Variable friction based in-hand manipulation of fabrics applied to unfolding operations

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***Abstract*— As a typical deformable object, a fabric is characterized by its difficulties in automatic state recognition and handling. The development of the related technology on fabric manipulation is still far from practical deployment. This research was inspired by the process that humans handle fabrics with fingers. We proposed an in-hand manipulation method for fabrics based on variable friction and verified its effectiveness by experiments of sliding a single sheet of fabric and unfolding utilizing the in-hand manipulation functions. The experimental results demonstrated that the in-hand manipulation functions proposed in this paper have the potential to wisely solve some complex problems confronted with fabric handling.**

I. INTRODUCTION

With the increasing demand for automation in the clothing industry and housekeeping, the research on automatic operation methods for fabrics has attracted people's attention. Compared to rigid objects, fabrics are characterized by low bending rigidity, and complex dynamic behaviors. Hence, the grasping and handling of fabrics are highly unpredictable [1]. As a result, the degree of automation for handling fabrics is far less than for rigid objects. Despite the complexity of fabric's properties, various solutions to cloth manipulation have been proposed [1]–[17] , many of which were based on imitation of corresponding human behaviors.

Daily experience indicates that a human can wisely adjust his fingers' contact position and force in handling a fabric. We observed the movement of the thumb and index finger when a human handles a fabric held within the two fingers. We found that a human can easily move a fabric with respect to his hand by coordinating the two fingers. The mechanism involved within the capability can be explained as the variable friction states realized on the two sides of the held fabric. It inspired us to propose a similar in-hand operation method for fabric manipulation.

The original contribution of the paper includes 1) We proposed a method based on variable frictions for in-hand manipulation of fabrics; 2) Through experiments, we demonstrated the advantage of using it in unfolding tasks; 3) Based on the tactile sensor and camera embedded inside the fingers, we proposed and verified methods for estimating the sliding distance of the fabrics within the hand and recognizing several critical states in the manipulation. The paper is organized as follows. In section II, the related research on gripper designs and operation methods for handling fabrics is summarized. In section III, we introduce the principle of our proposed method and the hardware implementation. Section IV presents the fabric manipulation experiments based on our proposed method. Finally, the summary and a discussion on future work are addressed in section V.

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II. RELATED WORK

Researchers have contributed many solutions for fabric manipulation tasks. The commercial gripper products cannot adopt to the complex fabric operation tasks. Specially designed ones are generally utilized.

Koustoumpardis et al. [1] [2] studied the action of human fingers when picking up a piece of fabric laid on a flat surface. They summarized the motion trajectory and developed underactuated grippers to imitate the action taken by humans. Donaire et al. [3] developed a three-fingered gripper for manipulating fabrics. The thumb of the gripper contains a cam mechanism, which drives two structures with different friction properties to eject alternately as the contact surface. This enables the gripper to perform both gripping and pinching-slipping that requires less friction. Hinwood et al. [4] were inspired by human hands and proposed a prototype of cloth handling gripper that adopts the lateral grasp [18]. They demonstrated that their gripper could grab flat fabrics from arbitrary positions. Digumarti et al. [5] developed a two-fingered gripper with electroadhesive skin. With the electroadhesion force, the gripper is capable of separating overlapped fabrics. Ku et al. [6] were inspired by the oral disc with sharp teeth of lamprey and proposed a microneedle-embedded soft robotic gripper. They demonstrated that the microneedle-embedded gripper could pick up a single sheet of fabric from a pile.

In addition to the research realized with specially designed grippers, some researchers have also proposed more general fabric manipulation methods by analyzing the fabric deformation process. Shibata et al. [7] proposed the concept of wiping motion. The wiping motion is defined as a motion that causes the movement and deformation of the fabric during handling. And they demonstrated an experiment in which a simple gripper grasped a piece of fabric by interacting with the environment. Shibata et al. [8] also proposed a fabric manipulation method through interacting with a rigid environment. They analyzed in detail the deformation of the fabric as it came into contact with the environment and demonstrated an experiment on how to utilize the motion

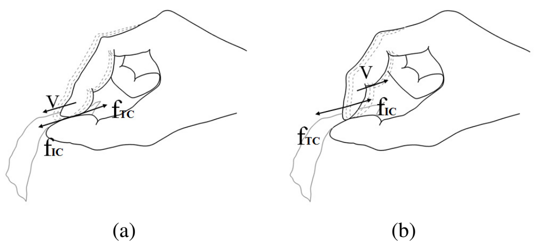


Fig. 1. Index finger and thumb move the fabric in hand by adjusting the contact and contact force(f_{IC} represents the tangential force of the index finger exerted on the fabric, f_{TC} represents the tangential force of the thumb exerted on the fabric)

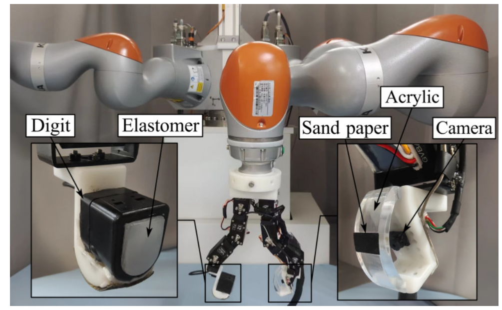


Fig. 2. Two-fingered gripper with each of fingers comprised of three serially connected servo motors.

in fabric manipulation. This method requires controlling the contact point between the fabric and the environment, so there are requirements on the fabric shape. Borràs et al. [9] summarized the fabric manipulation methods and gripper designs proposed. They found that in some vision-based solutions of unfolding fabrics, it was necessary to locate the corners and regrasp the fabric [10]–[15]. Some studies simplified the recognition and grasping of cloth corners with relatively complex manipulations, such as by sliding a cloth on a table [16] or by sliding one gripper along the edge of the fabric with another gripper grasping one corner [17]. That implies that adjusting the grasping position is an essential action in the task of manipulating fabrics. Based on the analysis of many studies, Borràs et al. [9] proposed a generic framework that provides a classification of cloth manipulation primitives.

