

Dynamic Manipulation of a Cloth by High-speed Robot System using High-speed Visual Feedback

Yuji Yamakawa * Akio Namiki ** Masatoshi Ishikawa ***

* Univ. of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-8656 Japan
(Tel: +81-3-5841-6937; e-mail: Yuji_Yamakawa@ipc.i.u-tokyo.ac.jp).

** Chiba Univ., 1-33 Yayoi-cho, Inage-ku, Chiba, 263-8522 Japan
(e-mail: namiki@faculty.chiba-u.jp)

*** Univ. of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-8656 Japan
(e-mail: Masatoshi_Ishikawa@ipc.i.u-tokyo.ac.jp)

Abstract: In this paper, we propose an entirely new strategy for dynamic manipulation of sheet-like flexible objects. As one example, we consider dynamic folding of a cloth by a high-speed robot system consisting of two high-speed multifingered hands mounted on two sliders and a high-speed vision system. First, the dynamic folding performed by a human subject is analyzed in order to extract the necessary motion for this task. Second, a model of a sheet-like flexible object is proposed by extending a linear flexible object model (algebraic equation) using high-speed motion. Third, motion planning of the robot system is performed by using the proposed model, and the simulation result of the dynamic folding is shown. Fourth, high-speed visual feedback control is proposed in order to enhance the manipulation strategy. Finally, experimental results of the dynamic folding of the cloth by the high-speed robot system are shown.

1. INTRODUCTION

Robotic manipulation is an important technique in the robotics field. Various tasks involving the manipulation of rigid bodies have been actively performed. On the other hand, although the manipulation of flexible objects has been anticipated, it is extremely difficult to execute the required manipulations because many problems exist, such as the manipulation strategy, motion planning, and modeling and control of the flexible object. The crucial reasons for the difficulties faced in flexible object manipulation are deformation of the flexible object during manipulation and estimating this deformation.

Recently, there have been some successful demonstrations of the manipulation of sheet-like flexible objects, such as unfolding of a cloth [1], origami [2, 3], and towel folding [4]. As described above, the conventional manipulation of flexible objects has been executed by static manipulation. Thus, high-speed manipulation of flexible objects has been considered infeasible. In order to achieve high-speed, dynamic manipulation of flexible objects, as one example, we have performed dynamic knotting of a flexible rope [5]. In that study, we proposed a simple model (algebraic equation) that takes advantage of high-speed robot motion, and the effectiveness of this model has been confirmed. We have also proposed a motion planning method that derives the robot trajectory from the rope configuration.

In this paper, as an extension of the research described in our previous paper [5], dynamic manipulation of a sheet-like flexible object is carried out. Concretely, the task involves dynamic folding of a cloth held in the air, as shown in Fig. 1. First, we extract the necessary elements in

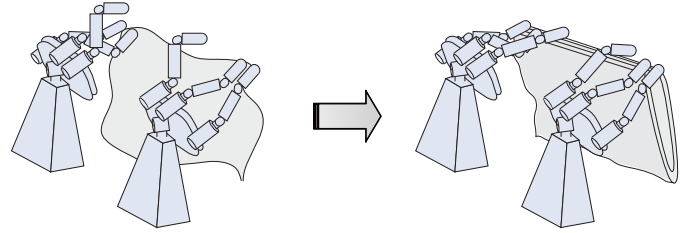


Fig. 1. Image of this study.

order to achieve this task by analyzing the dynamic folding performed by a human subject. Second, we construct a simple deformation model of the cloth by extending the previous rope model [5]. Third, a motion planning method based on the proposed model is discussed, and the validity of the robot motion obtained by the motion planning method is confirmed by simulation. Fourth, a high-speed visual feedback control scheme is introduced in order to enhance the manipulation strategy and to improve the success rate of this task. Finally, dynamic folding of the cloth by a high-speed robot system is demonstrated experimentally.

In general, cloth folding can be executed by placing the cloth on a table. However, this method is not effective and is considerably difficult to perform at high-speed. In this research, we aim to achieve high-speed folding of the cloth held in the air. Since this folding method dynamically uses the deformation of the cloth, we expect that it can achieve high-speed, dynamic manipulation of the cloth.

