A Dual-Arm Manipulation System for Unfolding and Folding Rectangular Cloth

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***Abstract* - This paper describes a robot system that can perform several cloth manipulation tasks. Many commendable activities on deformable object manipulation are underway in the research community. One such activity is the Cloth Manipulation Track organized as part of the Robotic Grasping and Manipulation Competitions. Although limited to rectangular fabrics, the imposed tasks incorporate many of the basics of cloth manipulation and are well thought out. In order to realize these tasks, it is necessary to take into account the properties of the fabric, which can be deformed into various shapes. In this paper, we introduce our robot system that can perform corner detection, unfolding, and folding operations on rectangular fabric products of different sizes and types. We have devised an appropriate motion sequence based on our empirical knowledge of cloth deformation and adopted a feed-forward motion approach to realize these tasks. This approach was confirmed to be feasible for different types of cloth products.**

Index Terms – Cloth manipulation, dual-arm robot, household cloth object set

I. Introduction

The manipulation of a cloth product by an automatic machine is a challenging and difficult task. Cloth is a deformable object, i.e., an object that has the property of changing its shape. This means that, from the point of view of manipulation, the number of possible states is infinite. This makes it difficult to predict or estimate the state of the object, and, as a result, it is difficult to formulate a strategy for manipulation. This fact is well recognized in the field of intelligent robotics, and there are many studies that have attempted to realize manipulations, such as folding, by robots [1-3]. However, this technology is not yet mature.

In order to get good cloth manipulation, various studies are being conducted in the cloth manipulation research community. In addition, it is worth mentioning that challenging activities are underway to raise the level of research. One such activity is the Cloth Manipulation Track (CMT) [4] organized as part of the Robotic Grasping and Manipulation Competitions (RGMC) [5]. The RGMC is held in conjunction with top-class international conferences such as IROS and ICRA, and the CMT was held in October 2022 as a part of these conferences. Various types of rectangular fabric products were set up, and the tasks were to properly detect the gripping points, unfold the fabric product on the table, and fold it into the appropriate shape. Although limited to rectangular fabrics, these tasks incorporate many of the basics of fabric manipulation and are well thought out.

The purpose of this study was to build a robotic system that could handle all the tasks imposed in the CMT. For this purpose, an RGBD camera, and two serial link manipulators were used and recognition and motion generation functions were implemented. In addition, an end-effector was newly developed to properly complete the grasping process. These innovations enabled proper unfolding and folding of fabric products of different sizes, fabric stiffnesses, and surface properties.

The contributions of this study are as follows:

- We have devised a sequence of manipulations to accomplish unfolding and folding. We show how to apply the desired manipulation, e.g., shaping using a table, to small rectangular fabrics as well as to fabrics that are larger than the manipulator's range of motion.
- Grasping of a fabric can be done both by gripping the edge and by picking up a part of the fabric other than the edge. We have proposed a dual end-effector to perform both these manipulations and also show how to use the dual end-effector.
- Using a robot system equipped with the above two functions, we conducted unfolding and folding experiments on a cloth set [6] used in the CMT and have organized the results.

The structure of this paper is as follows. The next section discusses related work. Section III explains the rules of CMT and summarizes the appropriateness of the task. Section IV describes our robot system and its recognition and motion generation functions. Section V describes the end-effector for the cloth pick-up. In Section VI, we report the experimental results and conclude this study in Section VII. Please also refer to the movie to see how the proposed system works.

(YouTube: https://www.youtube.com/watch?v=vK88JKubcSc).

II. Related work

Various studies have attempted to manipulate cloth products using robots [7]. Maitin-Shepard et al. [8] were able to fold towels picked from a random stack of the towels. Osawa et al. [1] were able to unfold cloth products using dual-arm manipulation. Monsó et al. [9] proposed a planning method to pick up one cloth product from a stack of clothes and verified it experimentally. Demura et al. [10] proposed a method to pick up the top towel from a stack of folded towels kept on a table. The requirement was not to disturb the folded state while picking up the towel. They presented grasping-point detection and a proper motion sequence and showed experimental results using an actual mobile manipulator. Basically, these studies generate robot motions by combining pick-up motions and transfer motions. This means that the grasped cloth product can be fully lifted up and separated from the table. Cloth products larger than the robot's range of movement are not considered.

