Robotic Unfolding of Hemmed Fabric using Pinching Slip Motion

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Abstract

This paper describes an unfolding motion of fabric in air using pinching slip motion. During the pinching slip motion, the weight of the fabric generates relative movement between the moving fingertips and the fabric. The moving fingertips can hook into the hem of the fabric during the unfolding motion if the appropriate shaped fingertips and the grasping force are selected. In this paper, we simulate the pressure distribution of moving fingertips during the unfolding. We make a model of the contact between a fingertip and the hem of fabric based on fluid dynamics; the contact is considered as the collision between fluid and a block.

1 Introduction

In the past few decades, there have been several researches of fabric handling using robotic systems. These have included the construction of a robotic manipulator with pins to pick up single plies from stacks of fabrics [1], and the construction of a robotic pneumatic hand to grasp fabrics, with the acquisition points on the fabrics detected via visual perception [2]. Additionally, the robotic unfolding of a folded fabric on a floor has been realized applying visual and touch sensing; this robotic system could pinch the corner edge of a fabric to unfold it [3]. They have also constructed a robotic hand with three fingers and a palm to pick up one fabric from a stack [4]. Based on hierarchical control, a system has been proposed for handling flat fabrics on a table [5]; this hand was able to grasp, unfold, and flatten the fabrics using vision and force/torque sensors. Several studies have been interested in the robotic handling of messy fabrics. For example, a rotational hand, which can roll up a fabric using two rotational wheels on the fingertips, has been proposed for fabric grasping [6], along with a visual strategy to detect grasping points for messy fabrics [7]. Besides, a gripper based on two passively turning fingers and a simple on-off pneumatic drive mechanism has been developed and applied experimentally to grasp pieces of furs from a pell-mell bundle [8]. Although these have been realized as basic methods of fabric handling, each of these is applicable exclusively to its specified tasks. In earlier works, we have constructed a robotic system that could handle messy fabrics in series [9]. We have classified the setting process into wiping, pinching, unfolding, and placing motions, as in a human setting strategy of fabric handling. Based on these strategies, we have developed a robotic system to manipulate hemmed fabrics.

This paper describes a modeling of an unfolding motion of fabrics in air using pinching slip motion. During the pinching slip motion, the weight of the fabric generates relative movement between the moving fingertips and the fabric. The moving fingertips can hook into the hem of the fabric during the unfolding motion if the appropriate shaped fingertips and the grasping force are selected. Through several experiments, we can make a model to simulate the pressure distribution of moving fingertips during the unfolding. We deal with the contact between a fingertip and the hem of the fabric in terms of fluid dynamics; the contact is considered as the collision between fluid and a block.

2 Unfolding by pinching slip motion for hemmed fabrics [9]

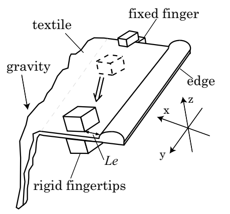
2.1 Principle

In this section, we discuss an unfolding motion by robotic grippers. During unfolding, humans usually allow their fingertips to slip on the fabric surfaces while grasping dexterously. This motion is referred to as a *pinching slip motion.* Figure 1 shows an overview of the proposed pinching slip motion by robotic hands. We assume that two pairs of fingertips grasp a fabric. While pinching, one pair of fingertips slide in the horizontal direction against the direction of gravity force (Figure 1-(a)); here the other pair of fingertips does not move along the surface because the fabric is strongly gripped. During the pinching slip motion, the weight of the fabric generates relative movement between the moving fingertips and the fabric, as shown in Figure 1-(b). In this unfolding, we apply edges of a fabric. Edges such as a handkerchief are sewn so that they do not fray; each sewn edge is referred as a hem (Figure 2-(a)). In fabrics such as handkerchief, the obverse and the reverse surface are distinguished. In this paper, we define that the reverse surface of the fabric has the hem. That is, the reverse surface of the fabric is upward against vertical direction in Figure 2. The moving fingertips can hook into the hem of the fabric during the unfolding motion (see Figure 2-(b)) if the appropriate shaped fingertips and the grasping force are selected. The grasping force depends on the length d between fingertips (Figure 1-(c)).

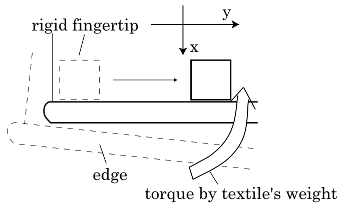
2.2 Experimental results

In this paper, we use a rectangular cotton handkerchief as a hemmed fabric. Table 1 shows the physical properties of the handkerchief. The parameters include those measured by Kawabata's Evaluation System for fabrics (KES) [11].

