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ORIGINAL ARTICLE

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From measured physical parameters to the haptic feeling of fabric

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Abstract Abstract real-time cloth simulation involves the solution of many computational challenges, particularly in the context of haptic applications, where high frame rates are necessary for obtaining a satisfactory tactile experience. In this paper, we present a real-time cloth simulation system that offers a compromise between a realistic physically-based simulation of fabrics and a haptic application with high requirements in terms of computation speed. We place emphasis on architecture and algorithmic choices for obtaining the best compromise in the context of haptic applications. A first implementation using a haptic device demonstrates the features of the proposed system and leads to the development of new approaches for haptic rendering using the proposed approach.

Keywords Haptics · Force feedback · Real-time · Cloth-simulation · Elastic deformation

1 Introduction

Realistic haptic integration requires the combination of computationally-intensive mechanically realistic simulation with hardware devices that need to be controlled through high-frequency control loops for producing smooth feedback of the contact with virtual objects.

In the context of the HAPTEX European project [24], the goal is to reproduce accurately the haptic and tactile feeling of various cloth materials. This challenging goal involves new advances in three fields:

- The design of a new simulation model that can simulate the anisotropic and nonlinear mechanical properties of various cloth materials in real-time, particularly suited for reproducing the dynamic motion of cloth.
- The design of new haptic devices and control schemes that allow multi-finger interaction with a virtual piece of cloth, with realistic force feedback.
- The design of new tactile devices for reproducing precisely the texture of cloth on the fingers.

The aim of this paper is to focus on the mechanical simulation aspect, and address the issues that are related to the integration of accurate mechanical simulation with the requirement of accurate rendering of the force feedback of haptic devices.

1.1 Haptics and mechanical simulation

The haptic simulation of fabrics involves two aspects of the mechanical behavior of cloth materials. The first one is a high-level consideration of the "feeling" of touching and grasping fabrics, which is called "fabric hand" [16]. The other results from low-level quantitative measurements of the physical properties of the fabric, usually through tensile and bending strain-stress experiments, from which a quantitative characterization of the mechanical behavior that may be used directly in a simulation system is extracted. The relationships between these two aspects are not obvious, and this is why a direct relationship between mechanical parameters and haptic feedback has to follow the entire road of low-level mechanical simulation from which haptic force feedback is extracted.

Accurate real-time simulation of cloth requires advanced simulation schemes in order to be carried out at speeds that are compatible to real-time applications. This is a first issue that is discussed in Sect. 2.

However, while in graphics a refresh rate of 30 frames per second is quite acceptable for a graphical output, correct haptic rendering requires a response frequency of at least 500 Hz, which cannot be reached with mechanical simulation schemes that have to deal with large pieces of material. A good approach for addressing this issue in the context of virtual reality systems is to consider a multilayer architecture for driving simultaneously a large-scale simulation that computes the coarse shape of the whole object with possibly low frame rates that are acceptable for display, with a small scale model that computes the actual shape of the object near the haptic contact points at frequencies that are compatible with haptic rendering [2]. This issue will be discussed in Sect. 3.

1.2 Related work

Cloth simulation has been done for some time in the context of computer graphics, and several simulation schemes now exist, which range from simple spring-mass particle systems to highly accurate, but very slow finite element methods.

An exhaustive overview of the state-of-the-art in cloth animation research is given by [17]. In recent years, several research activities have been carried out in the field of cloth simulation, focusing on different aspects ranging from physical based models [6, 7] to integration schemes [3, 14] and collision response [4, 26].

Particle systems are the most popular schemes for designing fast simulation systems without resorting to excessively complicated algorithms. These schemes represent the cloth surface as a set of vertices (typically the vertices of a mesh) that interact through each other through forces that represent the mechanical behavior of the cloth and are computed from the relative position of the particles. This leads to a large differential system that has to be numerically integrated along time using advanced numerical methods. These might be explicit, such as the popular Runge–Kutta methods, which offer high accuracy and simple implementation at the price of slow computation, mostly because of the small time steps required for preserving stability. A more efficient alternative is to use implicit integration methods, which offer high stability for large time steps at the price of more inaccuracy and the need for complex algorithms (the resolution of large sparse linear systems using the Jacobian of the forces). The semi-implicit backward Euler method was initially used by Baraff et al. [3] in the context of cloth simulation and since then many variations of semi-implicit integration methods (implicit midpoint, backward differential formula...) have been widely used for cloth animation, as they provide better results in terms of stability and speed compared to other integration schemes [25].