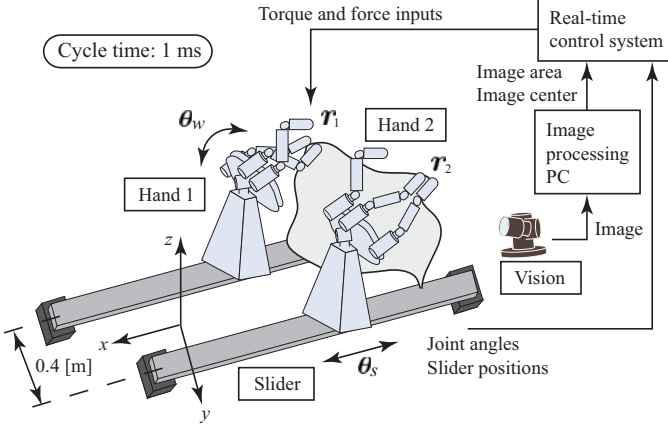


Fig. 2. Overview of robot system.

2. HIGH-SPEED ROBOT SYSTEM

The experimental system consists of two high-speed multi-fingered hands [6], two high-speed sliders, a vision system, and a real-time control system, as shown in Fig. 2. The high-speed multifingered hands are mounted on the high-speed sliders.

Each hand has three fingers: a left thumb, an index finger, and a right thumb. Each finger is divided into a top link and a root link. The index finger has two degrees of freedom (2-DOF), and the other fingers have 3-DOF. The joints of the hand can be closed at a speed of 180 deg./0.1 s. In addition, the hand has two wrist joints. The wrist part has a differential rotation mechanism, and it moves about two axes.

The slider has a 1-DOF translational motion mechanism. The maximum speed of the slider is about 2 m/s.

The vision system uses a high-speed camera called EoSens MC1362 (Mikrotron). Its resolution is 800×1024 . It is connected to an image processing PC (CPU: Core 2 Duo (3.16 GHz), Memory: 2.0 GB) by CameraLink. It takes 800×1024 , 8-bit, gray-scale images at a maximum speed of 740 fps. The image processing PC calculates feature values at almost 500 fps and sends the values to the real-time control system via Ethernet.

The real-time control system receives the values from the image processing PC and controls the hand and the slider at 1 kHz. The joint angles of the hand and the position of the slider can be controlled by PD action.

3. MOTION ANALYSIS OF DYNAMIC FOLDING

In order to extract the motions for performing dynamic folding of the cloth, we analyze the dynamic folding performed by a human subject. Fig. 3(a) is the initial condition. Fig. 3(b) shows the cloth being pulled toward the body using shoulder and elbow motions. Fig. 3(c) shows that when the shoulder and elbow motions stop, the free end (the point far from the grasp position) of the cloth is folded by an inertial force. Fig. 3(d) shows the subject grasping the free end of the cloth and the final condition where the dynamic folding is completed. As a result, the dynamic folding can be carried out by

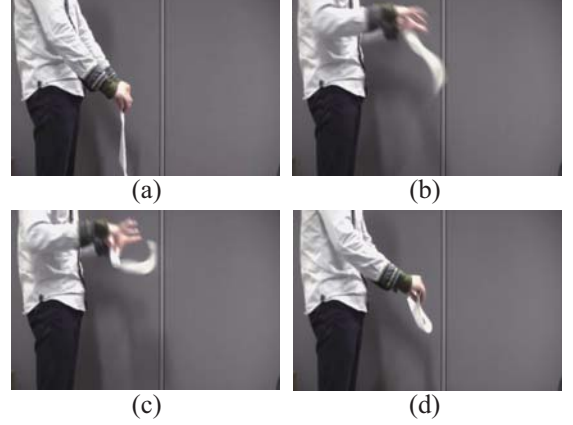


Fig. 3. Dynamic folding by human.

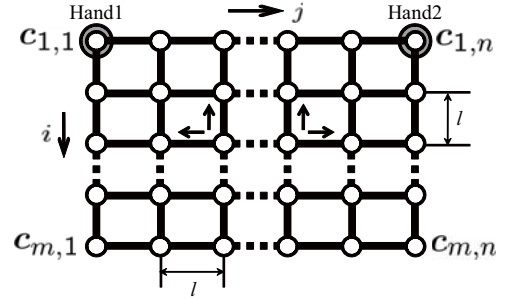


Fig. 4. Model of cloth.

deforming the cloth to fold it and then grasping the deformed cloth.