Shibata et al. [11] proposed pinch-and-slide unfolding, one more manipulation method except for the cloth pick-up part. They discussed the shape of the finger and achieved stable unfolding of a rectangular fabric. Yuba et al. [12] presented a unified manipulation process for a crumpled rectangular fabric by detecting the graspable corners, picking up one of them, and doing pinch-and-slide unfolding. Cuén-Rochín et al. [13] targeted a wrinkled fabric placed on a table and pushed it with the tip of a finger and slid it on the table. Doumanoglou et al. [3] succeeded in performing the full process of folding clothes. The various approaches in these studies relax the size of the manipulatable cloth and manipulate the cloth using available knowhow [6].

Studies have also been carried out on perception methods for deformable object manipulation. Willimon et al. [14] succeeded in selecting one grasping location for picking up a cloth product from the many available. Ramisa et al. [15] proposed a method to detect characteristic locations, such as sleeves and collars, from an image of cloth products lying crumpled on a table. Stria et al. [16] proposed a shape estimation method by introducing a polygon model. Twardon et al. [17] proposed a topological representation aiming at dressing support and applied it to estimate the open parts, such as sleeves. Li et al. [18] succeeded in recognizing the wrinkled state of a cloth product placed on a table and used the result to the plan the removal of wrinkles. The CMT includes a task that requires cloth corner detection. Overall, the abovementioned studies are informative.

III. Cloth Manipulation Track

A. *Required Tasks and Rules [4]*

The CMT consists of tasks that require unfolding and folding rectangular cloth pieces from the household cloth object set [6]. There are 15 types of cloth pieces in the competition, and the total number of individual pieces is 27. They have different sizes, stiffnesses, and thicknesses. There are bag-shaped cloth products such as pillow cases also.

The size of the table used is 700 x 1200 mm, and all the target cloth products can be placed on the table in fully unfolded condition. A sensor, required to capture color, and depth information, is installed above the table to cover the entire table area. In addition, as the CMT was held online, it was obligatory to set up a camera such that the entire robot system could be seen. The camera also had to be freely moveable.

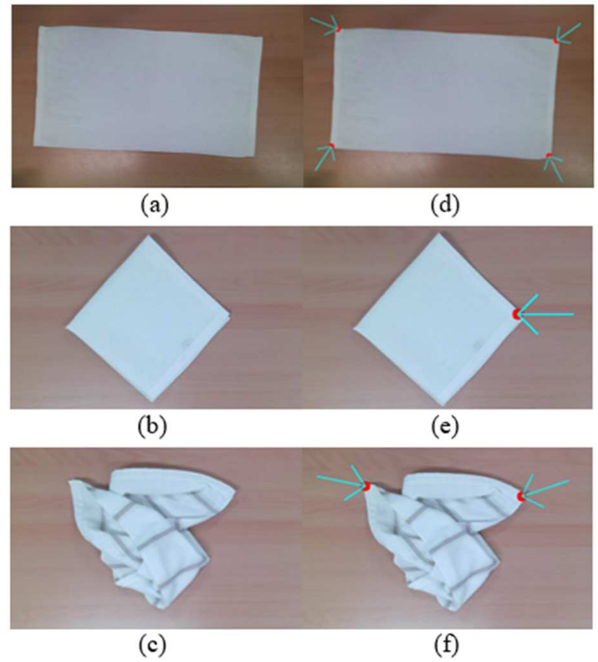


Fig. 1. Left: initial cloth shape, Right: the output of perception task

The competition is divided into a perception track and a manipulation track. The manipulation track consists of a folding task and an unfolding task. The following is a brief description of the rules for each track.

1. Perception track
   It requires detection of the corners to be grasped. Three types of shapes are presented: (a) fully unfolded, (b) folded in quarters with overlapping corners, and (c) randomly placed (crumpled shape). As shown in the right column of Fig. 1, the detected grasping locations should be rendered in the original color image, with an arrow showing the approaching direction of the robot hand. The score for this track is calculated from the results of ten trials with different cloth products and shapes. The detection success rate of the corner location and the accuracy of the approaching direction are evaluated.

