論文要旨

仮想布操作において、布の形状と力覚を同時に提示するためには、布の形状と力の両方を、実際の布における両者の関係を満たす形でシミュレーションする必要がある。現実の布における形状と力の関係を計測する手法として、KES(Kawabata's Evaluation Method for Fabric) があるが、布は履歴特性をもっているため、得られるデータは、特定の操作履歴における形状と力の間の一方向的な関係を記述したものとなる。従来の布形状シミュレーションの研究には、この点を考慮してKESデータを利用する手法も存在するが、布形状の生成に焦点を当てているため、本研究で目指すような、形状と力を同時にシミュレーションする処理には直接適用できない。そこで本稿では、KESデータに基づき、かつ、履歴特性を考慮しながら、布の形状と力を同時にシミュレーションするための布モデルを提案する。

論　文

物理計測データに基づく形状と力覚の提示のための仮想布モデリング*

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Modeling Virtual Cloth to Display Realistic Shape and Force Based on Physical Data*

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In this paper, we have proposed the modeling of cloth that realizes force together with shape to manipulate the virtual cloth. Researchers, in the community of computer graphics, have simulated only the realistic shape of cloth. However, it is also important to display the force generated from cloth for the environment where user manipulates the cloth with visual and haptic feedback. Inclusion of force with shape requires to simulate shape and force, based on the relation between them. The real relationship between shape and force can be measured by special device called "Kawabata Evaluation System(KES)". However, a cloth has hysteretic property, and relation between shape and force depends on the history of manipulation. KES data only describes incomplete unilateral relations between force and shape under specific histories of manipulation. Although there exists some previous work that simulates the shape of the cloth based on KES data, it is insufficient to simulate both shape and force considering their hysteretic relation. This paper discusses how to model a virtual cloth to simulate shape and force with realities by interpolating empirical data obtained from KES, considering their limitation due to the hysteresis.

1. Introduction

In the field of computer graphics, it has widely been studied how to simulate realistic shape of clothes. Clothes have many degrees of freedom, and change their shape very flexibly. Most of the previous work employs mass-spring model, which is formed by triangular or rectangular meshes of particles with mass connected by springs, and simulate rectangular-shaped clothes including flag and tablecloth[3,7] or complex garments and dresses[9,10]. More comprehensive survey of cloth modeling and its application is given in[5].

Those previous work[1–4,7–10] focuses on simulating the shape of a cloth. However, in order to realize an environment for virtual cloth manipulation with both haptic and visual feedback to the user, we need to simulate force generated from the cloth as well as shape. In this paper, we discuss how to model a cloth that can realize its shape with force.

In order to simulate realistic shape and force of a cloth, we have to consider three kinds of realities: (a) reality of shape, (b) reality of force, and (c) reality of the relation between shape and force. Since the previous work[3,7,10] employs mass-spring model, the force applying to each particle in the mesh is of course simulated. However, this force is not the same force generated in the real cloth but an imaginary force to achieve a realistic shape by the mass-spring model. Since real clothes have properties in between a sheet of paper and a rubber membrane, the force acting on the cloth is different from what is given by springs. In that sense, the previous work only achieves reality (a) but does not consider the reality (b) nor (c).

The relation between force and shape of a cloth in stretch, bend, shear, and so forth can be obtained by

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a special device called "Kawabata Evaluation System (KES)"[6]. For example, for stretch, KES measures the stretch of a certain size of a cloth by changing the external force to stretch the cloth. In measurement for bend, the recovery moment of a cloth is measured by changing the bending curvature.

Since a cloth has a hysteresis property, the relation between force and shape of the cloth is not actually described as a monomorphic mapping. The same shape can be obtained from different external forces, while the same force can cause different shapes depending on previous conditions. Due to this hysteresis, the KES data only describe incomplete unilateral relation of force and shape under specific histories of stretch, bend, shear and so on. When we employ the KES data for the reality (c), this limitation of the KES data has to be considered.

There are some previous work that simulates the shape of a cloth based on the KES data, in order to give the model more realistic physical grounding[2–4,9]. However, they are insufficient to simulate force together with shape because these methods employ the unilateral relation between force and shape supplied by the KES data to simulate only the shape of a cloth. In that sense, this work maintains the reality (a) and (b) for realistic shape yet it does not realize the reality (b) and (c) for realistic force.

This paper presents a method to maintain realities (a)-(c) at any moment of simulation, to display the shape and force of a cloth. In the remainder of this paper, the KES data and their limitations are explained in section 2. In section 3, a new approach is proposed to simulate force together with shape. The concrete procedure to realize the approach based on a cloth model and cost/ energy minimization is described in section 4. The results of experiments to evaluate our method are given in section 5. Section 6 discusses differences of our work from the related previous work, which had simulated the shape of cloth based on the KES data. Finally, conclusion and future work is discussed in section 7.