Thus, key points to achieve the dynamic folding of the cloth are: appropriate deformation to fold the cloth and grasping the end of the deformed cloth. A motion planning method and sensory feedback control are essential in order to execute these elements. We propose a new motion planning method to achieve appropriate deformation to fold the cloth and introduce high-speed visual feedback to carry out grasping of the end of the deformed cloth.

4. DEFORMATION MODEL AND SIMULATION

In this section, we explain a deformation model of the cloth that takes advantage of high-speed motion. In the previous paper [5], we demonstrated that the deformation model of a linear flexible object can be approximated by an algebraic equation using the high-speed motion of the robot. In this paper, we extend the deformation model of the linear flexible object to the deformation model of the sheet-like flexible object. As a physical model, we consider a multi-link model of the cloth and the grasp position of the cloth as shown in Fig. 4. Then, a motion planning method based on the proposed model is suggested. Finally, the simulation results of the dynamic folding with the robot motion obtained by the motion planning method is illustrated.

4.1 Kinematics of High-speed Robot System

Here we consider the kinematics of the high-speed robot system in order to derive the grasp position of the cloth. Using the fingers of the hand for grasping the cloth, the

grasp position does not depend on the finger positions. Also, the degrees of freedom of the fingers can be ignored. Thus, the robot system has 4-DOF: the bending-extension motions of the hands and the translational motions of the sliders. The 2-DOF variables for each hand are assumed to be described by $\theta = [\theta_w \ \theta_s]^T \in \mathbf{R}^2$. The grasp position of the cloth is defined by $\mathbf{r} \in \mathbf{R}^3$. In general, using a Denavit-Hartenberg description, the following equations hold:

$$\begin{aligned} \mathbf{r}_1(t) &= \mathbf{f}(\theta_1(t)) \\ \mathbf{r}_2(t) &= \mathbf{f}(\theta_2(t)) + [0 \ 0.4 \ 0]^T, \end{aligned} \quad (1)$$

where the subscripts (1, 2) are indexes representing the two hands.

4.2 Deformation Model of Cloth

The conventional mathematical models of flexible objects can be described by a partial differential equations as the physical model of a distributed parameter system and a matrix differential equations as the physical model of the multi-link system. These models have many parameters, and parameter estimation is quite difficult. As a result, the modeling is also very difficult. Furthermore, since these models are complicated, it is extremely hard to analyze these models and to propose a control scheme.

We demonstrated the possibility that the deformation model of a flexible rope can be approximated by an algebraic equation using high-speed robot motion [5]. In this paper, the deformation model of the cloth is described based on this result. In the modeling of the cloth, the following are assumed:

- (1) The physical model is approximated by a two-dimensional (2D) multi-link model.
- (2) The behavior of the part of the cloth located at the “near” position from the grasp position of the robot depends on the robot motion.
- (3) The distance between two joint coordinates of the cloth is not variable.
- (4) There exists a time delay between the robot motion and the cloth deformation.
- (5) The twist of the links of the cloth is not taken into account.

The second assumption means that the cloth deformation can be given by the grasp position of the robot system. The third assumption is the constraint that the link distance in the multi-link model does not change. The fourth assumption means that even if the robot moves, the part of the cloth that is located at the far position from the grasp position does not deform during the time delay.

Considering the above assumptions and extending the model of the linear flexible object [5], the deformation model of the cloth can be algebraically represented as follows:

$$\mathbf{c}_{i,j}(t) = \mathbf{r}_{1,2}(t - (d_i + d_j)), \quad (2)$$

where subscript (i, j) is the joint number of the cloth ($i = 1, 2, \dots, m = 20$, $j = 1, 2, \dots, n = 20$), $\mathbf{c}_{i,j} \in \mathbf{R}^3$ (“3” means $[x \ y \ z]^T$ coordinates) is the (i, j) joint coordinate of the cloth, $\mathbf{c}_{1,1}$ and $\mathbf{c}_{1,n}$ are the same as the grasp position of the robot hands 1 and 2, respectively, and d_i and d_j represent longitudinal and lateral time delays between the robot motion and the cloth deformation, respectively. At

the (i, j) joint, the time delays are given by $d_i = \lambda l(i - 1)$ and $d_j = \lambda l(j - 1)$ (if $j \leq n/2$) or $\lambda l(n - j)$ (otherwise) (λ is a normalized time delay, and l is the link length).