In this study, we attempt to propose an in-hand manipulation method for fabric manipulation. In-hand manipulation is a widely researched topic for rigid objects. Raymond et al. [19] designed a gripper consisting of a thumb with an active, belt-driven, conveyor surface and an opposing, underactuated finger with passive rollers. The actuated belt was used to adjust the position of the object being held. Inspired by the structure of the human finger pad, Spiers et al. [20] designed a 2-DOF gripper with a torque controller embedded in each finger for actuating the switch between high and low friction surfaces. And they proved that the gripper could translate an object distally from the middle of the grasp by switching between the constant friction surface and variable friction surface. Tincani et al. [21] presented a novel underactuated gripper with active surfaces which are able to simulate different levels of friction and able to apply tangential force on the objects in contact. Yuan et al. [22] proposed a three-fingered robot gripper with a 2-DOF active surface in each finger. The active surfaces are achieved by spherical rolling fingertips. The gripper can utilize the active surfaces to translate an object to an arbitrary target pose.

III. IN-HAND MANIPULATION OF FABRICS

A. Analysis of Fabric handling by Human

In daily life, human hands can dexterously complete various complex manipulation of fabrics. Some proposed fabric manipulation methods are also inspired by human actions [1] [2] [23]. We observed how humans handle fabrics, and found that humans can handle fabrics through cooperation between the index finger and thumb.

As shown in Fig.1(a), the index finger moves to the distal end of the thumb, with a fabric gripped between the index finger and the thumb. The friction force between the index finger and the fabric exceeds the maximum static friction, which results in relative sliding, while the friction between the thumb and the fabric does not exceed the maximum static friction. After the index finger reaches the distal end of the thumb, as shown in Fig.1(b), the index finger adjusts the contact angle. And then, the index fingertip moves in the opposite direction. This time, the static friction force between the thumb and the fabric exceeds the maximum first, and the fabric slides with respect to the thumb. The fabric is pulled by the index finger to the proximal end of the hand. The process described above is a simplification to the process of manipulating fabric with two fingers. Actually, a human can perceive slipping tendency against the fabric through the fingertip skin with high sensitivity and can adjust accordingly the contact angle, contact area, and contact position.

Studies have shown that the normal force [24] [25], skin water content [26] and sliding speed [27] [28] affect the friction coefficient of the hand. It was also proved that the contact angle between the finger and the object [29] affects the friction coefficient. When a fabric is gripped between an index finger and thumb, the contact area and interaction force on both sides of the fabric are the same. The difference in friction coefficients on both sides mainly determines the difference in the maximum static friction. The magnitude and distribution of the friction coefficient of each person's fingertip skin have specific characteristics due to the difference in fingerprint shape, skin elasticity, and skin water content. Therefore, there may be differences in the subtle motion of each person during handling fabrics. In general, the human adjusts the fingertip posture to change the friction coefficient in the contact area. This feature, combined with highly sensitive tactile feedback from the skin, contributes to the in-hand fabric manipulation capability of humans. Inspired by this, we proposed a two-fingered gripper with a variable friction coefficient fingertip to manipulate fabrics totally within the hand.

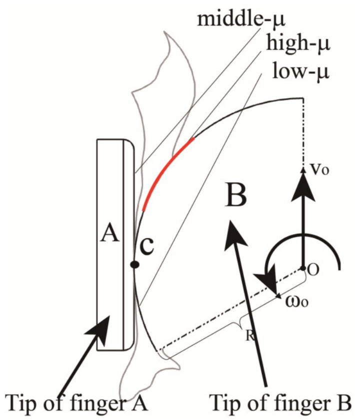


Fig. 3. 2D simplification sketch of the contact between two fingertips. Fingertip A has a flat surface, and fingertip B is shaped as a circular arc. (Point C represents the contact point on fingertip B.)

B. Gripper Design

The process of manipulating a fabric within two fingers can be simplified as a motion control in 2D space. We made a two-fingered gripper using six servo motors, as shown in Fig. 2, with each of the fingers containing three actuated degrees of freedom connected serially. In this paper, the process that a human adjusts his friction at the fingertip is mimicked by alternating between two contact surfaces with different friction properties. We used clear, easy-to-process acrylic as the material for the contact surface with a low friction coefficient. For the selection of surfaces with high friction coefficient, we compared several materials, such as velcro, electrostatic material, silicone, and sandpaper. Velcro is designed to be used in conjunction with male and female surfaces, so it has poor adaptability to the fabric of different materials. The actuation of electrostatic materials requires high voltage. And electrostatic materials are mostly used to provide adsorption force [5] [30] [31], while we need the material to provide tangential forces. Silicone can provide high friction when it is in contact with fabrics, but silicone is easy to absorb dust, which will lead to a decrease in the friction coefficient. So, in the end, we used a stable, cheap, and easy-to-process sandpaper in our gripper. We adopted an arc-shaped fingertip in one finger and pasted a piece of 18 mm*9 mm sandpaper in the center area of the fingertip as the contact area that provides high friction coefficient. For the other fingertip, we integrated a Digit sensor [32] to provide the necessary tactile feedback. Digit is a high-resolution and vision-based tactile sensor open-sourced by Facebook.

In order to identify the fabric position, we embedded a camera within the center of the arc-shaped fingertip.

C. Gripper Control based on Variable Friction Mechanism

The contact area between fingertip and fabric is classified based on the magnitude of friction coefficient: high-μarea(sandpaper vs. cloth), middle-μarea(digit elastomer vs. cloth), low-μarea(acrylic vs. cloth), as shown in Fig.3, where a fingertip with a flat surface (denoted as A) contacts with another fingertip with a circular arc surface (denoted as B).