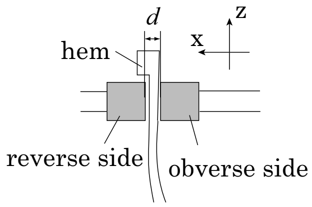
In the unfolding motion, we need to take into account the trajectory of the robotic arm, the shape of the robotic



(a) Diagonal view

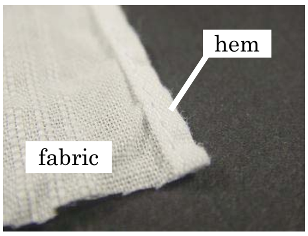


(b) Top view

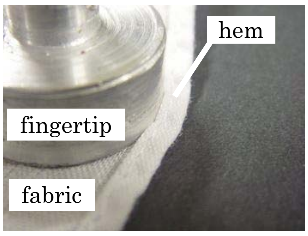


(c) Side view

Fig. 1: Horizontal pinching slip motion for fabric unfolding



(a) Fabric hem



(b) Contact state

Fig. 2: Unfolding motion using fabric hem

fingertip in contact with the fabric hem, the grasping force of the robotic hand, and the initial shape of the fabric. For simplicity, we have assumed that the path is a straight line horizontally for gravity force, at a speed of 9.95 mm/s. We confirm the distance between grasped fingertips to check the influence of the grasping force of the robotic hand. The distance d between the grasped fingertips has been set to 0.45, 0.50, 0.55, 0.60, 0.65, and 0.70 mm. The fingertips, which have circular (diameter; 30mm), half-rounded rectangular (diameter; 30mm) or, square (length; 30mm) with roundings shaped surfaces, are made of acrylic (Figure 3). We consider the hem directions relative to the initial shape, which can be classified into the obverse and reverse of the hem.

Table 2 shows results of the experimental unfolding motion. Symbols 'R', and 'O' indicate the hem direction; the reverse surface of the fabric is upward against vertical direction in the column of 'R'. Additionally, the obverse surface of the fabric is upward against vertical direction in the column of 'O'. Symbols 'S', 'F' and 'S/F' indicate that all trials were successes; all trials were failures, and trials were a mixture of successes and failures, respectively. The failure cases include jamming and dropping of the fabric. In a jamming case, the pinching fingertips do not reach at the hem of the fabric after the trial. In a dropping case, the fingertips fall down the fabric during the trial. We performed three trials for each condition. We varied the contact conditions between the fingertips and the hem of the fabric to check the various patterns as shown in Table 2. The figures in the first row show the shape of the fingertips and the type of contact between them and the fabric hem. The vertical lines in these figures show the fabric hem; for example, in the leftmost figure, the round surfaces of the circular shaped fingertips are in contact with the fabric hem. The figures in the second row show the hem direction of the fabric. Trial results showed that, for successful unfolding motions, the range between fingertips could be selected widely when the round surfaces of the fingertips are in contact with the hem.

Table 1: Physical properties of specimen

	Average	Standard deviation
Friction coefficient	0.17	8.91×10^{-3}
Flexural rigidity [gf·cm]	0.030	1.02×10^{-2}
Thickness [mm]	0.30	0.15

(a) Circular

(b) Half-rounded rectangular

(c) Square with roundings

Fig. 3: Robotic fingertips for unfolding motion

3 Observation of contact between fabric and robotic finger during unfolding

As shown is the previous section, the success rate of the unfolding motion using pinching slip motion depends on the grasping force and the shape of the fingertips. We assume that the distribution of the contacting force between the fingertips and the hem of the fabric depends on the success rate of the unfolding motion. We analyze the distribution of the contacting force among the fingertips and the hem through simulation. In this section, we observe the contact between the fingertips and the hem of the fabric during unfolding motion in air to make a model and to get the physical parameters for simulation.