Since the proposed model does not include an inertia term, Coriolis and centrifugal force terms, or a spring term, we do not need to estimate the dynamic model parameters; only the normalized time delay λ has to be estimated. The value of λ may be dependent on the characteristics of the cloth. Since the number of model parameters is smaller than in one of the typical models (the partial differential equation and the matrix differential equation), it is quite easy to estimate only one model parameter λ . Also, the proposed model itself is robust. Moreover, since the cloth model can be algebraically calculated, the simulation time becomes much shorter. In particular, the most important advantage is that the motion planning can be obtained by an algebraic calculation from the configuration of the flexible object.

In the calculation sequence, the joint coordinates of the cloth can be calculated, while changing each joint number in the longitudinal direction and the lateral direction from the hand grasp position. In this study, since there are two hand grasp positions, the calculation of the joint coordinates is performed from the grasp positions of hands 1 and 2. Then, the central joint coordinate of the cloth is finally calculated.

4.3 Correction of Link Distance

Describing the cloth deformation using Eqn. (2), there exists a case where the distance between two joint coordinates cannot be kept constant. Therefore, in order to satisfy assumption (3), the joint coordinates of the cloth need to be converted as follows:

The joint coordinate to be converted is defined as $\mathbf{c}_{i,j} = [x_{i,j} \ y_{i,j} \ z_{i,j}]$, and the prior (that is, nearer to the position grasped by the robot) joint coordinate is $\mathbf{c}_{i-1,j} = [x_{i-1,j} \ y_{i-1,j} \ z_{i-1,j}]$. The distance between these two joint coordinates can be described by

$$D = \|\mathbf{c}_{i,j} - \mathbf{c}_{i-1,j}\|. \quad (3)$$

In the case where D is not equal to l (l is the link distance), the joint coordinate $\mathbf{c}_{i,j}$ is corrected in terms of polar coordinates as follows:

$$\begin{aligned} x_{i,j} &= l \sin \theta \cos \phi + x_{i-1,j} \\ y_{i,j} &= l \sin \theta \sin \phi + y_{i-1,j} \\ z_{i,j} &= l \cos \theta + z_{i-1,j} \end{aligned} \quad (4)$$

where

$$\begin{aligned} \theta &= \cos^{-1} \left(\frac{z_{i,j} - z_{i-1,j}}{D} \right) \\ \phi &= \cos^{-1} \left(\frac{x_{i,j} - x_{i-1,j}}{\sqrt{(x_{i,j} - x_{i-1,j})^2 + (y_{i,j} - y_{i-1,j})^2}} \right). \end{aligned} \quad (5)$$

In the same way, the joint coordinate ($\mathbf{c}_{i,j} = [x_{i,j} \ y_{i,j} \ z_{i,j}]$) should also be corrected for the neighbor joint coordinate ($\mathbf{c}_{i,j-1} = [x_{i,j-1} \ y_{i,j-1} \ z_{i,j-1}]$). Then, the weighting factor can be calculated from each correction value of the longitudinal and lateral directions. Finally, correction of the joint coordinates in the longitudinal and lateral directions is performed.

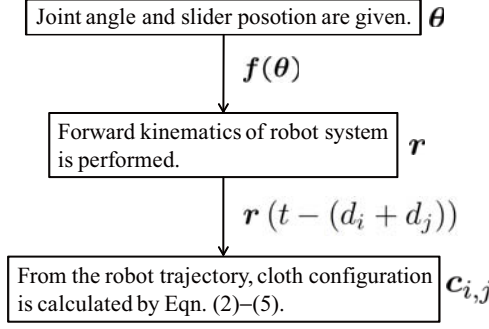


Fig. 5. Simulation flow of forward problem.