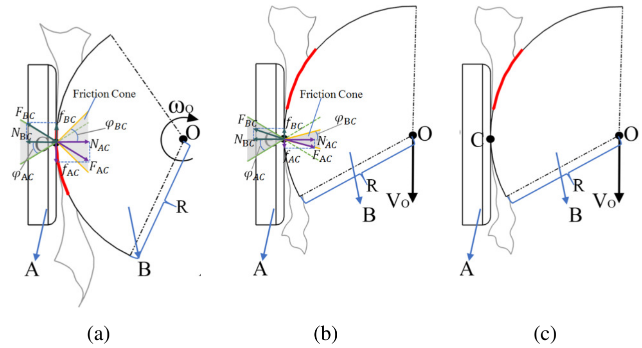


Fig. 4. Schematic diagram of three primitive-actions. (a) Rotation-action. (b) Sliding-action. (c) Rolling-action.

The flat contact surface of fingertip A is the elastomer of Digit sensor. The fingertip B is made of acrylic. The high μ area on fingertip B is realized by attaching a sanding sheet. The sliding of the fabric is realized by controlling the translational speed V_0 of fingertip B with respect to fingertip A and the rotation speed ω_0 of fingertip B around its center. We define three primitive actions to slide the fabric while keeping it held.

- ***Rotation-action***: As shown in Fig.4(a), by setting $V_0 = 0$, $\omega_0 \neq 0$, $V_C \neq 0$(the tangential velocity at point C), the fingertip B rotates around its center. When the high-μarea of fingertip B contacts the fabric, the friction between fingertip A and the fabric exceeds the maximum static friction force first. As a result, the fabric adheres to fingertip B.
- ***Sliding-action***: As shown in Fig.4(b), by setting $V_0 \neq 0$, $\omega_0 = 0$, $V_C \neq 0$, fingertip B translates along the surface of fingertip A. The low-μarea of fingertip B contacts the fabric, since the friction between fingertip A and the fabric is larger than that between the fabric and fingertip B, this time the fabric adheres to fingertip A.
- ***Rolling-action***: As shown in Fig.4(c), by setting $V_0 = \omega_0 R \neq 0$, $V_C = 0$, the fingertip B rolls against the surface of fingertip A. Since the composite velocity at the contact point C is zero, the fabric is stationary with respect to fingertip A.

In each cycle for translating the fabric, the above three primitive actions are executed sequentially. The rotation angle θ_1 in rotation-action, the translation distance d_2 in sliding-action and the scroll distance d_3 in rolling-action are related as: $\theta_1 R = d_2 = d_3$, and the directions of the motion are shown in Fig.4. Fabric movement occurs during rotation-action, while sliding-action and rolling-action play the role of rolling back the high μ area on finger B for use in the next cycle. The above operation cycle can not only realize the movement of a single piece of fabric without dropping it, but also pick up a single sheet of fabric from a stack.

Separating two layered fabrics: As shown in Fig.5(a), the gripper picks up two sheets of fabric: cloth1 and cloth2. In this paper, we ignore the difference between dynamic and static friction coefficients and assume that the friction coefficients satisfy cloth2 vs. sandpaper > cloth1 vs. elas-

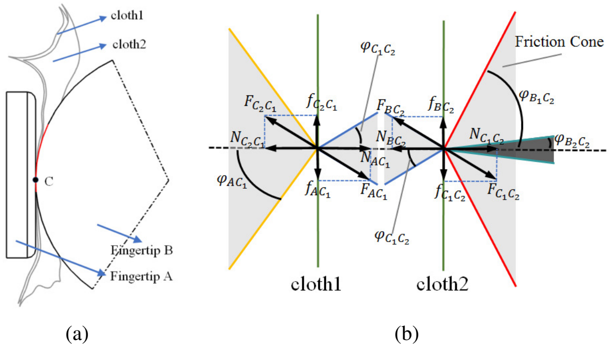


Fig. 5. Diagram of grasping and separating two layers of fabrics by the gripper. (a) The process of separating two layers of fabric (Point C represents the contact point on fingertip B). (b) Friction cones of the contacts on cloth1 and cloth2 during rotation-action and sliding-action. $\varphi_{B_1C_2}$ is the friction angle of the contact between cloth2 and fingertip B during rotation-action, and $\varphi_{B_2C_2}$ is the friction angle of the contact between cloth1 and cloth2 and fingertip B during sliding-action, and $\varphi_{B_1C_2} > \varphi_{AC_1} > \varphi_{C_1C_2} > \varphi_{B_2C_2}$.

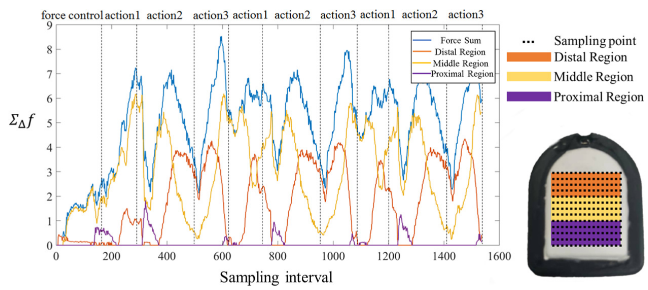


Fig. 6. Deformation measurement of the elastomer obtained from the tactile sensor Digit during Experiment I, which is proportional to press force. $\sum_\Delta f$ represents the sum of the deformation at the sampling points within the three regions.

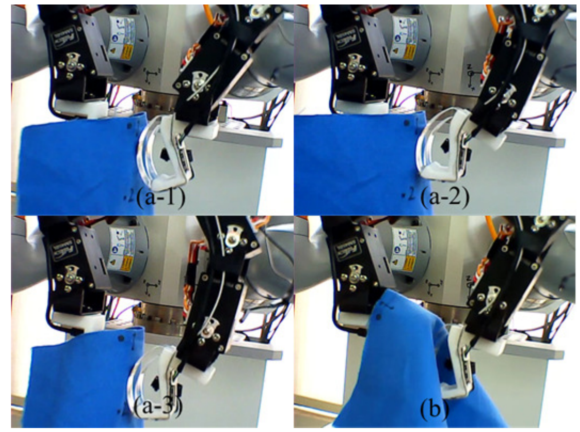


Fig. 7. Adjust the gripping position for a single layer of fabric. (a-1) Rotation-action. (a-2) Sliding-action. (a-3) Rolling-action. (b) Result after executing 10 cycles of primitive actions 1 through 3.

