole fabric. Then, we proposed a zigzag folding method for folding large pieces of fabric into smaller sizes and scooping them, while keeping the end-effector compact and capable of handling large pieces of fabric. Then we designed the motion trajectory of the end-effector and validated it through experiments. The results showed a success rate of 93.3%, confirming its feasibility. Next, we conducted experiments for the pick-and-place task of each part of the T-shirt made from three different materials in a factory setting. The total success rate was over 90%, indicating good performance with some room for improvement.

In the future, we aim to optimize the motion trajectory by making it a continuous motion trajectory rather than a simple linear motion. We also aim to increase the overall success rate on each part of clothes and evaluate more materials and shapes of clothing parts.

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