2. Kawabata Evaluation System for Fabric

KES is a standard set of fabric-testing device. It measures stretching, bending, shearing, surface roughness, compressibility and so on, of a real cloth. KES data is different for various types of materials like wool, cotton and so on. The measurement procedure for stretch and bend property is explained as the example in this section.

2.1 Bend

A bending measurement is obtained by clamping 20cm×1cm specimen of cloth along its long edges. One clamp is fixed and moves the other so that 1cm long side of cloth bends with constant curvature (see Fig. 1(a)). The curvature is first increased from 0 to reach 2.5cm^{-1}, then decreased it to -2.5cm^{-1} and again increased to 0. The bending moment measured while increasing and decreasing the bending curvature of wool is shown in the Fig. 2.

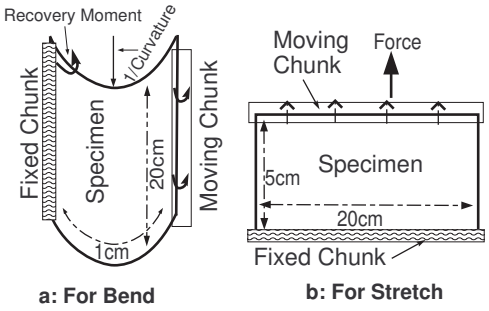

Fig. 1 KES measurements

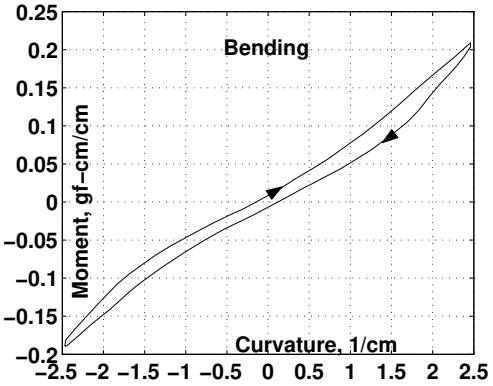

Fig. 2 KES for bend of wool

2.2 Stretch

The KES stretch measurement is done for a 5cm ×20cm specimen of cloth, clamped by two chunks of 20cm long. One side is fixed while other side is stretched by varying the external force to stretch the cloth along the side of 5cm length as shown in Fig. 1(b). The external force is increased to reach 500gf/cm, then decreased to 0. The stretch for wool is measured while increasing and decreasing the external force as shown in the Fig. 3.

2.3 Hysteresis of Cloth

The relation between shape and force generated by the cloth shows a hysteretic property, and depends

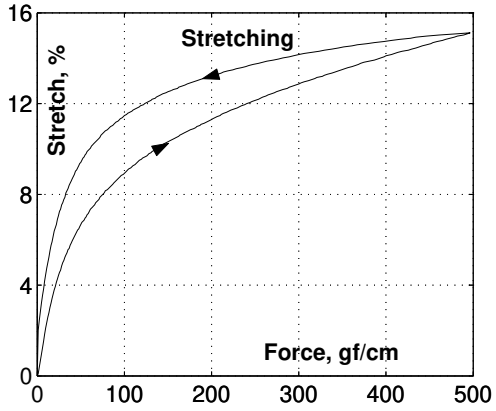

Fig. 3 KES for stretch of wool

on the history of manipulation. In this paper, we call shape and force of the cloth at each moment of manipulation, a "state". Each state of a cloth depends on the previous states due to this hysteretic property. Different states are possible for each shape and force depending on the history of manipulation.

The KES data describes the state transitions under specific histories. Let us consider Fig.4 as an example of KES data for bend. The same moment τ_1 is generated by the cloth for at least two different curvatures κ_1 and κ_3, while at least two different moments τ_1 and τ_2 can be generated by the cloth for the same curvatures κ_1, depending on the states reached in the history . However, this history is only one of the innumerable possible histories of manipulation of a cloth, different state transitions could be obtained if we set different histories of manipulation.