When modeling cloth with particle systems, the simplest system one can think of is a spring-mass system. In this scheme, the only interactions are forces exerted between neighboring particle couples, similarly as if they were attached by springs (described by a force/elongation law along its direction, which is actually a rigidity coefficient and a rest length in the case of linear springs) [10]. Spring-mass schemes are very popular methods, as they allow simple implementation and fast simulation of cloth objects. There has also been recent interest in this method as it allows quite a simple computation of the Jacobian of the spring forces, which is needed for implementing semi-implicit integration methods.

The simplest approach is to construct the springs along the edges of a triangular mesh describing the surface. This, however, leads to a very inaccurate model that cannot accurately describe the anisotropic strain-stress behavior of the cloth material, nor can it accurately describe the bending. More accurate models are constructed on regular square particle grids describing the surface. While the elongation stiffness is modeled by springs along the edges of the grid, the shear stiffness is modeled by diagonal springs, and the bending stiffness is modeled by leap frog springs along the edges (Fig. 1). This model is still fairly inaccurate because of the unavoidable cross-dependencies between the various deformation modes relative to the corresponding springs. It is also inappropriate for nonlinear elastic models and large deformations. More accurate variations of the model consider angular springs rather than straight springs for representing shear and bending stiffness, but the simplicity of the original spring-mass scheme is then lost. The model detailed in Sect. 2 alleviates these issues by combining the simplicity and speed of particle systems with the accuracy of a model that evaluates strain and stress on the true deformed surface of cloth.

More accurate approaches intend to simulate the real deformation of the surface by expressing the equations of continuum mechanics that express the deformation energy relative to its deformation. Such accurate schemes are, however, slow and not sufficiently versatile for handling large deformations and complex geometrical constraints

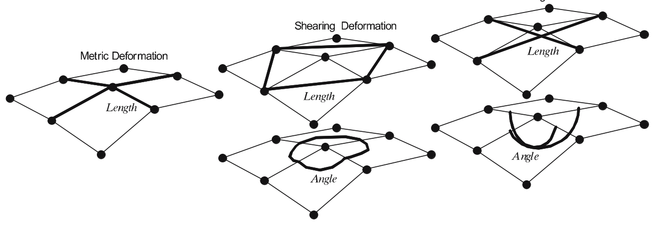

Fig. 1. Using length or angle springs for simulating cloth with a square particle system grid

(collisions) properly. Among them, finite element methods express the mechanical equations according to the deformation state of the surface within well-defined elements (usually triangular or quadrangular). Their resolution also involves large computational costs [12].

In the context of our project, we indeed need a quantitatively accurate representation of the nonlinear and anisotropic properties of cloth, which cannot be reached through spring-mass systems. In Sect. 2, we propose an accurate model that combines the accuracy of continuum-based methods with the speed and versatility of particle systems, which includes the use of very efficient numerical methods that enable real-time performance.

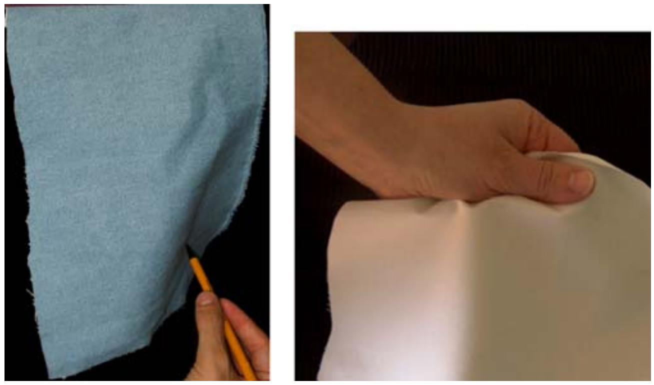

Fig. 2. Real counterpart: point and full hand interaction

1.3 Toward haptic rendering of textiles

Haptic rendering algorithms are responsible for reproducing the forces acting on the simulated objects and transmit them to the haptic interface. In the case of static, non-deformable objects, the computation of these forces is limited to reproducing the object's stiffness according to the user's position and interaction speed. When simulating dynamic deformable surfaces such as textiles, however, this issue grows in complexity, as the simulated surface has its own behavior, which influences the haptic feedback and, therefore, has to be taken into consideration.