2. Manipulation track
   In this track, two types of tasks, folding and unfolding, are imposed. The time limit for each task is 75 min. Although sticking color markers on cloth corners is permitted, a bonus point is given when such markers are not used. This track starts with a participant placing a cloth product on a table. However, to prevent the participants from making a shape that is favorable to them, the judge makes a slight shape change on the spot. The rules for each task are as follows:

2-a. Folding task

Fig. 2. An example of a cloth with the corners are inside the cloth area

As shown in Fig. 1(a), unfold, and place a cloth product on the table. Then, fold the cloth in quarters within the given time. The folding is attempted six times, each time with a different cloth product. The results are evaluated based on several criteria: the folded shape (the folded shape becomes a quarter of the original unfolded shape), alignment of the hems, and less wrinkles another criterion is that the folded cloth should be fully located within the table.

2-b. Unfolding task

The aim of this task is to unfold a cloth product on the table. There are two initial cloth states: folded in quarters and placed on the table as shown in Fig. 1(b), and placed with a random shape as shown in Fig. 1(c). For each case, three trials are carried out by changing the initial shape of the cloth. The results are evaluated based on the quality of the unfolded shape, which is decided with reference to wrinkles and the degree of overlapping. Another criterion is that the unfolded cloth should be fully located on the table.

B. *Organizing Issues*

The tasks mentioned above pertain to important issues with respect to deformable object manipulation. These issues are listed in this subsection.

Perception track: For folding or unfolding a cloth, the appropriate grasping locations must be determined at each manipulation step. Grasping point detection for crumpled cloth has been focused on in [15, 19]. A similar solution is required in this track. Moreover, as shown in Fig. 1(b), it is technically difficult to select one appropriate corner from a cloth folded in quarters. Moreover, in one case, the cloth corners are arranged inside. In such a situation, the robot must be able to recognize that the corner part cannot be observed for the presented shape.

Manipulation track: The cloth object set introduced in Section III-A consists of various sizes, aspect ratios, and materials even though the unfolded shape is limited to a rectangle. One single robot system must be able to manipulate them all. In general, manipulations that include folding require a large range of robot motions. As a result, the robot system becomes large [3]. In addition, since different cloth products have different properties, such as hardness, and thickness, a folding manipulation that is successful for one type of cloth often does not work for another type. Also, when fabrics are stacked on top of each other, it is difficult to pick up only the top layer. However, all such manipulations should be stably achieved in the unfolding task.

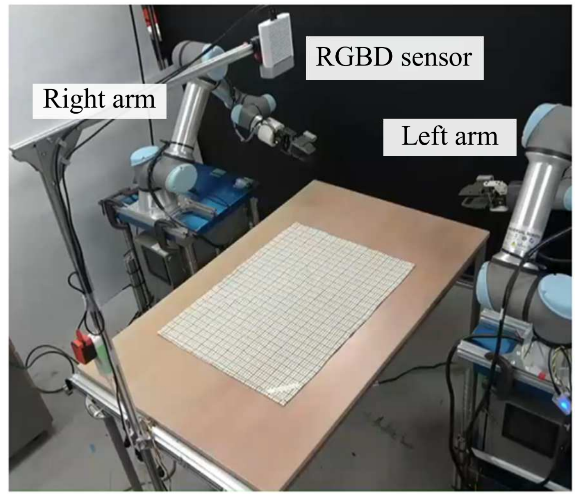


Fig. 3. Overview of robot system

C. *Our Approach*

To address the issues outlined earlier, we adopt the following approach. An RGB-D camera installed above the table is used to automatically detect the grasping points. The details are described in IV-B. To keep the system compact, two serial link manipulators, each about the size of a human arm, are used for manipulation. However, the range of movement is too small for purposes such as completely lifting up the cloth. Therefore, we will devise a manipulation procedure that actively uses the environmental structures, for example, by actively hanging cloth products down from the table edge. The details are described in IV-C.

The robot hand is also an important element in the proper realization of manipulation. For some tasks, it may be appropriate to scoop up the edge of the cloth from the side, while for other tasks, it may be appropriate to pick up the inside of the cloth. In addition, this manipulation basically requires a dual-arm approach. However, it is not desirable to have as many manipulators as the number of end-effectors required. There is also the option of using a multi-fingered articulated hand that can perform all the tasks, but this is expensive. Therefore, our approach has been to install multiple, two-fingered hands in the end-effector section and use them according to the purpose of the work. The details of this approach are described in Section V.