Table 2: Experimental results of pinching slip motion [9]

d [mm]	R	O	R	O	R	O	R	O	R	O	R	O	R	O
0.45	S	S	S	S	S	S	S	S	S	S	S	S	S	S/F
0.50	S	S	S	S	S	S	S	S	S	S	S/F	S	S/F	F
0.55	S	S	S	S	S	S	S	S	S	S	S/F	S	F	F
0.60	S	S	S	S	S/F	S	F	S	F	S	S/F	S	F	F
0.65	S	S	S	S	S/F	S/F	F	S	F	S	S/F	S	F	F
0.70	S/F	S/F	S	S	F	F	F	S	F	S	S/F	S/F	F	F

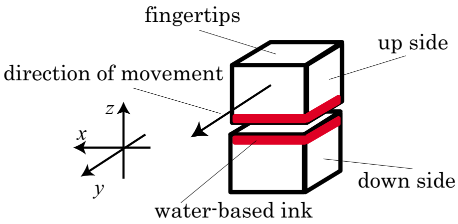
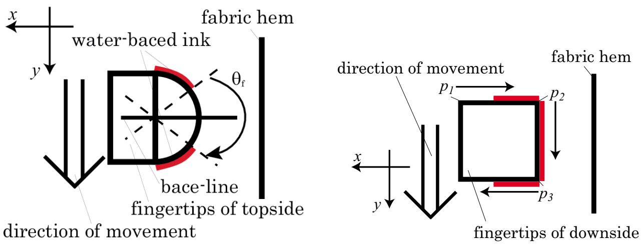
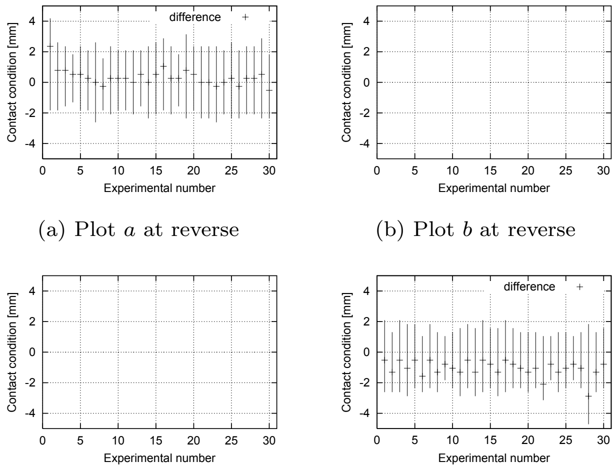


Fig. 4: Fingertip laid water-based ink



(a) Half-rounded rectangular (b) Rectangular

Fig. 5: Robot fingertips contact with hem of fabric



(a) Plot a at reverse (b) Plot b at reverse

(c) Plot a at obverse (d) Plot b at obverse

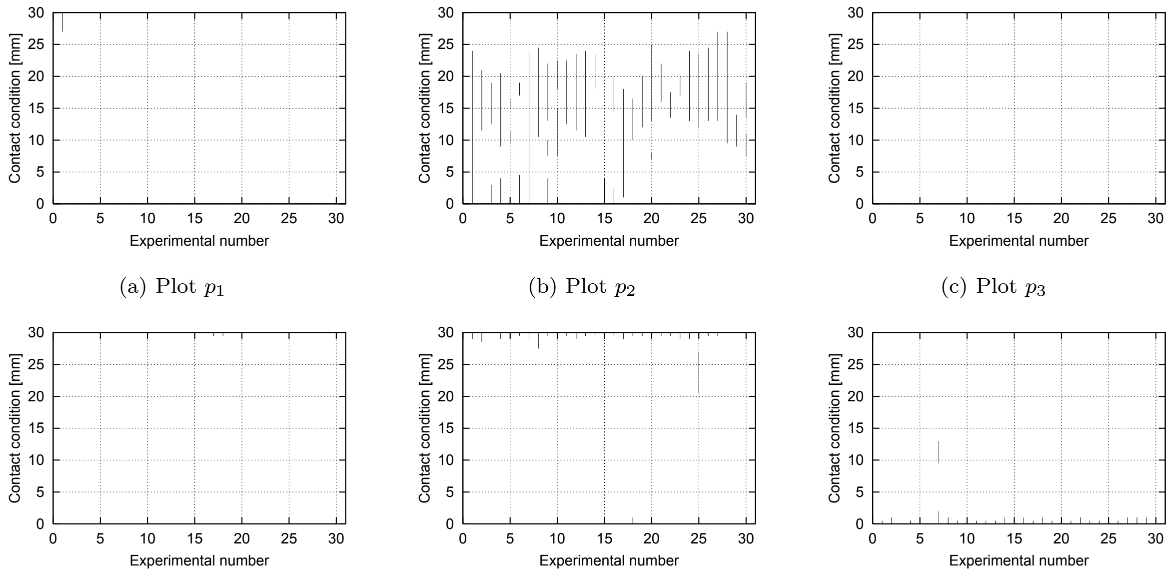
Fig. 6: Contact location by half-rounded rectangular