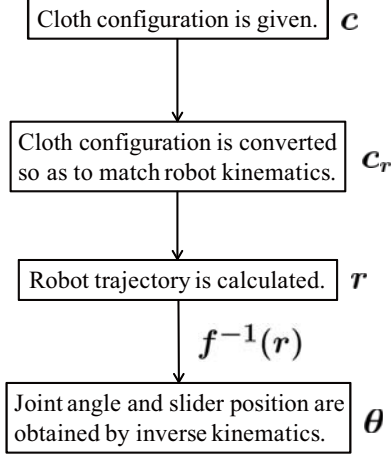


Fig. 6. Simulation flow of inverse problem.

Fig. 5 shows a simulation flow of the forward problem using the cloth deformation model. First, the joint angle of the wrist θ_w and the slider position θ_s are given. Then, the grasp position $r_{1,2}$ of the cloth with the robot system is calculated by the forward kinematics. Finally, the cloth deformation $c_{i,j}$ is derived using Eqns. (2)–(5).

4.4 Inverse problem

This section explains the inverse problem of deriving the joint angle of the wrist and the slider position from the cloth configuration. It is considerably difficult and complex to give all control points (the cloth configuration) of a curved surface on a 3D plane. Thus, let us consider the cloth configuration on the x - z plane (side-view) to simplify the inverse problem. Here, we assume that the cloth deformations at both hands are the same. Fig. 6 shows the simulation flow of the inverse problem.

First, we give the number of links of the multi-link system of the cloth. The desired cloth configuration (c) is graphically given in a 2D plane by a user. Here, there exists a case where the link distance between the two joint coordinates on the given cloth configuration is not equal to l . Therefore, the cloth configuration is corrected using the polar coordinates (Eqns. (3)–(5)).

Second, the cloth configuration (c) is converted so as to match the robot system kinematics to avoid problems such as a singular point.

Third, the trajectory of the grasp position (r) of the robot system is calculated from the converted cloth configuration

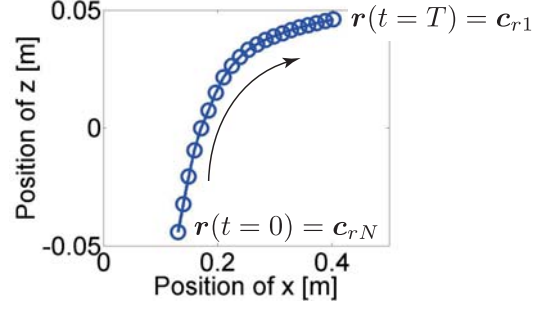


Fig. 7. Configuration of cloth.

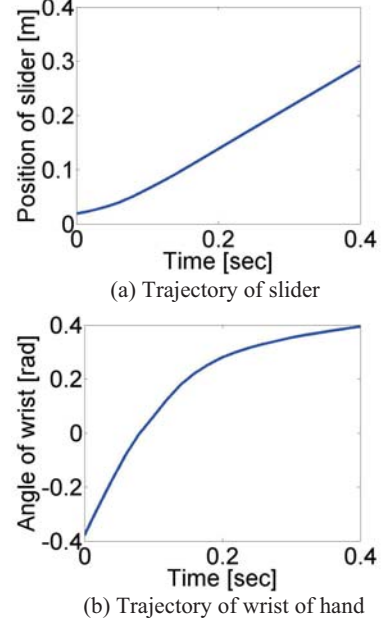


Fig. 8. Result of motion planning.

(c_r). From the assumption that the cloth deformation depends on the high-speed robot motion, the trajectory (r) of the robot system can be obtained, to track the given coordinate of each joint of the cloth. Namely, we have the following equations:

$$r(t=0) = c_{rN}, \quad r(t=T) = c_{r1}, \quad (6)$$

where N ($=20$) is the number of joints, and T ($=0.4$ s) is the motion time. The trajectory is determined so as to linearly move from the N -th link to the first link during the motion time T . Here, the trajectory is calculated so as to compensate for the effects of gravity.

Finally, the joint variables (θ) of the robot system can be obtained by solving the inverse kinematics.

As described above, the motion planning of the robot system can be achieved by solving the inverse problem from the given cloth configuration. We can consider that the proposed method is a general method.