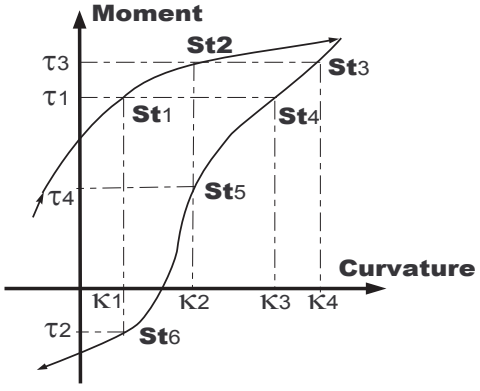

Fig. 4 State transition map of KES data

Due to the fact described above, we cannot obtain bilateral relation between shape and force of a cloth but only a unilateral relation between them with a specific history of manipulation from each kind of the KES data. Let us denote a state of a cloth with curvature κ and moment τ in the KES data for bend by $st = (\kappa, \tau)$. In the KES measurement for bend, the moment to bend the cloth is not controlled but only the curvature of the specimen is controlled. The KES data obtained by this history of manipulation describes that $st_2 = (\kappa_2, \tau_3)$ is reached when the curvature is increased from κ_1 to κ_2 after $st_1 = (\kappa_1, \tau_1)$ is realized. However, there is no guarantee that the same st_2 is reached when moment is increased from τ_1 to τ_3 after st_1 is realized, because innumerable states including st_2 and $st_3 = (\kappa_4, \tau_3)$ are possible for τ_3. The same discussion is possible for the KES data for the other kinds of properties.

3. New Approach to Simulate Force Together with Shape

In this paper, we propose an approach to employ the KES data for simulating shape and force generated by the cloth, given the positions and external forces at manipulation points. The KES data for bend gives unilateral relations from shape to force of a cloth: the moment(force) generated by the cloth against controlled bend(shape). On the other hand KES data for stretch describes the relation from force to shape: stretch (shape) of the cloth in a controlled history of external force. Thus we employ the KES data for stretch and bend because we aim to consider different kinds of unilateral relations between shape and force given by the KES data. Other properties can be employed as the similar manner as one of these two properties. In order to simulate both shape and force at the same time by considering unilateral relations of shape and force given by KES data for stretch and bend, we minimize the cost function that represents those unilateral relations of shape and force as well as their bilateral relations given by the Newton's law as shown in Fig.5.

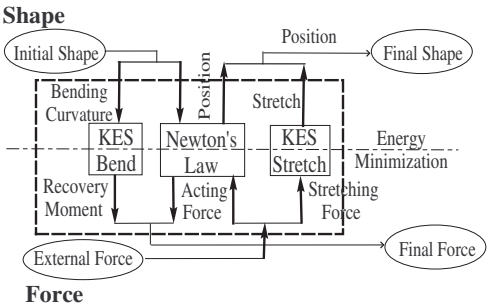

Fig. 5 Flow diagram of proposed method

It is also considered in our approach that KES data only describes the states transition in a specific history of manipulation. When the user manipulates the

cloth with the history different from the KES measurement, we cannot simply apply the KES data to simulate shape and force. However, it is impossible to obtain the data for that history by measuring a real cloth in advance because innumerable variations are possible for the user's manipulation of the cloth. In order to obtain the data for each possible histories of the states, we need to interpolate the KES data by considering that KES data serves as the boundary condition. That is, the interpolation data should coincide with the KES data when the history is same as the measurement of the KES data in order to maintain the consistency between the KES data and the interpolated data. Following this issue, we define cost function for the state of cloth with the minima corresponding to the inside of the KES curve satisfying the Newton's law, so that each point in the area surrounded by the KES curve is acceptable as a state of cloth.

Realization of hysteretic property requires that within the boundary condition, the interpolated state transition constitutes continuous sequence of states depending on each history of manipulation. To handle this property, we have to ensure that each state taken by cloth depends on its previous state as the result of previous manipulation. It means that model must have some internal variables to represent the previous state. Instead of including those variables, we represent the previous state by the initial values for minimization of the cost function. Since the optimization processes by usual iterative algorithm find the minimum closest to the initial values, the state of the cloth found by the process depends on the previous state by setting the initial value of the process to represent the previous state. The fact that the optimization only find a minimum closest to the initial value often causes a big problem in usual application of optimization because the process often reaches local minima. In those applications, it is important to set the "proper" initial value for each variable to be updated by the algorithm for avoiding the local minima. On the other hand in our case, different from those applications, all the states within the KES curve are acceptable though those may be local minima as far as Newton's law is satisfied. Thus, in our approach, function optimization is used not only to search the minimum of function but also to select the state most close to the previous state from all the states within the KES curve.

Based on above idea, when we simulate shape and force of a cloth under changing conditions in manipulation by the user, we set the initial value of cost function so that it corresponds to the previous state and minimize the function under the new condition given as the result of manipulation. This result will be again the initial value of the cost minimization under another new condition by further manipulation. In this procedure, the initial state for each minimization serves as the internal variable to realize hysteretic property of a cloth and continuous sequence of states depending on the history of manipulation is realized as the the result. This state transition coincides with the KES data when the history of manipulation is the same as the KES measurement. The Fig.6 describes possible sequence of states obtained from user manipulation and minimization. As long as the user's manipulation is same as that for KES measurement, which is the monotonic stretch or bend followed by monotonic recovery, minimized states coincide with the KES curve (Fig.6-a). When the user's manipulation differs from KES measurement, a continuous sequence of states that interpolates the inside of the KES curve based on the history of manipulation is achieved as a result of this procedure (Fig.6-b).