3.1 Experimental conditions

It is difficult to embed tactile sensors in the fingertips to measure the contacting force in terms of the size of the fingertips. Instead, we lay a water-based ink on the edge surface of the fingertips. Figure 4 shows a fingertips laid water-based ink to observe the contact during unfolding the fabric. The contact with the fingertips and the hem of the fabric rubs off the water-based ink during the unfolding. We confirm the position rubbed off the water-based ink of the fingertip surfaces after the unfolding. We estimate the contacting area between the fingertips and the hem during the unfolding motion based on the position of the water-based ink. The fingertips, half-rounded rectangular or square shaped surfaces, are made of acrylic in these observations. The arc edge of the half-rounded rectangular contacts with the hem of the fabric during the unfolding (Figure 5). We conducted thirty trials to confirm the experimental variation. The distance d between pinching fingertips is 0.60 mm during the unfolding. The length a of the contacting area is evaluated by the angle θ_f in terms of the center of the rounded part of the fingertip that contacts with the reverse side of the hem (Figure 5-(a)). Similarly, the length b of the contacting area is evaluated by the angle ϕ_f in terms of the center of the rounded part of the fingertip that contacts with the obverse side of the hem. Figure 5-(b) shows an experimental setup in case of square shaped surfaces. The length p_1, p_2, and p_3 of the contacting area is evaluated for the fingertip that contacts with the reverse side of the hem. In the same way, the length q_1, q_2, and q_3 of the contacting area is evaluated for the fingertip that contacts with the obverse side of the hem.

3.2 Experimental results

Figures 6 shows the experimental results in terms of the contact with arc surface of the half-rounded rectangular fingertips and the hem. The horizontal axes indicate trial numbers. The solid lines in the vertical axes indicate the position of the contacting area at the trial number. In Figure 6-(a) and (b), the hem of the fabric is upward along the gravitational direction. In Figure 6-(c) and (d), the hem of the fabric is downward along the gravitational direction. The fabric contacts with one side of a pair of fingertips during unfolding motion mainly. Especially, the hem contacts with the surface of the fingertip (see Figure 6-(a) and (d)). The average of the contacting area in arc surface is within 5 mm. In addition, the variation of the contacting area in arc surface is low. Figures 7 and 8 show the experimental results in terms of the contact



(a) Plot p_1 (b) Plot p_2 (c) Plot p_3

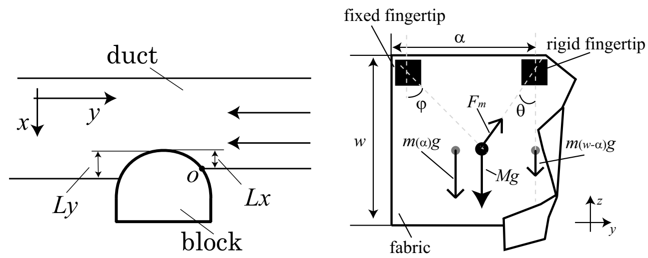
(d) Plot q_1 (e) Plot q_2 (e) Plot q_3

Fig. 7: Contact location by square with roundings at reverse

with rectangular surface of the fingertips and the hem. In Figures 7-(a), (b) and (c), the hem of the fabric is upward along the gravitational direction. In Figures 7-(d), (e) and (f), the hem of the fabric is downward along the gravitational direction. In the same way, Figures 8-(a), (b) and (c) indicate that the hem of the fabric is upward along the gravitational direction. Figures 8-(d), (e) and (f) indicate that the hem of the fabric is downward along the gravitational direction. From these observatios, the average of the contacting area of the square surface is within 13 mm. The contacting area is larger than the one of the arc surface of the fingertips; besides, the variation of the contacting area in the square surface is very high, resulting in being poorly-reproducible contact. From these observations, the success rate of the unfolding motion does not depends on the length of contacting area mainly if an appropriate grasping force of the fingertips is applied.