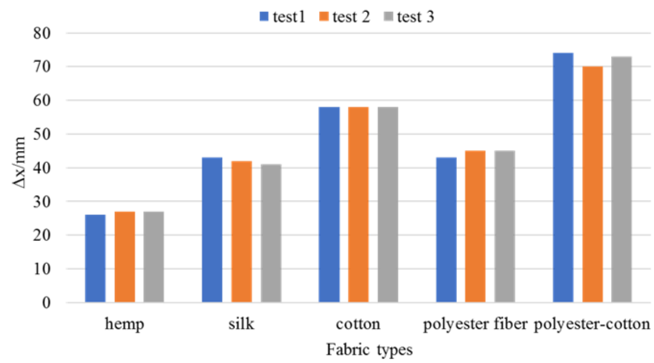


Fig. 8. Moving distance of fabrics after executing 10 cycles of the primitive actions.

tomer $>$ cloth1 vs. cloth2 in rotation-action. The friction cones of the contact are shown in Fig.5. In rotation-action, the relationship of friction angles is: $\varphi_{B_1C_2} > \varphi_{AC_1} > \varphi_{C_1C_2}$. Hence, the contact between cloth2 and cloth1 first breaks through the boundary of the friction cone, and cloth2 slides with respect to cloth1. In sliding-action, The relationship of friction angles is: $\varphi_{AC_1} > \varphi_{C_1C_2} > \varphi_{B_2C_2}$. Hence, the contact between fingertip B and cloth2 breaks through the boundary of the friction cone, and fingertip B slides with respect to cloth2. Ignoring the gravity of cloth fingertip B theoretically exerts no tangential force on the cloth2 in rolling-action. So in an operation cycle, cloth2 slides along the direction of V_c in the rotation-action. After several operation cycles, it is possible to separate cloth2 from cloth1.

IV. EXPERIMENT

In fabric manipulation tasks, it is necessary to choose and grasp specific region of the target, like corners. However, sometimes the first grasping position may not match the target. Using the method we proposed, the grasping position can be adjusted without dropping the fabric, and in this way, regrasping is effectively avoided. We demonstrated the effectiveness of our proposed method on fabrics handling through the following three experiments.

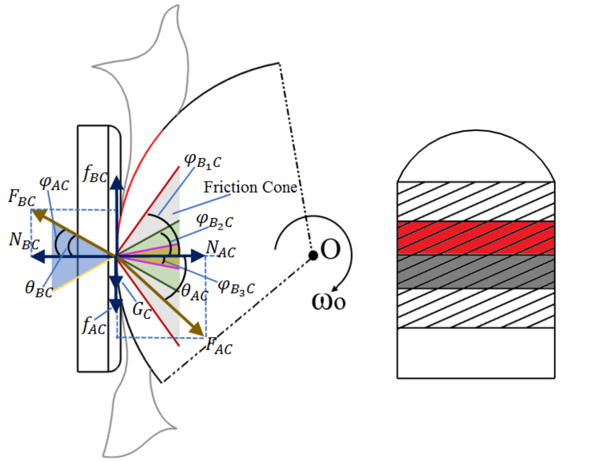
A. Experiment I: Gripping position adjustment for a single fabric

We collected the data describing pressure distribution from Digit during the process that the gripper started to grasp the fabric sample and executed three operation cycles, as shown in Fig.6. The effective detection area of Digit is divided into three regions (distal, middle, proximal in Fig.6). The detected deformation at sampling points evenly distributed within the regions are summed as the measure of neat pressure force. It can be seen that the gripper always maintains the grasp force on the fabric in each operation cycle, and the center of the pressed area changed during the process.

Theoretically, the sliding distance of fabrics in one operation cycle is proportional to the traveling distance of the high-μ region along the direction of fabrics slides. We measured the distance of various samples respectively when 10 cycles of the primitive actions were conducted on them. (as shown in Fig.7), and found that for fabrics of different materials, the sliding effects resulting from the operation cycle are different, shown in Fig.8).

The reasons for the difference in the effects of the samples can be analyzed as follows:

In fact, the contact between fingertip A and fingertip B is not an ideal line contact formulated by a plane and a



(a) (b)

Fig. 9. Analysis of Experiment I. (a) 2D simplification of surface contact in rotation-action (φ_{B_1C} is the friction angle of the contact between fingertip B and cloth when only the high-μ area of fingertip B contacts the cloth, φ_{B_3C} is the friction angle of the contact between fingertip B and cloth when only the low-μ area of fingertip B contacts the cloth and φ_{AC} is the friction angle of the contact between cloth and fingertip A ($\varphi_{AC} = \varphi_{B_2C}$)). In rotation-action, as the contact area changes, the friction angle between fabric and fingertip B decreases from φ_{B_1C} to φ_{B_3C}. (b) Schematic drawing of the stressed region of Digit elastomer. The shaded regions represent the effective regions of the tactile sensor; The red region represents where Digit elastomer contact with high-μ region of fingertip B; The gray region represents where Digit elastomer contacts with the low-μ region of fingertip B.

cylinder. Due to the deformation of the elastomer attached at fingertip A, plane contact is formed between fingertip A and fingertip B. Therefore, in rotation-action, the friction cone of the contact between cloth and fingertip B is affected by the ratio of the high-μ to low-μ areas, and there is a period, as shown in Fig.9, when both the high-μ region and low-μ region contact with the cloth. The friction angle of the contact between the cloth and fingertip B, φ_{BC}, will decrease until $\varphi_{BC} = \varphi_{B_2C}$, which we call the critical state. After that moment, the friction angle will be less than the friction angle of the contact between the cloth and fingertip A, and the cloth will stop sliding with respect to fingertip A. Similarly, at the beginning of the rotation-action, there will be a period of ineffective action. For different fabrics, φ_{B_2C} are different, which explains the difference demonstrated in the samples.