IV. The Robot System and Manipulation Strategy

A. *Robot System Overview*

The robot system is shown in Fig. 3. Two serial link manipulators are fixed around the table. The manipulators are UR5e from Universal Robots. Since these manipulators have their own distinct roles, they are distinguished as right and left as shown in the figure. An Azure Kinect camera that can acquire RGB-D images is used to detect the grasping point.

To avoid slow processing speeds and unforeseen processing delays, we decided to separate the PC that executes the robot's movements and the PC that recognizes the state of the cloth. The former was configured with a Core i9-10980 (2.40 Hz × 12) CPU, 64GB memory, and NVIDIA QuadroRTX5000 (8GB memory) GPU. The latter consisted of a Xeon Silver4216 (3.60 Hz × 12) CPU, 64GB memory, and NVIDIA Quadro RTX4000 (8GB memory) GPU. The software implementation of the robot system was based on ROS, which is widely used in the field of robotics.

B. Vision Functions

In this section, we mainly introduce the correspondence to the perception track shown in item 1 in Section III-B. Since YOLO [20] is an effective method for cloth fold detection [10], we constructed a corner detector by transferring the learning of YOLO v7.

For training the corner detector, color markers were attached to the corners of the cloth products, and training data were collected according to the following procedure. First, the RGB, and depth images of the cloth products are acquired. Then, HSV color extraction and GrabCut [21] are applied to the RGB image to eliminate the desk area so that only the cloth area is reflected. Next, the coordinates of the corners of the cloth are obtained by extracting the color markers. Finally, the coordinates of the corners are mapped to the depth image of the cloth and recorded as training data. The depth image used here is normalized so that the position of the desk is 0 and the position at a certain distance toward the camera is 1. This is done to highlight the characteristics of the depth information, distinguish wrinkles and folds from corners, and improve the detection accuracy. Training was performed on all patterns: unfolded cloth, folded cloth, and randomly shaped cloth (there were three cases of randomly shaped cloth: two corners located inside the cloth region, two corners outside, or one corner inside and another outside). Approximately 5600 pieces of data were collected. Four patterns of padding were used: rotation, magnification, translation, and image merging.

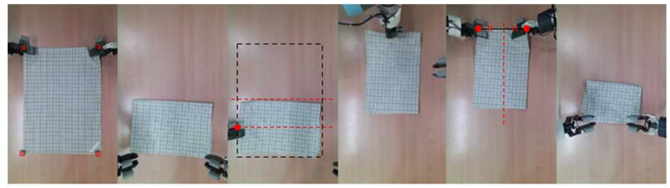
The method for determining the direction of the hand approach is as follows. First, a grasping point is selected slightly inside a corner by the method described above. Then, the straight edges of the corner are detected in the color image, and their point of intersection is calculated. Then, the straight line passing through this intersection point and the grasping point is obtained, and the straight line is defined as the approach direction.

C. Manipulation Strategy

We introduce our manipulation strategy with respect to the tasks described as 2-a and 2-b in Section III-B. The strategies are built against each of the following three patterns:

(a) Folding an unfolded cloth product
(b) Unfolding a cloth product folded in quarters
(c) Unfolding of a cloth product with a crumpled shape

Other possible tasks include folding a cloth product starting from a crumpled state and a combination of the above tasks; specifically, performing a procedure for task (a) after doing a procedure for task (c)



(a)

(b)

(c)

Fig. 4. Motion sequences to solve each task

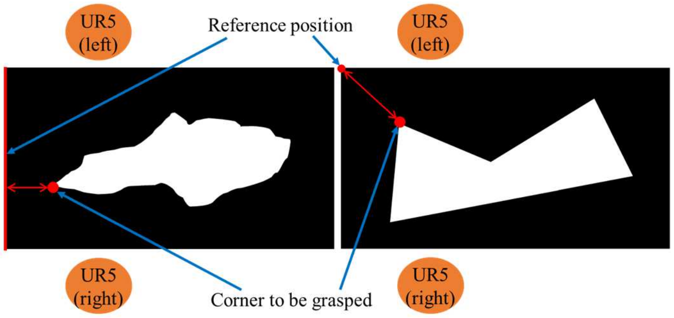
Each manipulation procedure for tasks (a) to (c) is introduced in order. The following is a procedure for doing task (a). See also Fig. 4 (a).