4.5 Simulation of Dynamic Folding

In this section, the simulation results of dynamic folding are shown. In this simulation, the size of the cloth is $0.4 \text{ m} \times 0.4 \text{ m}$. Since the number of joints (m, n) of the multi-link model is $(20, 20)$, the link distance l is 0.02 m .

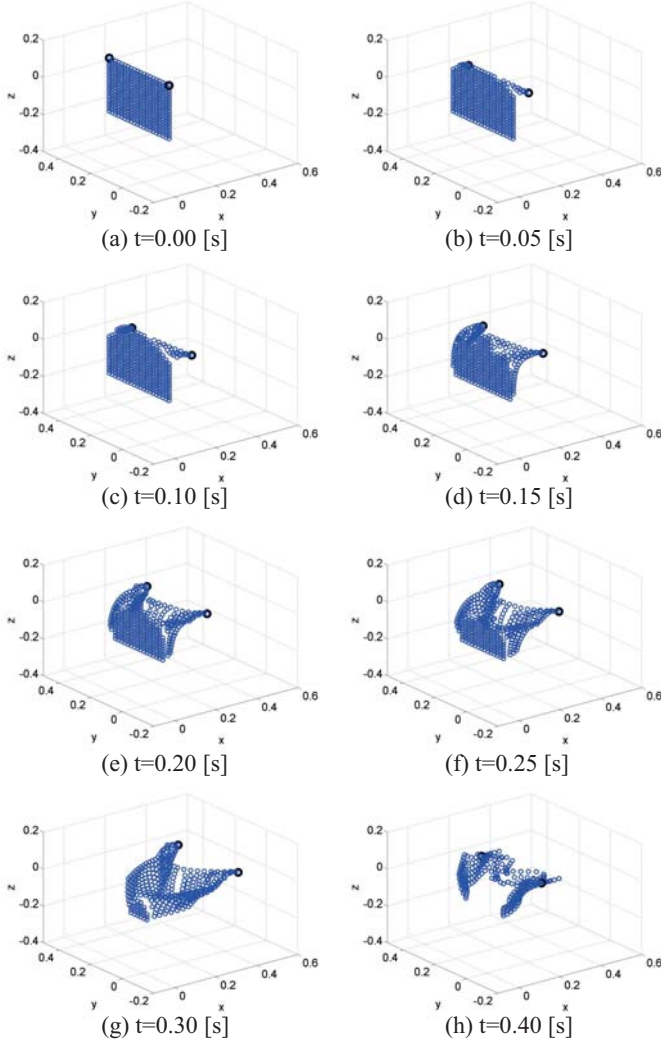


Fig. 9. Simulation result of dynamic folding.

In order to achieve dynamic folding of the cloth, motion planning of the robot system is extremely important. In particular, obtaining the desired cloth configuration is key to the success of this task. Thus, motion planning is required to achieve this.

In this simulation, the 2-D cloth configuration (\mathbf{c}_r) is given as shown in Fig. 7. In Fig. 7, the blue circles are the given cloth configuration on the x - z plane. Then, the joint variables (θ) of the robot system can be calculated by solving the inverse kinematics. Fig. 8 shows the results of the trajectories of the wrist joint angle θ_w of the hand and the slider position θ_s . Fig. 9 shows the simulation result of the dynamic folding using the robot motion obtained with the inverse problem. In Fig. 9, the black circles and the blue circles depict the positions of both hands and the cloth coordinates, respectively. It can be seen from Fig. 9 that the cloth deforms depending on the hand and slider actions. The folding aspect of the cloth can be confirmed. Therefore, the validity of the cloth deformation model can be verified. Also, the robot motion obtained by the simulation can be used in the experiment. By using the proposed model, the trajectory of the robot system can be algebraically obtained when an arbitrary cloth configuration is given.

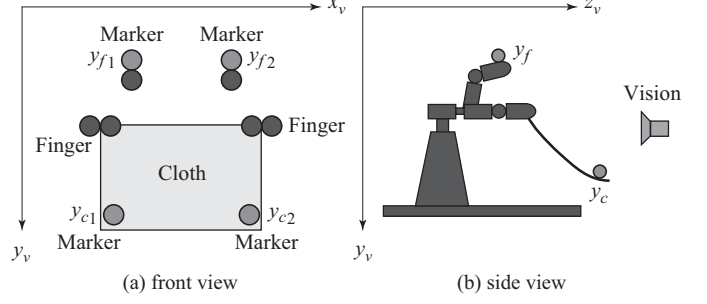


Fig. 10. Set-up for high-speed visual feedback.