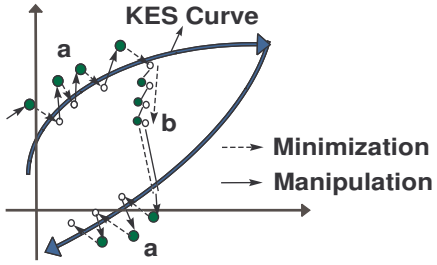

Fig. 6 Sequence of manipulation and minimization

4. Simulating Shape and Force

4.1 Particle Model

We represent a piece of cloth as a 2D rectangular grid of $I \times J$ particles in 3D space as shown in Fig. 7(a). Each particle represents a crossing point of warp and weft threads and denoted by $P_{ij}(1 \leq i \leq I, 1 \leq j \leq J)$. Particle P_{ij} possesses mass M, position $\mathbf{X}_{ij}$, acceleration $\mathbf{a}_{ij}$, velocity $\mathbf{v}_{ij}$ and total force $\mathbf{F}_{ij}$ acting on it. The average acceleration and average velocity for a particle P_{ij} at time t are defined as

$$\mathbf{a}_{ij}(t) = \frac{\mathbf{X}_{ij}(t) - 2\mathbf{X}_{ij}(t-\Delta t) + \mathbf{X}_{ij}(t-2\Delta t)}{\Delta t^2}$$

$$\mathbf{v}_{ij}(t) = \frac{\mathbf{X}_{ij}(t) - \mathbf{X}_{ij}(t-\Delta t)}{\Delta t}$$

where Δt is the time interval.

Each pair of adjacent particles along warp or weft direction P_{ij} and P_{kl} forms an edge $Edge_{ijkl}$. Each edge describes tensile property between the pair of particles. The length of the $Edge_{ijkl} = Edge_{klij}$ is denoted by $L_{ijkl} = L_{klij} = ||\mathbf{X}_{kl} - \mathbf{X}_{ij}||$ and unit vector along the edge direction is defined by $\mathbf{U}_{ijkl} = (\mathbf{X}_{kl} - \mathbf{X}_{ij})/L_{ijkl}$. The amount of the tensile force to recover against stretch from natural length Lo is denoted by $f^s_{ijkl} = f^s_{klij}$. The tensile force applied to particles P_{ij} and P_{kl} are represented by $\mathbf{f}^s_{ijkl} = f^s_{ijkl}\mathbf{U}_{ijkl}$ and $\mathbf{f}^s_{klij} = f^s_{ijkl}\mathbf{U}_{klij}$ respectively (see Fig. 7(b)).

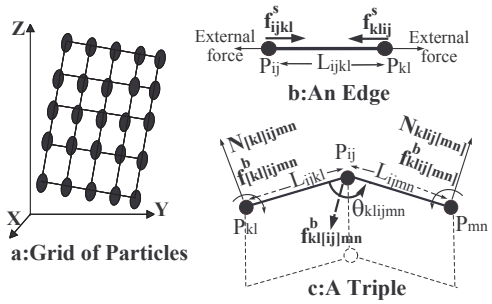

Fig. 7 Model of cloth

Three adjacent particles along weft or warp direction P_{kl},P_{ij} and P_{mn} constitute a triple $Triple_{klijmn} = Triple_{mnijkl}$. Bending curvature $\kappa_{klijmn} = \kappa_{mnijkl}$ for a triple is evaluated by the angle formed by the two segments joining the particles P_{kl}, P_{ij} and P_{mn} as shown in the Fig. 7(c).

$$\kappa_{klijmn} = \sqrt{\frac{4(1-COS^2)}{L^2_{ijkl} + L^2_{ijmn} - 2L_{ijkl}L_{ijmn}COS}}$$

where $COS = \cos(\theta_{klijmn})$ and $\theta_{klijmn} = \theta_{mnijkl}$ is the angle for $Triple_{klijmn}$.

$$\theta_{klijmn} = \cos^{-1}\left(\frac{\mathbf{X}_{kl} - \mathbf{X}_{ij}}{L_{ijkl}} \cdot \frac{\mathbf{X}_{mn} - \mathbf{X}_{ij}}{L_{ijmn}}\right)$$