Table 3: Average of length

	obverse	reverse
L_x[mm]	0.152	0.426
L_y[mm]	0.438	0.278



(a) Fingertip in a duct (b) Fabric's mass

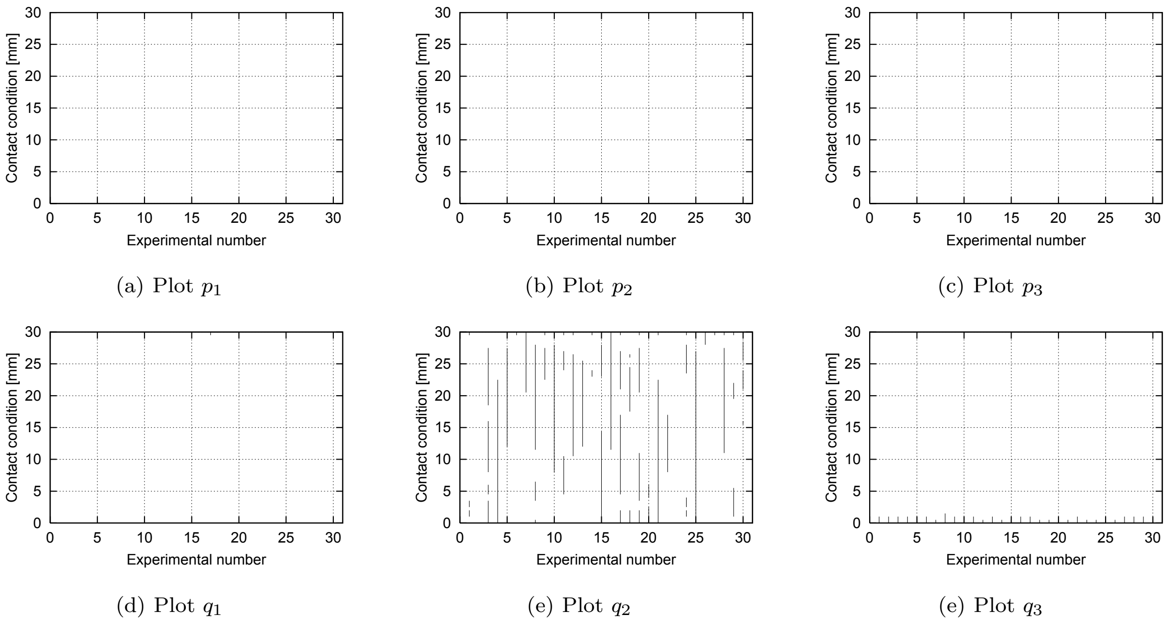
Fig. 9: Simulation setup

4 Pressure distribution through simulations

In this section, we simulate pressure distributions of moving fingertips during the unfolding. It is difficult to describe a contact between a soft object and a rigid object. We utilized two fingertips to pinch a fabric in previous experiments. For simplicity, we make a model of the contact between a fingertip and the hem of fabric based on fluid dynamics; the contact is considered as the collision between a fluid and a rigid block in this paper. That is, the pressure distribution of moving fingertips is considered as the pressure distribution of the block on the duct in flow field. We deal with two-dimensional space for this modeling (Figure 9). The contacting length in terms of the center line of the rounded part of the fingertip is described using the widths of the duct (Figure 9-(a)). Let L_x and L_y be distances between the top of the fingertip and the duct surfaces. We set the lengths L_x and L_y based on the previous experimental results (see Section 3 and Table 3). We assume that the fluid through the duct is incompressible flow because the volume of the fabric does not change during the unfolding.

4.1 Modeling based on fluid analysis

In this simulation, we apply ANSYS to calculate fluid dynamics. We do not consider disturbed flow because we deal with fabrics in this model. We calculate the equation of continuity and the Navier-Stokes equations for incom-



(a) Plot p_1 (b) Plot p_2 (c) Plot p_3

(d) Plot q_1 (e) Plot q_2 (e) Plot q_3

Fig. 8: Contact location by square with roundings at obverse

pressive fluid as follows;

$$\frac{\partial u}{\partial x} + \frac{\partial u}{\partial x} = 0, \tag{1}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}), \tag{2}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial y} + \nu(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}). \tag{3}$$

We also apply SIMPLER method as computation scheme for the discrete formulations of these equations. The fluid characteristics take account fabric characteristics into consideration. Let R_e, ν, U, and L be the Reynolds number, the viscosity factor, the characteristic velocity, and the characteristic length, respectively. Here, the following equation is satisfied;

$$R_e = \frac{UL}{\nu}. \tag{4}$$

We obtain the Reynolds number $R_e = 23.3$; determining the viscosity factor ν based on the friction coefficient of the fabric (see Table 1). This Reynolds number is low; resulting in being consistent in terms of a velocity of fingertips during unfolding.