5. HIGH-SPEED VISUAL FEEDBACK

Since it is extremely difficult to robustly achieve dynamic folding with the motion planning obtained by simulation, we need to introduce high-speed visual feedback control. In this task, the timing at which the deformed cloth is grasped is extremely important. Thus, we propose a grasping strategy using the grasp timing extracted by the high-speed vision system. Here, let us consider the relationship between the positions of the cloth and finger from the view acquired by the high-speed vision system, as shown in Fig. 10. Markers are attached to the cloth and fingers in order to measure the center positions and the areas of these markers. The high-speed vision system can track these markers. Then, the center positions ($x_{\{c,f\},\{1,2\}}$, $y_{\{c,f\},\{1,2\}}$) and the areas ($a_{\{c,f\},\{1,2\}}$) of these markers can be derived within 2 ms by calculating image moments. The subscripts (c , f) indicate cloth and finger, respectively.

The goal of the visual feedback control is to grasp the deformed cloth. First, in order to perform position correction in the z direction, the slider position can be controlled so as to match the areas between the finger's marker and the cloth's marker using the following control law:

$$\theta_{s\{1,2\}} = k_p(a_{c\{1,2\}} - a_{f\{1,2\}}) + k_d(\dot{a}_{c\{1,2\}} - \dot{a}_{f\{1,2\}}), \quad (7)$$

where k_p and k_d represent the proportional gain and the differential gain, respectively. Next, when the relative position between the finger and cloth in the y direction becomes smaller than the threshold, as follows:

$$|y_{c\{1,2\}} - y_{f\{1,2\}}| < y_{thre}, \quad (8)$$

the vision system can recognize the timing at which the cloth is grasped. At the same time, the hand can grasp the deformed cloth. Here, y_{thre} is the threshold that determines the grasp timing and is adjusted depending on the system configuration.

6. EXPERIMENTAL RESULT

In this experiment, the robot motion obtained by the simulation and the high-speed visual feedback control are implemented.

Fig. 11 shows continuous photographs of the experimental results. Fig. 11(a) represents the initial condition of the experiment, where the two hands grasp the cloth. Fig. 11(b-c) show the cloth being pulled toward the grasp position using the hand and slider motions. Fig. 11(d) shows that when the hand and slider motions stop, the free end (the point far from the grasp position) of the cloth

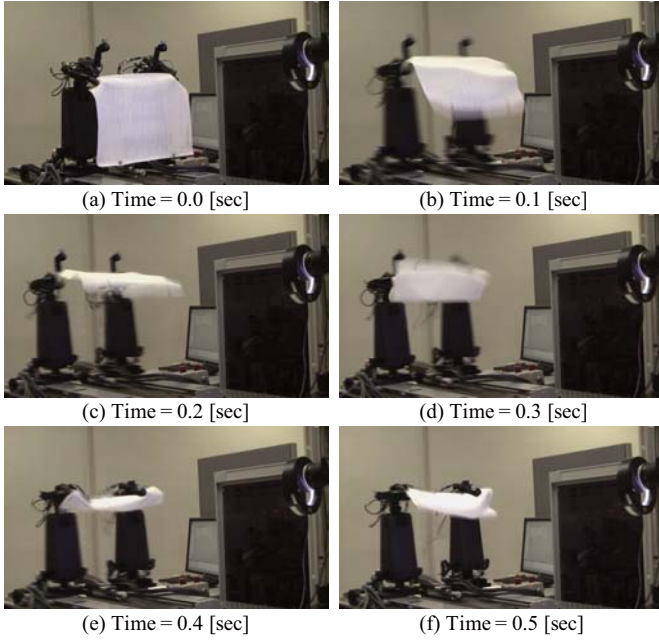


Fig. 11. Dynamic folding by robot system.

is folded by an inertial force. Fig. 11(e-f) show grasping of the free end of the cloth. As can be seen from the experimental results, dynamic folding of the cloth can be achieved by the two high-speed multifingered hands and two high-speed sliders. In addition, since the action time of the dynamic folding performed by the robot system is 0.4 s, high-speed folding can be achieved.