When the gravity of cloth can not be negligible, it also affects rotation-action. Let N_{AC}, N_{BC}, f_{AC}, f_{BC}, and G_C be the normal force exerted on the cloth by fingertip A, the normal force exerted on the cloth by fingertip B, the friction exerted on the cloth by fingertip A, the friction force exerted on the cloth by fingertip B, and the gravity of the cloth, respectively, the force balance satisfies:

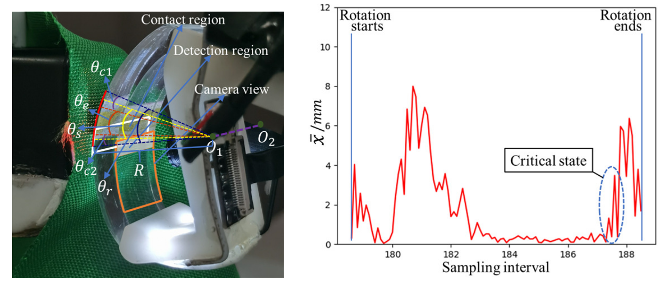
$$\begin{aligned} ||f_{BC}|| &= ||f_{AC}|| + ||G_C|| \\ ||N_{BC}|| &= ||N_{AC}|| \end{aligned} \tag{1}$$

For the contact between fingertip A and cloth, the external force, $F_{BC} = f_{BC} + f_{BC} + G_C$ and for the contact between fingertip B and cloth, the external force $F_{AC} = f_{AC} + N_{AC} + G_C$. The angle between F_{AC} and N_{AC}, θ_{AC} and the angle between F_{BC} and N_{BC}, θ_{BC} satisfy:

$$\theta_{AC} = tan^{-1}\frac{||f_{AC}|| + ||G_C||}{||N_{AC}||} \tag{2}$$

$$\begin{aligned} \theta_{BC} &= tan^{-1}\frac{||f_{BC}|| - ||G_C||}{||N_{BC}||} \\ &= tan^{-1}\frac{||f_{AC}||}{||N_{AC}||} \end{aligned} \tag{3}$$

Hence, when $\theta_{BC} = \varphi_{BC}$, $\varphi_{BC} = \theta_{AC} > \theta_{B_2C}$. It means that the effective range of rotation-action will become shorter. As a result, it is necessary to increase the squeezing force of the gripper in order to ensure the sliding effect of rotation-action when the cloth is heavy.



(a) (b)

Fig. 10. Detect the critical state before rotation-action ends. (a) Schematic diagram of slip detection(O_1O_2 represents the axis of rotation for the rotation-action, R represents the distance from the surface of the fingertip B to the axis O_1O_2). (b)Average displacement of the held fabric of polyester-cotton measured by optical flow captured within the detection region.

OpticalFlow-based visual odometry: In order to confirm the sliding distance resulting from rotation-action, we use Gunnar Farneback algorithm [33] to estimate the change in two successive frames taken by the camera embedded inside the fingertip B. The detection region is as shown in Fig.10(a). Average displacement of the held fabric in a whole rotation-action cycle is measured by optical flow detected within the detection region. The curve in Fig.10(b) indicates a distinct displacement in the first half of the cycle. This period corresponds to the approaching phase of the detection region on fingertip B to the fabric. Thus the detected displacement in the first half of the cycle is not the intended one. And in the figure, the flat segment of the curve after the first distinct visual change indicates close contact between the detection region on fingertip B to the fabric. Since there is almost no relative displacement between the fabric and the fingertip during this period (the fabric adheres to the finger as desired), no effective optical flow can be detected. As seen in the second half, the average displacement increases drastically before the end of the cycle. The distinct variation is detected as the critical state(as shown in Fig.10(b)), denoted as state C_2. The state C_2 implies that the held fabric begins to slip with respect to the fingertip B. The movement of the fabric becomes inconsistent with that of the finger. Similarly, there is also such a critical state at the beginning of rotation-action, denoted as state C_1. When the rotation-action reaches the state C_1, the fabric stops slipping with respect to fingertip B

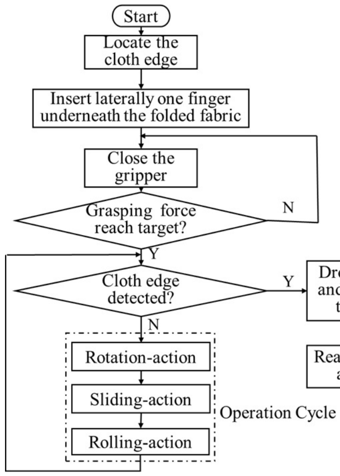


Fig. 11. Block diagram of the proposed algorithm for unfolding a piece of folding fabric when it is initially gripped at its edge.

and begins to adhere to it. Therefore it is the period from state C_1 to C_2 when the fingertip B effectively pulls the fabric. Theoretically, for both of the states C_1 and C_2, the proportion of high/low friction areas to the whole contact area is the same. Thus the timing when C_1 occurs can be estimated from the timing of C_2. As shown in Fig.10(a), θ_{c1}, θ_{c2} represent the angles that the fingertip B rotates from rotation-action start to state C_1, C_2 to rotation-action end, respectively. θ_e represents the rotation angle of fingertip B, which corresponds to effective fabric pulling. θ_r represents the rotation angle of fingertip B during the whole rotation-action cycle. The angles satisfy:

$$\begin{aligned} \theta_{c1} &= \theta_{c2} \\ \theta_e &= \theta_r - \theta_{c1} - \theta_{c2} \end{aligned} \tag{4}$$

And the slipping distance of the fabric during the rotation-action can be calculated as: $\theta_r R$. As shown in Fig.8, the sliding distance of fabric of polyester-cotton in one cycle of the primitive actions is approximately 7.2 mm. And the average displacement of the held fabric of polyester-cotton in one cycle is shown in Fig.10(b). θ_r was set to 20° and R was set to 30 mm in experiment I. According to the data in the Fig.10(b), θ_{c2}/θ_r is approximately 0.12. So,

$$\begin{aligned} \theta_e &= \theta_r - \theta_{c1} - \theta c2 \\ &= 20^\circ \times (1 - 2\frac{\theta_{c2}}{\theta_r}) \quad = 15.2^\circ \end{aligned}$$

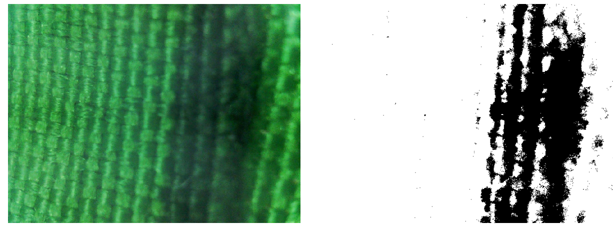
and

$$x = \theta_e R = 8.0mm$$

The odometer estimate has a certain error compared to the true value, which may be caused by the error between the model and the reality.