(1) Detect the corners of the cloth product using the method described in the previous section.
(2) Of the corners found, the corner closest to the root of each manipulator is determined as the grasping target, and each manipulator grasps it and folds the cloth product in half.
(3) Grasp a location one-quarter of the length of the long side of the cloth from the position where the corner was grasped. Rotate the cloth by 90 degrees around the vertical axis.
(4) Assuming that the center line of the cloth passes through the gripped position, estimate the corner of the cloth, and grasp it with both hands. Then, fold the cloth again.

The above procedure completes the folding process by rotating the cloth and changing the grasping positions so that the manipulator’s range of motion is not exceeded.

The following is a procedure for doing task (b). See also Fig. 4 (b).

(1) Detect a corner of the cloth product. Since the corner is made up of four overlapping fabrics, the top two fabrics are gripped. See the next section for the grasping method.
(2) Lift up the corner part and unfold the cloth by moving it along a circular arc so that the grasped surface does not get caught on the lower surface.
(3) Detect a corner of the unfolded fabric that is located in the lower part in a captured image. Pick up only the top piece of the fabric by gripping near the detected corner and unfold it once.



(a) (b)

Fig. 5. An example of the intermediate cloth shape for tasks starting from a crumpled shape

(4) Move the hand back to an appropriate position according to the size of the cloth product, and moves its entire body with both robot hands such that a part of the fabric hangs down from the edge of the table.
(5) Without releasing the hand hold, the hand position is moved to in the middle of the table that the cloth product is unfolded on the table.

The purpose of this action is to achieve the shaping of the cloth by draping it off the table. In addition, this manipulation requires dexterity in grasping – grasping only the top of the overlapping cloth. Therefore, the robot hand, and its operation have to be derived a way. The details are described in the next section.

Finally, the following is a procedure for doing task (c). See also Fig. 4 (c).

(1) Detect the corners of the cloth product and grasp the corner closest to the root of UR5 (left) with one hand.
(2) While grasping the cloth, lift it up once, and spread it out on the desk while hooking it to the edge of the desk. At this time, as shown in Fig. 5(a), the corner opposite the corner being grasped should be at the end of the cloth.
(3) Based on the earlier knowledge that the other corner to be grasped is at the opposite end, the far corner on the table is detected.
(4) Once again, spread out the cloth on the desk using the edge of the desk. At this time, as shown in Fig. 5(b), create a shape such that the adjacent corner on the short side of the corner that UR5 (right) is grasping is in front of UR5 (left).
(5) UR5 (left) grasps the nearby corner. Again, the system detects the corner to be grasped with the earlier information that it is in front of UR5 (left).

The key point in this manipulation is that it does not require advanced recognition techniques or skillful grasping methods, and by using the edge of the table, it is possible to create similar shapes with various types of cloth. In other words, the same sequence of movements can be used to perform the task.

V. Picking up a Part of Cloth

A. *Required Grasping Types and Our Approach*

In the folding and unfolding of cloth products, it is necessary to change where and how the hand grips the cloth, depending on how it is to be deformed. However, building and controlling a complex hand is burdensome. In this study, we take the approach of organizing the grasping methods required for a given task, and then respond to them with a simple hand that can be constructed inexpensively.

Accordingly, there are two types of grasping methods required. One is picking the hem of the cloth to turn it over, and the other is pinching and lifting the surface of the cloth. However, the hardware and/or software required to construct a hand system that can stably perform both these grasping tasks would be complicated. Therefore, we decided to construct individual hands that can perform each of these grasping tasks. However, we did not wish to increase the number of manipulators by the number of hands, as this would increase the complexity of the system. Therefore, we decided to attach two parallel grippers to the tip of one manipulator and use them differently depending on the part of the cloth to be grasped.