Although the success rate of the cloth deformation is almost 100 %, the success rate of the cloth grasping is about 70 %. Thus, the success rate of the dynamic folding is about 70 %. Since the desired cloth deformation can be obtained by the motion planning method, the effectiveness of the proposed deformation model of the cloth and the motion planning method, as well as the validity of the simulation result, can be verified. Possible reasons for failure include the initial condition of the cloth and the tracking error in the image processing.

Fig. 12 shows the area and y position of the markers at hand 1 obtained by the high-speed vision system. The blue and green lines depict the responses for the markers attached on the cloth and the finger, respectively. As can be seen from Fig. 12, the slider position can be controlled so as to match the areas between the cloth and finger markers. As a result, the difference between these areas becomes smaller. Then, when the relative y position between the cloth and the finger becomes lower than the threshold y_{thre} , the vision system can recognize the grasp timing. It is confirmed that these positions become exactly the same, thus confirming the effectiveness of the proposed high-speed visual feedback control method.

This video can be seen at the web page [7].

7. CONCLUSIONS

In this study, we aimed to achieve dynamic folding of a cloth with a high-speed robot system using high-speed visual feedback control.

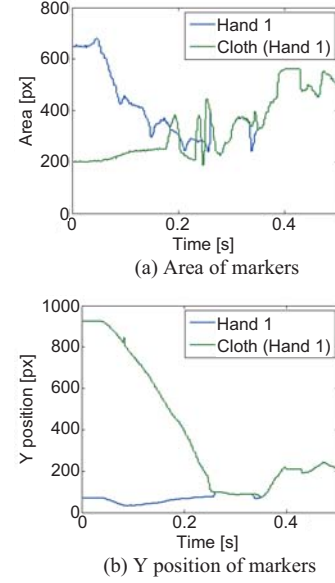


Fig. 12. Experimental result of visual feedback.

First, we extended the model of a linear flexible object using high-speed robot motion to the model of a sheet-like flexible object. Then, we proposed a motion planning method based on the proposed model of the sheet-like flexible object. The robot trajectory obtained from the motion planning method was validated with simulation results. Second, a high-speed visual feedback control method was introduced to recognize the grasp timing of the deformed cloth and to improve the proposed strategy. Finally, we implemented the robot trajectory and the visual feedback control method and demonstrated dynamic folding experimentally. We also confirmed the effectiveness of the proposed model, the motion planning method, and the high-speed visual feedback control method.

REFERENCES

- [1] M. Shibata, T. Ohta and S. Hirai. Fabric Unfolding Using Pinching Slip Motion. *Journal of Robotics Society Japan*. Vol. 27, No. 9, pp. 1029-1036, 2009.
- [2] K. Tanaka, Y. Kamotani and Y. Yokokohji. Origami Folding by a Robotic Hand. *Proc. Int. Conf. on Intelligent Robot Systems*. pp. 2540-2547, 2007.
- [3] D. J. Balkcom and M. T. Mason. Robotic origami folding. *Int. Journal of Robotics Research*. Vol. 27, No. 5, pp. 613-627, 2008.
- [4] J. M. Shepard, M. C. Towner, J. Lei and P. Abbeel. Cloth Grasp Point Detection based on Multiple-View Geometric Cues with Application to Robotic Towel Folding. *Proc. Int. Conf. on Robotics and Automation*. pp. 2308-2315, 2010.
- [5] Y. Yamakawa, A. Namiki and M. Ishikawa. Motion Planning for Dynamic Knotting of a Flexible Rope by a High-speed Robot Arm. *Proc. Int. Conf. on Intelligent Robot Systems*. pp. 49-54, 2010.
- [6] A. Namiki, Y. Imai, M. Ishikawa, and M. Kaneko. Development of a High-speed Multifingered Hand System and Its Application to Catching. *Proc. Int. Conf. Intelligent Robots and Systems*. pp. 2666-2671, 2003.
- [7] <http://www.k2.t.u-tokyo.ac.jp/fusion/DynamicFolding/>