Let us calculate the velocities u and v along x and y axes of the unfolding, respectively. At initial condition, the hem do not contact the fingertip (Figure 10-(a)). The fabric fall down by the gravitational force so that the distance between the hem and the fingertip decreases during the unfolding. In the end, the hem contacts the fingertip with relative velocity u (Figure 10-(b)). We assume that the fall velocity of the fabric at the contact dominates for velocities u and v.

Figure 9-(b) shows a mass distribution model during the unfolding. In the unfolding, one pair of fingertips is fixed at one corner and the other pair of fingertips is moving along the hem. We deal with a square fabric in this model. Let w be the length of one side of the fabric. Let α be the length between two pairs of fingertips. Here, we consider the mass of folded and no unfolded parts. We assume that the horizontal positions of the center of the mass of folded parts correspond to the moving fingertips. The force applied a fingertip until the contact between the hem and the fingertip is calculated as follows;

$$F = F_m + \mu N, \tag{5}$$

where F_m is the gravitational force from the fabric and N is normal force in terms of the grasping. Normal force N is calculated by the compression characteristic of the fabric and the distance d of the grasping fingertips. Let θ, φ be the angles between each fingertips and the mass center. We obtain the force F_m;

$$F_m = \frac{Mg\,\sin\varphi}{\sin(\theta+\varphi)}. \tag{6}$$

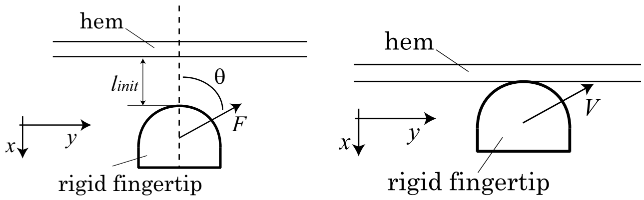
We define the α is equal to $w/2$ at the contact. Based on these equations, we can calculate the velocity V, when the hem contact with fingertip (Figure 10-(b));

$$V = \sqrt{\frac{2\,l_{init}\,F}{M\,\cos\theta}}. \tag{7}$$

We set the initial length l_{init} between the fingertips the hem to 5 mm.

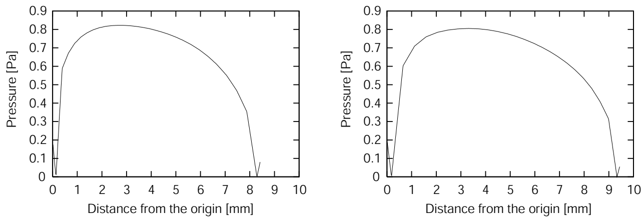
4.2 Simulation results

Figure 11 shows simulation results. The horizontal axis means the distance from the origin. The origine O is on the surface of the fingertip (see Figure 9-(a)). The



(a) Initial state (b) Final state

Fig. 10: Condition between fingertip and hem



(a) At obverse (b) At reverse

Fig. 11: Simulation results

coordination is set on one part of the arc along the surface of the fingertip. The distributions at obverse (Figure 11-(a)) and reverse (Figure 11-(b)) of the fabric are similar. These results reinforce the previous experimental results without the both ends of the graphs. However, small jumps of the pressure in both ends of the graphs are shown in terms of the boundary conditions between the duct and the fingertip. We are going to investigate the validity of the model we proposed in future.

5 Summary

This paper described an unfolding motion of fabric in air using pinching slip motion. During the pinching slip motion, the weight of the fabric generates relative movement between the moving fingertips and the fabric. The moving fingertips could hook into the hem of the fabric during the unfolding motion if the appropriate shaped fingertips and the grasping force are selected. In this paper, we could simulate the pressure distribution of moving fingertips during the unfolding. From these observations, the contacting area of the square surface is larger than the one of the arc surface of the fingertips; besides, the variation of the contacting area in the square surface is very high, resulting in being poorly reproducible contact. In addition, the success rate of the unfolding motion does not depends on the length of contacting area mainly if an appropriate grasping force of the fingertips is applied. We made a model of the contact between a fingertip and the hem of fabric based on fluid dynamics; the contact is considered as the collision between fluid and a block. In these simulations, the distributions at obverse and reverse of the fabric are similar. These results reinforce the previous experimental results. Future work includes the expansion of this simulation, especially the square surface of pinching fingertips, as stated in the discussion.

Acknowledgment

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