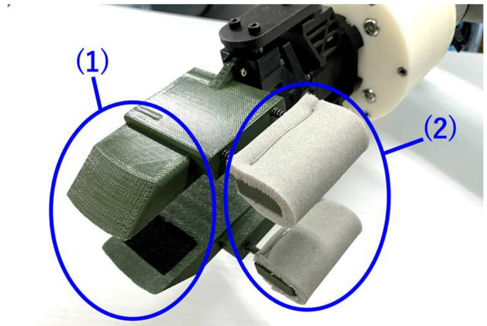
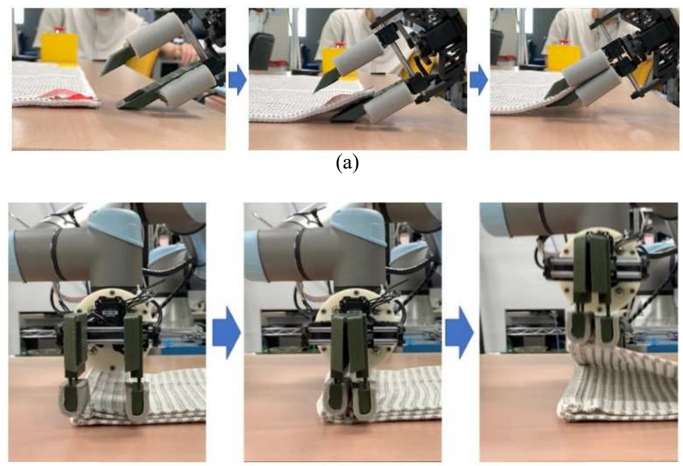


Fig. 6. Proposed end-effector



(a)

(b)

Fig. 7. Picking action of each gripper

B. *End-effector Configuration*

An overview of the end-effector is shown in Fig. 6. Two parallel grippers are orthogonal to each other. The part circled as (1) is the gripper for gripping the hem of the cloth product. The gripper is used by slipping one finger under the hem and closing the finger afterwards. This is shown in Fig. 7(a). The gripper is suitable for picking up the fabric from the table.

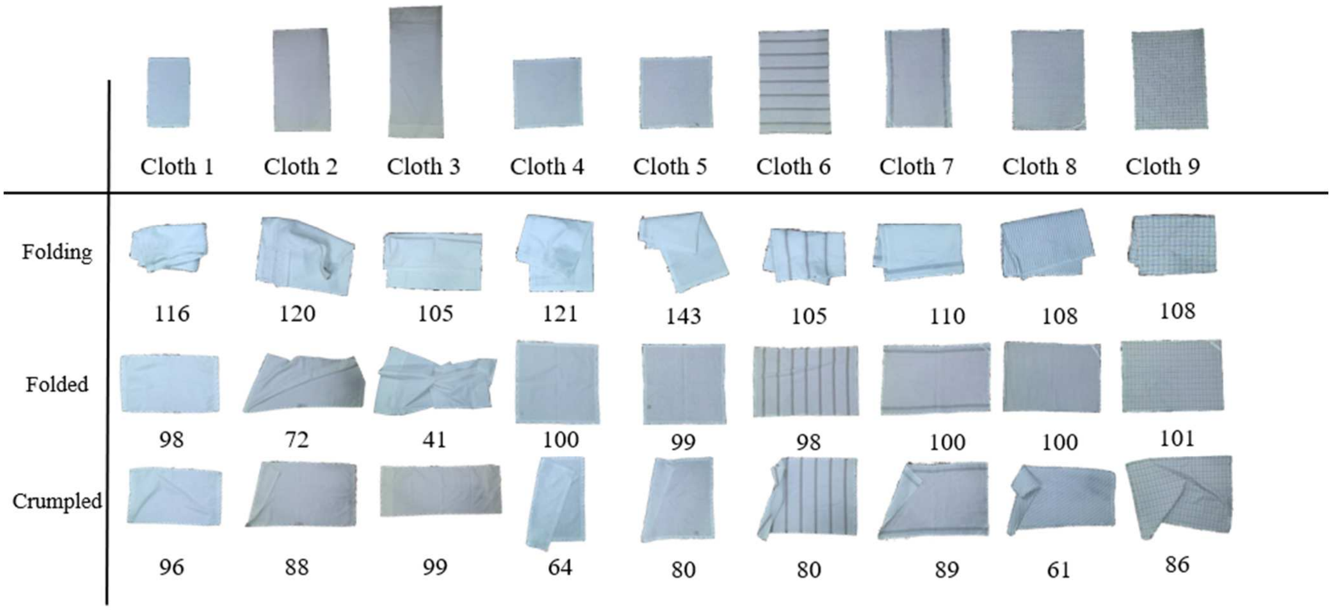


Fig. 8. Results of each task execution. The numerical values in the figure indicate the overlap rate as per Eq. (1).