There has been very little research on the haptic rendering of textiles so far [9, 13, 15]. In all cases, projects dealing with haptic perception of textiles targeted very specific scenarios and were severely limited in terms of visual rendering (no real-time animation), used hardware (low-cost commercial products or expensive ad-hoc devices) or targeted realism (static, nondeformable textiles).

A system that provides both force feedback and tactile perception of virtual textiles through a haptic device, and is synchronized with a real-time, physical based graphical simulation of the fabric has not been developed yet. The finality of what is proposed is to reproduce in a virtual environment the following experience: touching a piece of fabric with a small area of contact first and then with the full hand (Fig. 2).

To achieve this challenging goal, several advances in all related fields are necessary: from the techniques of fabric measurement to the development of novel haptic devices and the improvement of physical based models for real-time cloth simulation.

1.4 Measuring the mechanical properties of fabrics

Haptic interaction with virtual objects is instinctively and unavoidably compared to everyday interaction with real objects. End users dealing with visuo-haptic simulation applications are confronted with a multimodal system that stimulates both the sense of vision and the sense of touch. To achieve a realistic correlation between what is already known in reality and what is simulated in VR, we use real physical properties of fabrics to simulate the virtual counterpart. To obtain these fabric properties, we use objective measurement methods stemming from the textile research area and well-adapted for the specific needs of computer simulation.

In the textile/apparel industry, the evaluation of the quality of a fabric or a yarn is generally called "fabric hand" [16], and can be performed either by textile experts (subjective evaluation) or by specific textile measuring devices (objective evaluation). From all definitions of this term in the literature, where it is referred to, e.g., as "the tactile sensations or impressions which arise when fabrics are touched, squeezed, rubbed or otherwise handled" [1], it is evident that the sense of touch is fundamental for the assessment of fabric hand. Nonetheless, other senses also have an important influence on the evaluation of fabric hand, and in particular the sense of vision [5].

To simulate the visuo-haptic behavior of textiles it is, therefore, of great importance to analyze the objective methods used for assessing fabric hand, and identify which properties of a fabric can be considered most relevant for its visuo-haptic evaluation.

An objective assessment of fabric hand is achieved through hardware equipment, such as the Kawabata evaluation system for fabrics (KES-F) or tensile testers. This equipment is able to test for textile properties by extracting the strain-stress curves for, e.g., weft and warp elongation, shear deformation, bending, pressure-thickness, surface friction and surface roughness. The values of the extracted parameters vary depending on the fiber type or fabric type and dimension. However, for the specific needs of virtual simulations, where we need information on nonlinear fabric properties, we are not interested in the fabric hand parameters themselves, but rather in the measured load/unload envelopes. Typical output curves of the KES-F System for weft/warp elongation of a fabric are depicted in Fig. 3.

The KES-F measurement standard is defined to record the behavior of one fabric at only one load, whereas during