The amount of the bending force to recover against bend for the $Triple_{klijmn}$ is denoted by $f^b_{klijmn} = f^b_{mnijkl}$. The bending force applied to particles P_{kl} and P_{mn} are represented as $\mathbf{f}^b_{[kl]ijmn} = f^b_{klijmn}\mathbf{N}_{[kl]ijmn}$ and $\mathbf{f}^b_{klij[mn]} = f^b_{klijmn}\mathbf{N}_{klij[mn]}$, and reaction force acting at P_{ij} is $\mathbf{f}^b_{kl[ij]mn} = -(\mathbf{f}^b_{[kl]ijmn} + \mathbf{f}^b_{klij[mn]})$ (see Fig. 7(c)). The $\mathbf{N}_{[kl]ijmn} = \mathbf{U}_{ijkl} \times (\mathbf{U}_{ijkl} \times \mathbf{U}_{ijmn})$ and $\mathbf{N}_{klij[mn]} = (\mathbf{U}_{ijkl} \times \mathbf{U}_{ijmn}) \times \mathbf{U}_{ijmn}$ are the unit normal vectors at particles P_{kl} and P_{mn} respectively. The bending moment generated in $Triple_{klijmn}$ is defined as follows:

$$\tau_{klijmn} = \tau_{mnijkl} = ||\mathbf{f}^b_{[kl]ijmn} \times L_{ijkl}\mathbf{U}_{ijkl} - \mathbf{f}^b_{klij[mn]} \times L_{ijmn}\mathbf{U}_{ijmn}||$$

The total force acting on each particle is sum of the all forces applied to a particle.

$$\begin{aligned}\mathbf{F}_{ij} &= \mathbf{f}^s_{ij(i+1)j} + \mathbf{f}^s_{ij(i-1)j} + \mathbf{f}^s_{iji(j+1)} + \mathbf{f}^s_{iji(j-1)} \\ &+ \mathbf{f}^b_{[ij](i+1)j(i+2)j} + \mathbf{f}^b_{(i-2)j(i-1)j[ij]} + \mathbf{f}^b_{[ij]i(j+1)i(j+2)} \\ &+ \mathbf{f}^b_{i(j-1)i(j-2)[ij]} + \mathbf{f}^b_{(i-1)j[ij](i+1)j} + \mathbf{f}^b_{i(j-1)[ij]i(j+1)} \\ &+ \mathbf{f}^{ext}_{ij} + M\mathbf{g}\end{aligned}$$

where $\mathbf{F}^{ext}_{ij}$ and $M\mathbf{g}$ are external force and gravitational force acting on P_{ij} respectively.

It is to be noted that only the variables $\mathbf{X}_{ij}, f^b_{klijmn}$ and f^s_{ijkl} are the independent variables and all other variables are function of theses variables.

4.2 Cost Function for Bend

The KES data for bend describes the moment for the controlled history of bending curvature. There are two possible moments $\Phi_f(\kappa)$ and $\Phi_r(\kappa)$ as function of curvature κ but inverse $\Phi_f^{-1}(\kappa), \Phi_r^{-1}(\kappa)$ is not defined. KES measurement is considered as an extreme history of manipulation as discussed in section 3. and KES data gives extreme values for κ. It means that possible values of moment should be in between these two extreme values depending on history of manipulation. Thus, in our model the amount of violation from this requirement is represented by a cost function for each $Triple_{klijmn}$ as follows:

$$\begin{aligned}E^b_{klijmn} = E^b_{mnijkl} = [1/2\{&|\Phi_f(\kappa_{klijmn}) - \tau_{klijmn}| \\ &+ |\Phi_r(\kappa_{klijmn}) - \tau_{klijmn}| \\ &- |\Phi_r(\kappa_{klijmn}) - \Phi_f(\kappa_{klijmn})|\}]^2\end{aligned}$$

The total cost function for bend due to all triples along warp and weft direction is given below:

$$E^b = \sum_{Triple_{klijmn}} E^b_{klijmn}$$

4.3 Cost Function for Stretch

The KES data for stretch gives the stretch for external force to stretch the cloth. The KES data draw a closed loop curve in the graph and two possible stretch $\Psi_f(F^{tns})$ and $\Psi_r(F^{tns})$ are given for each amount of the external force F^{tns}. Similar to the cost function for bend, we define cost function to represent the amount of violation of the requirement that the stretch of each $Edge_{ijkl}$ must be in between the two extreme values given by KES data, as follows:

$$E^s_{ijkl} = E^s_{klij} = [1/2\{|\Psi_f(F^{tns}_{ijkl}) - S_{ijkl}|$$
$$+|\Psi_r(F^{tns}_{ijkl}) - S_{ijkl}|$$
$$-|\Psi_r(F^{tns}_{ijkl}) - \Psi_f(F^{tns}_{ijkl})|\}]^2$$

where $S_{ijkl} = S_{klij} = \dfrac{L_{ijkl} - L_o}{Lo}$ is the stretch generated in $Edge_{ijkl}$. The amount of external force to stretch the edge is represented as follows:

$$F^{tns}_{ijkl} = \frac{(\mathbf{F}_{ij} - \mathbf{f}^s_{ijkl}) \cdot \mathbf{U}_{klij} + (\mathbf{F}_{kl} - \mathbf{f}^s_{klij}) \cdot \mathbf{U}_{ijkl}}{2}$$