B. Experiment II: Unfolding a piece of folded fabric(1)

We conducted another experiment of unfolding a piece of folded fabric to test the effectiveness of our proposed method on related applications. Based on the primitive actions described above, we proposed an algorithm for unfolding a piece of folded fabric. The block diagram of the proposed algorithm is shown in Fig.11.



(a) (b)

Fig. 12. (a) Image taken by the camera embedded within the center of fingertip B. (b) Image obtained by binarizing Fig.12(a).

We utilized the camera embedded inside the acrylic fingertip to detect the edges of a fabric. The fabric samples used in the experiment are all in solid color, so we painted fabrics' edges black to make fabric detection easier. The number of black pixels in the camera's field of view will be used to indicate whether an edge of the fabric is detected. As shown in Fig.12, when the edge appears in the image, the number of black pixels will exceed the threshold. Seeing a fabric edge indicates that one of the two layers of fabric is about to come out of the gripper. The unfolding process is shown in Fig.13. The difficulties for an unmarked solution come from several aspects. Firstly we found that the Digit sensor is not sensitive enough to detect the timing of separation from the tactile information. Secondly, there is only a short period when the state of the gripped fabrics can be seen. In addition, since the fabrics are gripped vertically with limited contact area, the contour of the fabric edge is not as clear as when they are laid on a plane.

We have carried out experiments on five kinds of fabric, and the success rate is summarized in Table I. For the fabrics other than hemp, the success rate of Experiment II is high. The fiber structure of hemp results in a significant friction coefficient between the two layers of hemp fabric, so the assumption: cloth2 vs. acrylic(highμ) $>$ cloth1 vs. elastomer $>$ cloth1 vs. cloth2 in rotation-action cannot be satisfied.

C. Experiment III: Unfolding a piece of folded fabric(2)

In Experiment II, the folded fabric is initially gripped at its edge with one finger inserted underneath the two layers from the lateral direction. When a folded fabric is initially gripped at its edge, like the situation in experiment II, two layers of fabric will be gripped between the fingers. While if a folded fabric is initially gripped at a point inside it,

TABLE I

SUCCESS RATE OF EXPERIMENT II AND III

Fabrics Type	Experiment II	Experiment III
Hemp	0/5	0/5
Silk	3/5	0/5
Cotton	4/5	3/5
Polyester	4/5	3/5
Polyester-Cotton	4/5	3/5

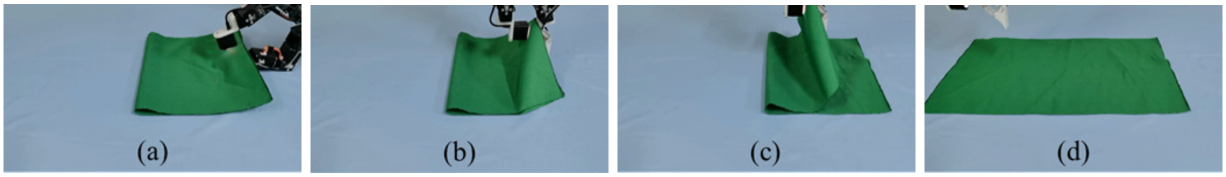


Fig. 13. The process of unfolding a piece of folded fabric. (a) Initially grip the folded fabric at its edge. In order to grip the folded fabric, we installed a nail on fingertip B so that fingertip B could be inserted smoothly underneath the fabric. (b) Separate one from two layers, based on our proposed in-hand manipulation operation cycle. (c) Grab the upper layer of fabric and move it towards the target position. (d) Finish.

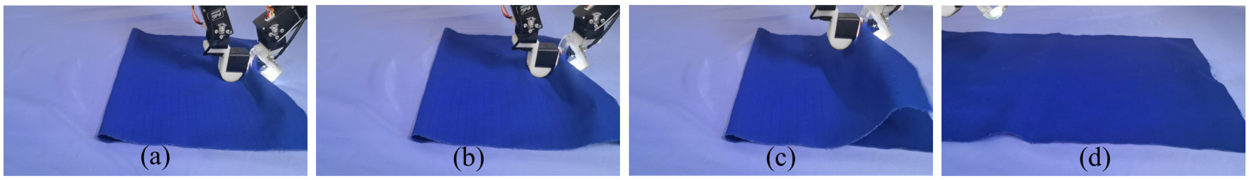


Fig. 14. The process of unfolding a folded fabric. (a) Pick up the fabric at a position inside the fabric. (b) Separate one from two layers. (c) Grab the upper fabric and move it towards the target position. (d) Finish.

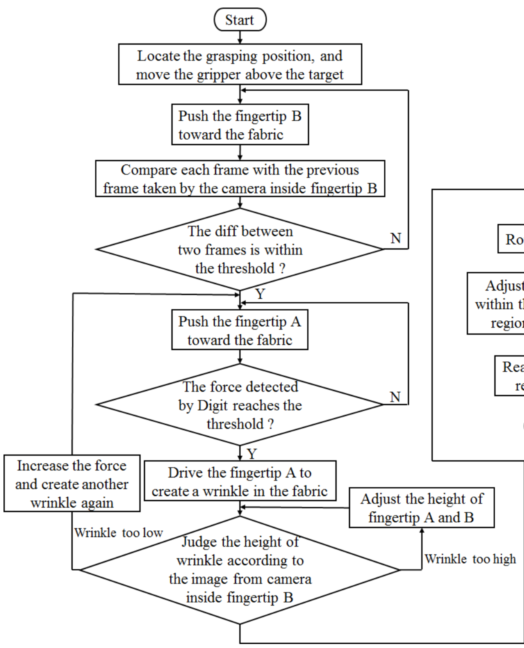


Fig. 15. Block diagram of our proposed algorithm (2) for unfolding a piece of folding fabric when it is initially gripped at a point inside. When the fingertip B is pushed on the fabric, the texture size of the fabric in the image taken by the camera inside the fingertip B will no longer change.

there will be four layers of fabric gripped together, as shown in Fig.14. In Experiment III, we tested another situation of unfolding, i.e., the gripper initially grips the folded fabric at a point inside the fabric. The gripper has to first produce a wrinkle for gripping. We found that the height of the wrinkle affects the success rate of separating the layers. Therefore, our algorithm contains an additional process for detecting the height of the wrinkle, and the block diagram is shown in Fig.15. The success rate of Experiment III is summarized in Table I.