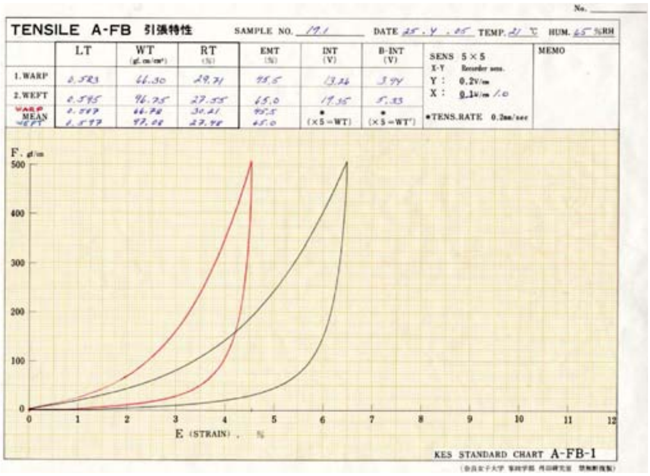

Fig. 3. Strain–stress curve from KES-F tensile test

dynamic simulation different intense forces occur. Hence, multiple load/unload experiments with different applied forces are necessary for an accurate derivation of mechanical parameters for dynamic simulations. To better study the fabric behavior at different forces, we have performed some additional measurements with tensile testers. Our empirical studies have resulted in a measuring procedure that reflects more the properties of worn garments: samples are elongated at slow deformation rate to get a good view of the behaviour of the fabric for small forces and deformations, typical for when a garment is worn. Our "step tensile" test measures the fabric in five step tensile loops with progressive amplitude. Figure 4 shows the output of these measurements.

As mentioned before, the values of the parameters are not sufficient for modeling the actual nonlinear behavior of the material, and we take into consideration the whole load/unload envelope instead. We exploit directly the measured strain-stress curves, modeling them as polynomial splines. Other parameters, such as the viscosity or the aerodynamic damping required for modeling the dissipative behavior of cloth during animation, cannot be

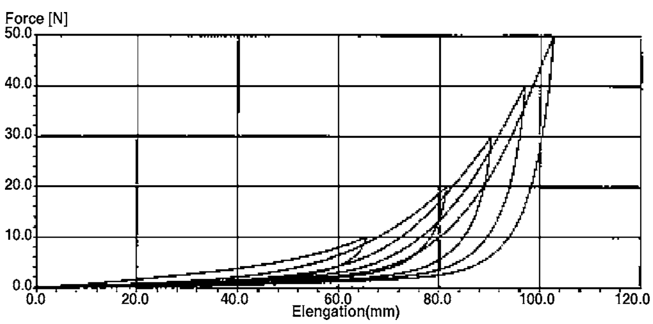

Fig. 4. Strain–stress curve from KES-F tensile test

measured using available testing hardware and need to be defined empirically.

The data obtained from the described measurements on fabrics serves as an input to the mechanical model driving our real-time cloth simulation system described in part 2, and can be used for the haptic feedback as described in part 3. This data flow can be seen as a digitalization of cloth: it is thanks to this chain of events that we get from measured physical parameters to the haptic feeling of fabrics.

2 A mechanical model for real-time cloth simulation

Modeling the behavior of textiles is a complex task because it depends on a large number of parameters such as tensile and bending elasticity and viscosity, compressibility, resilience, density, surface contour (roughness, smoothness), surface friction and thermal characteristics [18]. For large-scale simulation, many of these characteristics can be ignored, since our aim is to obtain the whole shape of the cloth object with decent realism down to centimeter-size details. Hence, fabrics are approximated as thin 2D surfaces, represented through a mesh of centimeter-size triangles. We can thus avoid taking into consideration thickness and compressibility, surface friction and surface roughness.

2.1 Key techniques for real-time cloth simulation

The most important challenge is to simulate in real-time cloth materials that are accurately described by nonlinear anisotropic mechanical models (weft, warp and shear strain-stress curves).

Most existing real-time simulation systems consider drastic simplifications in the mechanical model (isotropic linear elasticity) and even change the mechanical nature of the material (for example, reduce stiffness by simulating very deformable materials) for achieving more computation speed. However, our application requires the simulation of precise mechanical behavior of cloth.

Leaving from traditional grid-based spring-mass approaches, we propose a very accurate particle system that reaches the accuracy of first-order nonlinear finite elements while retaining the simplicity of particle systems. This model uses a fast computational method for evaluating precisely the strain state of a triangle of the cloth surface, and may then turn the corresponding stress back into particle forces.

Real-time constraints, however, impose a severely limited complexity of the mechanical system. Here are the main simplifications that we consider:

- Simulation of a coarse grid typically limited to a thousand triangle elements. What matters for the computation time is not only the number of elements to be computed, but also the size of these elements (the smaller they are, the stiffer the numerical system will be). In practice, we will consider about centimeter-size elements.