The total cost function for stretch due to all edges along warp and weft direction is given below:

$$E^s = \sum_{Edge_{ijkl}} E^s_{ijkl}$$

4.4 Cost Function for Newton's Law

The KES data describes unilateral relation between shape and force of a cloth. We introduce Newton's law as the general bilateral relation between the position of each particle P_{ij} and the force acting on it. This cost function is represented as the amount of force deviated from Newton's law at each particle and is defined as follows:

$$E^n_{ij} = (M\mathbf{a}_{ij} - \mathbf{F}_{ij})^2$$

The cost function due to all particles is given below:

$$E^n = \sum_{P_{ij}} E^n_{ij}$$

Since the cost functions E^b and E^s only represent unilateral relations between force and shape given by the KES data, it is not guaranteed that the bilateral basic relation between shape and force given by Newton's law is satisfied even if both of the two cost functions are minimized. The cost function E^n requires this basic bilateral relation by the Newton's law. While E^b and E^s are completely satisfied, the E^n becomes the only requirement of each particle constituting the cloth model. However, it does not cause the particle to move like free particles because they cannot move independently as far as the distance and angle between each pair or triple of the particles are constrained within a certain range given by the KES curve. Actually this range is not so wide, it is just 2% of stretch or 0.025 gf-cm/cm of bending moment.

4.5 Cost Minimization

In order to find the value of each variable defined in section 4.1 that minimize all the cost functions described in section 4.2-4.4, total cost E is defined by weighted sum of those cost functions.

$$E = C_b E^b + C_s E^s + C_n E^n$$

where C_b,C_s and C_n are weighting coefficients.

When the values of all variables of the model are given as a result of manipulation by the user, these values can be modified to satisfy the constraints described in section 4.2-4.4 by minimizing the total cost using an iterative algorithm.

The cost function E is a function of position of each particle $\mathbf{X}_{ij}$, the amount of tensile force f^s_{ijkl} acting on each $Edge_{ijkl}$ and the amount of bending force f^b_{klijmn} acting on each $Triple_{klijmn}$ generated by the cloth against stretch and bend. We employ the steepest descent method to update each of those variable as follows:

$$\mathbf{X}_{ij}(itt+1) = \mathbf{X}_{ij}(itt) - \alpha \left(\frac{\partial E}{\partial \mathbf{X}_{ij}}\right)_{itt}$$

$$f^b_{klijmn}(itt+1) = f^b_{klijmn}(itt) - \alpha \left(\frac{\partial E}{\partial f^b_{klijmn}}\right)_{itt}$$

$$f^s_{ijkl}(itt+1) = f^s_{ijkl}(itt) - \alpha \left(\frac{\partial E}{\partial f^s_{ijkl}}\right)_{itt}$$

where itt is the number of iteration and α is the step size.

Since this minimization technique searches the values of the variables that correspond to the minimum closest to the initial values. We can get a continuous sequence of the states of a cloth with the history of manipulation by the user, by repeating cost minimization preceded by the user's manipulation. As the result, the state of the cloth obtained in the optimization is not only constrained by the cost function but also by the previous state given by the initial value, and continuous state transition of the cloth is realized in spite that the cost functions E^b and E^s a little bit loosely constrain the acceptable states of the cloth.

5. Experimental Results

5.1 Reproducing the KES Data

As discussed in section 4, we aim to realize state transition of cloth that satisfies the following two conditions:

(I) The state transition coincides with the KES data when the history of manipulation is the same as the KES measurement, (II) Continuity: The state transition in any history of manipulation realizes a continuous sequence of states without going beyond the boundary states given by the KES data.

In order to verify whether our model actually shows state transition aimed above, we first simulate shape and force in the same manipulation of the KES measurement for stretch and bend. The calculated moment at each bending curvature and calculated stretch at each stretching force are shown by points on the KES data for comparison in the Fig. 8 and Fig. 9 respectively.