The reason why the height of the wrinkle initially created is important is analyzed as follows. It is easy to understand that if the height of the wrinkle is too low, it will be difficult to grip with the gripper. On the other hand, if the wrinkle being grasped is too high, the state of the fabric will be as shown in Fig.16. There is stress in the fabric at the wrinkle. Under the influence of stress, cloth1 and cloth2 adhere to each other tightly. Therefore, the rotation-action will make the left and right sides of cloth1 and cloth2 slide with respect to each other, while the cloth 1 and 2 are kept relatively stationary. In this experiment, we locate the grasping point at wrinkle's top to solve the above problem.

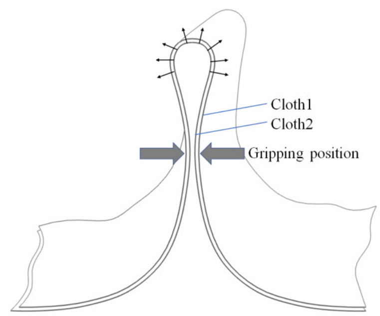


Fig. 16. The state of fabric if the wrinkle is too high when grasping.

As shown in Table I, the success rate of Experiment III for hemp and silk is low. This is because that silk is too soft, and hemp is too hard to form the desired wrinkle shape.

V. CONCLUSIONS

In this paper, we proposed a method for handling fabrics totally in hand. And we proved that our proposed method could not only be used to slide the fabric between fingers but also be used for unfolding a piece of folded fabric. In the future, we will apply this method to some complex fabric handling tasks, such as folding clothes. In the task of folding clothes, sometimes we need to track the edge or the crease of the clothes, when our in-hand manipulation method may play an important role in adjusting. In addition, the gripper we proposed is simple and is only used to test the feasibility of our proposed method. We plan to design a more complex gripper based on our proposed method in the future to operate fabric more flexibly.

ACKNOWLEDGMENT

This work was supported by Natural Science Foundation of China (61873072, U1813202), and Shenzhen Fundamental Research Grant (JCYJ20180507183456108).

REFERENCES

[1] P. N. Koustoumpardis, S. Smyrnis, and N. A. Aspragathos, "A 3-finger robotic gripper for grasping fabrics based on cams-followers mechanism," *Mechanisms and Machine Science*, vol. 49, pp. 612–620, 2018.

[2] P. N. Koustoumpardis, K. X. Nastos, and N. A. Aspragathos, "Underactuated 3-finger robotic gripper for grasping fabrics," *23rd International Conference on Robotics in Alpe-Adria-Danube Region, IEEE RAAD 2014 - Conference Proceedings*, 2015.

[3] S. Donaire, J. Borras, G. Alenya, and C. Torras, "A Versatile Gripper for Cloth Manipulation," *IEEE Robotics and Automation Letters*, vol. 5, no. 4, pp. 6520–6527, 2020.

[4] D. Hinwood, D. Herath, and R. Goecke, "Towards the Design of a Human-Inspired Gripper for Textile Manipulation," *IEEE International Conference on Automation Science and Engineering*, vol. 2020-Augus, pp. 913–920, 2020.

[5] K. M. Digumarti, V. Cacucciolo, and H. Shea, "Dexterous textile manipulation using electroadhesive fingers," in *2021 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Sep. 2021, pp. 6104–6109.

[6] S. Ku, J. Myeong, H. Y. Kim, and Y. L. Park, "Delicate Fabric Handling Using a Soft Robotic Gripper with Embedded Microneedles," *IEEE Robotics and Automation Letters*, vol. 5, no. 3, pp. 4852–4858, 2020.

[7] M. Shibata, T. Ota, and S. Hirai, "Wiping motion for deformable object handling," *Proceedings - IEEE International Conference on Robotics and Automation*, pp. 134–139, 2009.

[8] M. Shibata and S. Hirai, "Fabric manipulation utilizing contacts with the environment," *IEEE International Conference on Automation Science and Engineering*, pp. 442–447, 2012.

[9] J. Borràs, G. Alenyà, and C. Torras, "A Grasping-Centered Analysis for Cloth Manipulation," *IEEE Transactions on Robotics*, vol. 36, no. 3, pp. 924–936, 2020.

[10] J. Maitin-Shepard, M. Cusumano-Towner, J. Lei, and P. Abbeel, "Cloth grasp point detection based on multiple-view geometric cues with application to robotic towel folding," *Proceedings - IEEE International Conference on Robotics and Automation*, pp. 2308–2315, 2010.

[11] Y. Kita, F. Kanehiro, T. Ueshiba, and N. Kita, "Clothes handling based on recognition by strategic observation," *IEEE-RAS International Conference on Humanoid Robots*, pp. 53–58, 2011.

[12] F. Osawa, H. Seki, and Y. Kamiya, "Unfolding of massive laundry and classification types by dual manipulator," *Journal of Advanced Computational Intelligence and Intelligent Informatics*, vol. 11, no. 5, pp. 457–463, 2007.

[13] A. Doumanoglou, J. Stria, G. Peleka, I. Mariolis, V. Petrik, A. Kargakos, L. Wagner, V. Hlavac, T. K. Kim, and S. Malassiotis, "Folding clothes autonomously: A complete pipeline," *IEEE Transactions on Robotics*, vol. 32, no. 6, pp. 1461–1478, 2016.