- Neglecting bending stiffness. The bending stiffness is usually very low in usual fabric materials, and it usually does not make any sense to simulate bending effects producing millimeter wrinkles with centimeter-size mesh elements. Bending properties are also quite costly to compute.
- Not performing self-collision within the cloth. Self-collision techniques are usually quite costly in computational resources, and processing the detected collisions is also complex. Given the simple context of our animation (a hanging piece of cloth), we restrict collision processing to detecting contacts between the cloth object and the haptic virtual fingertips.

Large simulation time steps should be considered for the numerical integration of the system, and this is obtained through the use of implicit numerical integration methods. This, however, slightly alters the dynamic behavior of the cloth (numerical damping). Experimental tests can help to find the best time steps producing animation of cloth objects with damping in par with the damping observed in real cloth materials.

2.2 Mechanical modeling of cloth

The mechanical behavior of cloth (approximated as a thin surface) is decomposed in in-plane deformations (the 2D deformations along the cloth surface plane) and bending deformation (the 3D surface curvature).

The tensile behavior of cloth is described by relationships relating, for any cloth element, the stress $\boldsymbol{\sigma}$ to the strain $\boldsymbol{\varepsilon}$ (for elasticity) and its speed $\boldsymbol{\varepsilon}'$ (for viscosity) according to the laws of viscoelasticity. For cloth materials, strain and stress are described relatively to the weave directions weft and warp following three components: weft and warp elongation (***uu*** and ***vv***), and shear (***uv***). Thus, the general viscoelastic behavior of a cloth element is described by strain-stress relationships as follows:

$$\begin{aligned}&\sigma_{uu}(\varepsilon_{uu}, \varepsilon_{vv}, \varepsilon_{uv}, \varepsilon'_{uu}, \varepsilon'_{vv}, \varepsilon'_{uv}) ,\\ &\sigma_{vv}(\varepsilon_{uu}, \varepsilon_{vv}, \varepsilon_{uv}, \varepsilon'_{uu}, \varepsilon'_{vv}, \varepsilon'_{uv}) ,\\ &\sigma_{uv}(\varepsilon_{uu}, \varepsilon_{vv}, \varepsilon_{uv}, \varepsilon'_{uu}, \varepsilon'_{vv}, \varepsilon'_{uv}) .\end{aligned} \tag{1}$$

Assuming that we are dealing with an orthotropic material (usually resulting from the symmetry of the cloth weave structure relative to the weave directions), there is no dependency between the elongation components (***uu*** and ***vv***) and the shear component (***uv***). Assuming a null Poisson coefficient as well (a rough approximation), all components are independent, and the fabric elasticity is simply described by three independent elastic strain-stress curves $\sigma_{uu}(\varepsilon_{uu})$, $\sigma_{vv}(\varepsilon_{vv})$, $\sigma_{uv}(\varepsilon_{uv})$ (weft, warp, shear), along with their possible viscosity counterparts.

In the same manner, viscoelastic strain-stress relationships relate the bending momentum to the surface curvature for weft, warp and shear. With the typical approximations used with cloth materials, the elastic laws are only two independent curves along weft and warp directions (shear is neglected), with their possible viscosity counterparts.

2.3 A fast and accurate particle system

Our initial goal is to design an efficient mechanical simulation scheme for simulating the large-scale behavior of the cloth.

Because of the real need for accurate representation of the anisotropic nonlinear mechanical behavior of cloth in applications, spring-mass models are inadequate, and we need to find a scheme that really simulates the viscoelastic behavior of actual surfaces. For this, we have defined a particle system model that relates this accurately over any arbitrary cloth triangle through simultaneous interaction between the three particles that are the triangle vertices. Such a model integrates directly and accurately any strain-stress model using polynomial spline approximations of the strain-stress curves, and remains accurate for large deformations.