The area circled as (2) is a gripper for gripping the surface of a fabric. The fingertips are pressed against the surface, and by narrowing the distance between the fingers, a part of the fabric is lifted up and gripped. Fig. 7(b) illustrates this process.

The gripper device and the grasping method in (2) are described below. First, a sponge is attached to the fingertip to prevent slippage. In addition, there is a mechanism that allows the gripper to slide freely in the vertical direction in order to accommodate differences in the hardness and the number of layers of the fabrics. This part is equipped with a spring, which, together with the sponge, generates an appropriate frictional force between the cloth and the fingers.

In order to lift only one or two pieces of the fabric stably from a state in which multiple fabrics are stacked on top of each other, it is effective to raise the hand little by little and, at the same time, to narrow the opening width of the gripper little by little, so that they are interlocked. In concrete terms, the first step is to close the gripper by a small amount while pressing down on the cloth with the gripper (2). This minute amount is set according to each cloth. Then, every 0.1[s], the gripper is raised by 4[mm] and closed by 1.25[mm], and the operation is repeated 20 times. These values were determined empirically.

VI. Experiments

A. Experiment Settings

Nine types of fabrics were selected from the set of fabric products shown in III-A. Specifically, bath towels (small and mid-sized), a rectangular pillowcase, dining napkins (cotton and linen), and kitchen rags (towel, linen, waffle, and checkered) were selected. Three tasks were performed on these fabrics using the methods described in Sections IV and V. The fabric after execution should be either spread out on the table or folded into fours. Therefore, the difference between the area of the final shape and the area of the target shape was evaluated by using the images taken from the camera located directly above the table. The evaluation formula is as follows.

$$e = \frac{P_r}{P_t} \times 100 \tag{1}$$

where e is the overlap rate, P_r is the number of pixels in the final shape, and P_t and is the number of pixels in the target shape.

B. Experimental Results

Figure 8 shows the final shape of the cloth for each task. The leftmost column shows the initial shape of the cloth products. The numerical values below each cloth image are the overlap rate of the cloth as expressed by Eq. (1). The sequence of manipulations for each task was implemented as a single function, passing only parameters based on cloth size and thickness as arguments. This implementation confirmed that the task could be performed with all nine selected cloth products. The following is a summary of the difficulties encountered in each task.

The folding task requires two folding movements. The second folding involves a smaller area of the cloth, and the resistance force of the cloth is greater because of the overlapping cloth fold. For these reasons, it was difficult for our robot system to generate folding movements for small pieces of cloth. In particular, Cloth 5, which was made of a stiff material, rebounded at the folds during the folding process, and the folded cloth was not in good shape after folding.

In the task of unfolding the folded cloth, when handling large cloths such as Cloth 2 and Cloth 3, the cloth sometimes did not fall off the edge of the table properly as expected during the procedure of dropping a part of the cloth from the edge. As a result, the overlaps of the cloth could not be resolved.

For the task of unfolding of a crumpled cloth, we added the action of shaping the cloth before unfolding it using the edge of the table. This action was determined by trial and error. Although relatively good results were obtained for the feed-forward method, the final shape of the cloth seemed to be highly dependent on the way the cloth was twisted and folded when grasped.

VII. Conclusions

This paper describes a robot system that can perform corner detection, unfolding, and folding operations on rectangular fabric products of different sizes and types. In order to realize these tasks, it was necessary to take into account the properties of the fabric, which can be deformed into various shapes. We devised an appropriate motion sequence based on our empirical knowledge of cloth deformation and adopted a feed-forward motion approach to realize these tasks. This approach was confirmed to be feasible for nine different types of fabric products.

In the future, we will reconsider the motion sequences, add sequential feedback, and improve the recognition accuracy.

Acknowledgment

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