[14] Y. Li, D. Xu, Y. Yue, Y. Wang, S. F. Chang, E. Grinspun, and P. K. Allen, "Regrasping and unfolding of garments using predictive thin shell modeling," *Proceedings - IEEE International Conference on Robotics and Automation*, vol. 2015-June, no. June, pp. 1382–1388, 2015.

[15] C. Bersch, B. Pitzer, and S. Kammel, "Bimanual robotic cloth manipulation for laundry folding," *IEEE International Conference on Intelligent Robots and Systems*, pp. 1413–1419, 2011.

[16] M. Cusumano-Towner, A. Singh, S. Miller, J. F. O'Brien, and P. Abbeel, "Bringing clothing into desired configurations with limited perception," *Proceedings - IEEE International Conference on Robotics and Automation*, pp. 3893–3900, 2011.

[17] H. Yuba, S. Arnold, and K. Yamazaki, "Unfolding of a rectangular cloth from unarranged starting shapes by a dual-armed robot with a mechanism for managing recognition error and uncertainty," *Advanced Robotics*, vol. 31, no. 10, pp. 544–556, 2017. [Online]. Available: https://doi.org/10.1080/01691864.2017.1285722

[18] T. Feix, J. Romero, H.-B. Schmiedmayer, A. M. Dollar, and D. Kragic, "The GRASP Taxonomy of Human Grasp Types," *IEEE TRANSACTIONS ON HUMAN-MACHINE SYSTEMS*, vol. 46, no. 1, 2016. [Online]. Available: http://ieeexplore.ieee.org.

[19] R. R. Ma and A. M. Dollar, "In-hand manipulation primitives for a minimal, underactuated gripper with active surfaces," in *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, vol. 50152. American Society of Mechanical Engineers, 2016, p. V05AT07A072.

[20] A. J. Spiers, B. Calli, and A. M. Dollar, "Variable-Friction Finger Surfaces to Enable Within-Hand Manipulation via Gripping and Sliding," *IEEE Robotics and Automation Letters*, vol. 3, no. 4, pp. 4116–4123, 2018.

[21] V. Tincani, G. Grioli, M. G. Catalano, M. Garabini, S. Grechi, G. Fantoni, and A. Bicchi, "Implementation and control of the velvet fingers: A dexterous gripper with active surfaces," in *2013 IEEE International Conference on Robotics and Automation*, May 2013, pp. 2744–2750.

[22] S. Yuan, L. Shao, C. L. Yako, A. Gruebele, and J. K. Salisbury, "Design and control of roller grasper V2 for in-hand manipulation," *IEEE International Conference on Intelligent Robots and Systems*, pp. 9151–9158, 2020.

[23] E. Ono, K. Kitagaki, and M. Kakikura, "Picking up a piece of fabric from layers by a hand with 3 fingers and a palm," in *Proceedings 2001 IEEE/RSJ International Conference on Intelligent Robots and Systems. Expanding the Societal Role of Robotics in the the Next Millennium (Cat. No.01CH37180)*, vol. 2, Oct 2001, pp. 931–936 vol.2.

[24] H. Y. Han, A. Shimada, and S. Kawamura, "Analysis of friction on human fingers and design of artificial fingers," *Proceedings - IEEE International Conference on Robotics and Automation*, vol. 4, no. April, pp. 3061–3066, 1996.

[25] S. Derler, L. C. Gerhardt, A. Lenz, E. Bertaux, and M. Hadad, "Friction of human skin against smooth and rough glass as a function of the contact pressure," *Tribology International*, vol. 42, no. 11-12, pp. 1565–1574, 2009. [Online]. Available: http://dx.doi.org/10.1016/j.triboint.2008.11.009

[26] H. T. Lin, T. F. Hong, and W. L. Li, "Grip performance affected by water-induced wrinkling of fingers," *Tribology Letters*, vol. 58, no. 3, pp. 1–9, 2015. [Online]. Available: http://dx.doi.org/10.1007/s11249-015-0515-4

[27] L. Skedung, K. Danerlöv, U. Olofsson, M. Aikala, K. Niemi, J. Kettle, and M. W. Rutland, "Finger friction measurements on coated and uncoated printing papers," *Tribology Letters*, vol. 37, no. 2, pp. 389–399, 2010.

[28] M. A. Masen, "A systems based experimental approach to tactile friction," *Journal of the Mechanical Behavior of Biomedical Materials*, vol. 4, no. 8, pp. 1620–1626, 2011. [Online]. Available: http://dx.doi.org/10.1016/j.jmbbm.2011.04.007

[29] M. Zhang, J. L. Mo, J. Y. Xu, X. Zhang, D. W. Wang, and Z. R. Zhou, "The Effect of Changing Fingerprinting Directions on Finger Friction," *Tribology Letters*, vol. 65, no. 2, pp. 1–9, 2017.

[30] P. Taylor, G. Monkman, and G. Taylor, "Electrostatic grippers for fabric handling," in *Proceedings. 1988 IEEE International Conference on Robotics and Automation*, April 1988, pp. 431–433 vol.1.

[31] B. Sun and X. Zhang, "A new electrostatic gripper for flexible handling of fabrics in automated garment manufacturing," in *2019 IEEE 15th International Conference on Automation Science and Engineering (CASE)*, Aug 2019, pp. 879–884.

[32] M. Lambeta, P. W. Chou, S. Tian, B. Yang, B. Maloon, V. R. Most, D. Stroud, R. Santos, A. Byagowi, G. Kammerer, D. Jayaraman, and R. Calandra, "DIGIT: A Novel Design for a Low-Cost Compact High-Resolution Tactile Sensor with Application to In-Hand Manipulation," *IEEE Robotics and Automation Letters*, vol. 5, no. 3, pp. 3838–3845, 2020.

[33] G. Farnebäck, "Two-frame motion estimation based on polynomial expansion," in *Image Analysis*, J. Bigun and T. Gustavsson, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2003, pp. 363–370.