2.3.1 Assumptions

Cloth is typically represented by curved surfaces composed of polygonal meshes, being either triangular or quadrangular, and regular or irregular. In order to enrich these geometrical surfaces with the above-mentioned mechanical properties, we need to define a specific mechanical model.

We consider the following constraints for designing the large-scale simulation system:

- The geometrical description of the cloth surface should be any triangular mesh.
- The mechanical properties of the cloth material is described by strain-stress curves, approximated analytically as independent piece-wise polynomial splines (weft, warp, shear).
- Bending stiffness is neglected, as it does not make sense to spend time computing accurately its very weak effect comparatively to the scale required for real-time simulation of the model (the size of the elements is much more likely to limit the sharpness of the wrinkle patterns than the bending stiffness of the cloth).

2.3.2 Description of the model

In this model, a triangle element of cloth is described by three 2D coordinates (***ua***, ***va***), (***ub***, ***vb***), (***uc***, ***vc***) describ-

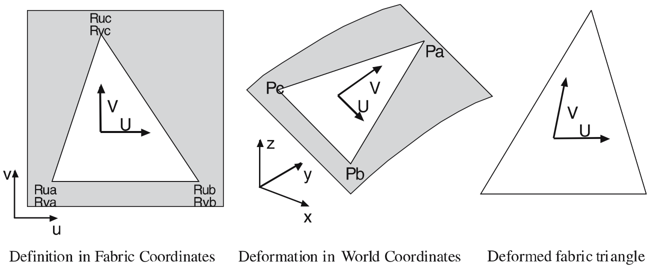

Fig. 5. A triangle of cloth element defined on the 2D cloth surface (*left*) is deformed in 3D space (center) and its deformation state is computed from the deformation of its weft-warp coordinate system (*right*)

ing the location of its vertices $\boldsymbol{A}$, $\boldsymbol{B}$, $\boldsymbol{C}$ on the weft-warp coordinate system defined by the directions $\boldsymbol{U}$ and $\boldsymbol{V}$ with an arbitrary origin. They are orthonormal on the undeformed cloth (Fig. 5). Out of them, a pre-computation process evaluates the following values:

$$\begin{aligned}
Rua &= d^{-1}(vb - vc) \quad Rva = -d^{-1}(ub - uc)\,,\\
Rub &= -d^{-1}(va - vc) \quad Rvb = d^{-1}(ua - uc)\,,\\
Ruc &= d^{-1}(va - vb) \quad Rvc = -d^{-1}(ua - ub)\,,
\end{aligned}$$

with

$$d = ua(vb - vc) + ub(vc - va) + uc(va - vb)\,. \tag{2}$$

During the computation process, the current deformation state of the cloth triangle is evaluated using the current 3D direction and length of the deformed weft and warp direction vectors $\boldsymbol{U}$ and $\boldsymbol{V}$. They are computed from the current positions $\boldsymbol{Pa}$, $\boldsymbol{Pb}$, $\boldsymbol{Pc}$ of its supporting vertices as follows:

$$\begin{aligned}
U &= Rua\ Pa + Rub\ Pb + Ruc\ Pc\,,\\
V &= Rva\ Pa + Rvb\ Pb + Rvc\ Pc\,.
\end{aligned} \tag{3}$$

The current in-plane strains ε of the cloth triangle are then computed with the following formula:

$$\begin{aligned}
\varepsilon_{uu} &= |U| - 1 \qquad \varepsilon_{VV} = |V| - 1\,,\\
\varepsilon_{uv} &= \frac{|U+V|}{\sqrt{2}} - \frac{|U-V|}{\sqrt{2}}\,.
\end{aligned} \tag{4}$$

We have chosen to replace the traditional shear deformation evaluation based on the angle measurement between the thread directions by an evaluation based on the length of the diagonal directions. The main advantage of this is a better accuracy for large deformations (the computation of the behavior of an isotropic material under large deformations remains more axis-independent).