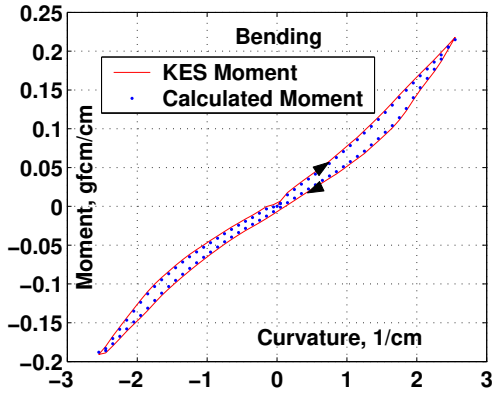

Fig. 8 Reproduced moment for wool

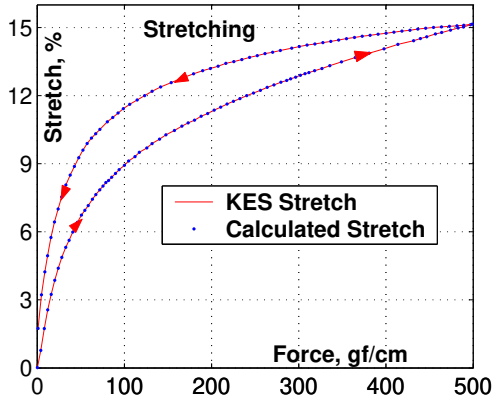

Fig. 9 Reproduced stretch for wool

In both of the experiments above, the calculated data matches the KES data very well. It shows that our model satisfies the boundary condition for the interpolation of the KES data.

5.2 State Transition under Arbitrary History of Manipulation

In order to verify the second condition (II) required for interpolation, we simulate shape and force under arbitrary history of manipulation.

A rectangular piece of cloth is used for experiment and a constant gravitational force $M\mathbf{g}$ is acting on each particle. One corner of the cloth is fixed and other three corners are used as manipulation points. Force applied to two corners is in up direction and those are moving up and one other corner is moving down under the external force. Some images taken during this experiments are shown in the Fig. 10. While the positions and the external force applied to the point are changed in various ways, the positions of the other particles and the force applied to them are calculated by the procedure discussed in section 4. Figure 11 shows the state of the external stretching force and the stretch for some representative edges. Similarly the state of the bending angle of each triple and moment generated by the cloth for some representative triples are shown Fig. 12. In above figures, solid continuous line represent the KES data and state transition lies around or within the KES data. The change of order of state for representative edges and triples is indicated by arrow.

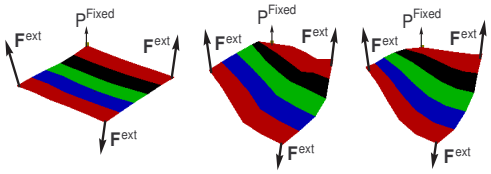

Fig. 10 Images during manipulation of cloth

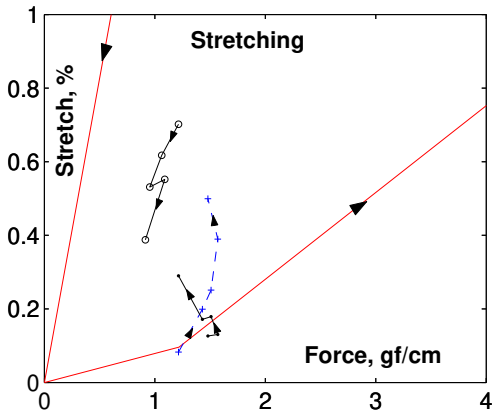

Fig. 11 State transition during manipulation for stretch

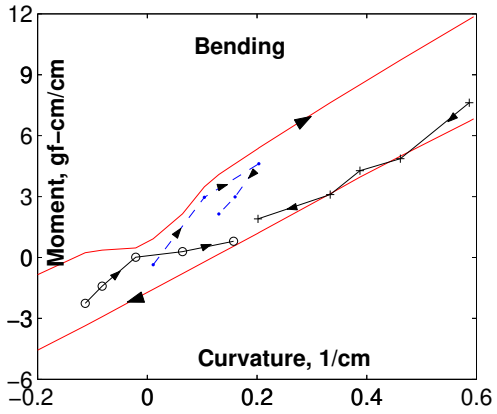

Fig. 12 State transition during manipulation for bend

Unlike KES measurement, the manipulation of this

experiment is not uniform for all the part of the cloth and each part is given different history of manipulation. The change of shape and force is not monotonic. Even if the same value is attained for one of the force and shape, different state is reached depending on the history. At the same time, the state transition for each part respectively traverses a continuous path within the closed loop of KES-curves. It shows that our model fulfills the second condition required for interpolation of the KES data.

6. Related Previous Work

6.1 Simulating Shape Based on the Data for Bend and Shear

Breen et al.[2] employ KES data for bending and shearing to simulate the shape of a cloth based on a model that represents a cloth as a grid of particles. The KES data for shearing give the same kind of unilateral relations from shape to force of a cloth as bending. That is, this work represents these unilateral relations by the functions that give force from shape and simulate the shape using only these functions without considering their inverse functions. That is, the moment against bend M_b and the force against shear F_{sh}, and are presented by the functions of bending angle and shearing angle. The shape is simulated by finding the positions of vertexes that minimize the bending energy and shearing energy together with gravitational energy defined by those functions (see Fig. 13).

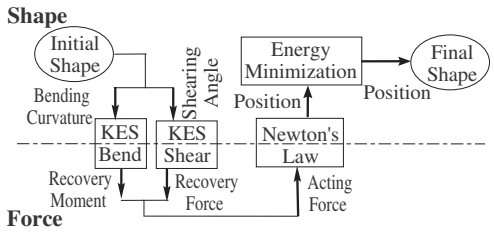

Fig. 13 Flow diagram of Breen's work

However, this approach is not directly applicable to simulate shape and force for visual and haptic feedback to the user who manipulates the cloth. When the user manipulates the cloth, external forces are given from the user to the cloth at manipulation points, and shape and force affected by the external force have to be simulated. However, this work only considers internal energy of the cloth to simulate the shape. In order to simulate the shape and force affected by the external force, the inverse relations from force to shape are needed, but they are not given by the KES for bending and shearing.

6.2 Simulating Shape Based on the Data for Bend and Stretch

Sakaguchi et al.[9] has simulated the shape of a cloth represented by a grid of particles based on the KES data for stretch and bend similar to our work. Considering the difference between the KES data for stretch and bend in the unilateral relation between shape and force of a cloth, shape is simulated in two phases (see Fig. 14). In first phase, the moment generated by the cloth at the initial shape is obtained from the KES data for bend, and position and force applying to each particle under the moment and the force of gravity are simulated based on the Newton's law. In this phase, KES data for stretch is not employed because it does not describes the relation from shape to force. In the second phase, the stretch of the cloth is obtained from the KES tensile data for the force achieved in the first phase by modifying the positions of particles so that those positions realize the stretch for that force. In this phase, KES data for bend is not employed because it does not describe the relation from force to shape.

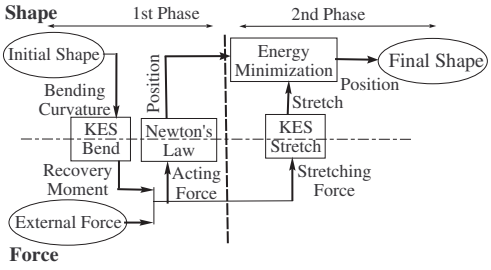

Fig. 14 Flow diagram of Sakaguchi's work

The above approach is quite useful to employ different kinds of unilateral relations between force and shape given by the KES data for stretch and bend. However, force can not be obtained in this work because shape of the cloth is modified to satisfy the KES data for stretch in the second phase, and similar to Breen[2] relation from shape to force described by the KES data for bend is not satisfied in the result.

Different from these two works, our work simulates shape together with force at the same time and considers that KES data describe state transitions for specific history of manipulation.

7. Conclusion and Future Work

In this paper, we proposed a model of a cloth to simulate both shape and force based on the KES data. The KES data describes unilateral relations between

shape and force. Those relations are represented by cost functions so that shape and force satisfying the relation can be found without using the inverse relation by minimizing the cost function. Representation of the cost functions considers that the KES data describes the state transition in the extreme history of manipulation. The KES data is employed as the boundary condition for the state transition of the cloth. The cost functions represent the all unilateral relations between shape and force based on the boundary condition given by the KES data as well as the bilateral relation given by the Newton's law. By minimizing the cost functions all of these relations are always maintained between shape and force during their simulation for the manipulation of a cloth. Different continuous state transitions within the boundary condition depending on the history of manipulation are realized.

Although we employed the KES data for stretch and bend, other properties like shear can be included. These factors can be considered as future targets.

Our model simulates force together with shape of a cloth, yet the simulated force is not currently presented to the user by a force feedback device, such as PHANToM[11]. We need to develop an environment for interactive manipulation of a cloth with visual and haptic feedback by introducing such devices.

When we apply our approach to the interactive manipulation of a cloth by the user, it is also important to realize real time simulation. Similar to the previous work on cloth simulation based on cost/energy minimization, it takes a long time for minimization. This problem becomes more serious when the number of particles increases. Since the cost function is defined by local relations between particles, it is easy to execute the cost minimization at each particle in parallel way. We plan to develop parallel minimization algorithm in future.

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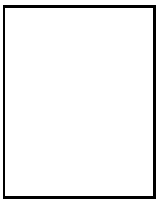

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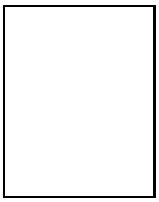

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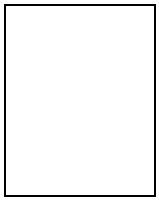

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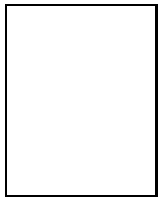

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