For applications that model the internal in-plane viscosity of the material, the "evolution speeds" of the weave direction vectors are needed as well. They are computed from the current triangle vertex speeds $\boldsymbol{Pa}'$, $\boldsymbol{Pb}'$, $\boldsymbol{Pc}'$ as follows:

$$\begin{aligned}
U' &= Rua\ Pa' + Rub\ Pb' + Ruc\ Pc'\,,\\
V' &= Rva\ Pa' + Rvb\ Pb' + Rvc\ Pc'\,.
\end{aligned} \tag{5}$$

Then, the current in-plane strain speeds $\boldsymbol{\varepsilon}'$ of the triangle is computed:

$$\begin{aligned}
\varepsilon'_{uu} &= \frac{U \cdot U'}{|U|} \qquad \varepsilon'_{VV} = \frac{V \cdot V'}{|V|}\,,\\
\varepsilon'_{uv} &= \frac{(U+V)\cdot(U'+V')}{|U+V|\sqrt{2}} - \frac{(U-V)\cdot(U'-V')}{|U-V|\sqrt{2}}\,.
\end{aligned} \tag{6}$$

At this point, the in-plane mechanical behavior of the material can be expressed for computing the stresses $\boldsymbol{\sigma}$ out of the strains $\boldsymbol{\varepsilon}$ (elasticity) and the strain speeds $\boldsymbol{\varepsilon}'$ (viscosity) using the curves (1). Finally, the force contributions of the cloth triangle to its support vertices are computed from the stresses $\boldsymbol{\sigma}$ as follows:

$$\begin{aligned}
Fa &= -\frac{d}{2}\Bigg((Rua\,\sigma_{uu} + Rva\,\sigma_{uv})\frac{U}{|U|}\\
&\qquad + (Rua\,\sigma_{uv} + Rva\,\sigma_{vv})\frac{V}{|V|}\Bigg)\,,\\
Fb &= -\frac{d}{2}\Bigg((Rub\,\sigma_{uu} + Rvb\,\sigma_{uv})\frac{U}{|U|}\\
&\qquad + (Rub\,\sigma_{uv} + Rvb\,\sigma_{vv})\frac{V}{|V|}\Bigg)\,,\\
Fc &= -\frac{d}{2}\Bigg((Ruc\,\sigma_{uu} + Rvc\,\sigma_{uv})\frac{U}{|U|}\\
&\qquad + (Ruc\,\sigma_{uv} + Rvc\,\sigma_{vv})\frac{V}{|V|}\Bigg)\,.
\end{aligned} \tag{7}$$

It is important to note that when using semi-implicit integration schemes, the contribution of these forces in the Jacobian $\partial \boldsymbol{F}/\partial P$ and $\partial \boldsymbol{F}/\partial \boldsymbol{P}'$ can easily be computed out of the curve derivatives $\partial\boldsymbol{\sigma}/\partial\boldsymbol{\varepsilon}$ and the orientation of the vectors $\boldsymbol{U}$ and $\boldsymbol{V}$.

2.3.3 Numerical integration

The equations resulting from the mechanical formulation of particle systems usually express particle forces $\boldsymbol{F}$ depending on the state of the system (particle positions $\boldsymbol{P}$ and speeds $\boldsymbol{P}'$). In turn, particle accelerations $\boldsymbol{P}''$ are related to particle forces $\boldsymbol{F}$ and masses $\boldsymbol{M}$ by Newton's second law of dynamics. This leads to a second-order ordinary differential equation system, which is turned to first-order by concatenation of particle position $\boldsymbol{P}$ and speed $\boldsymbol{P}'$ into a state vector $\boldsymbol{Q}$. A vast range of numerical methods for solving this kind of equations has been studied.

The most widely-used method for cloth simulation is currently the semi-implicit backward Euler method, which was first used by Baraff et al. [3] in the context of cloth simulation. As any implicit method, it alleviates the need of high accuracy for the simulation of stiff differential equations, offering convergence for large time steps rather than numerical instability (a step of the semi-implicit Euler method with "infinite" time step is actually equivalent to an iteration of the Newton resolution method) [6]. Many variations of this method are available, through various computational simplification approaches [7, 8, 19].

The formulation of a generalized implicit Euler integration is the following:

$$Q_{(t+\mathrm{d}t)} - Q_{(t)} = Q'_{(t+\alpha\,\mathrm{d}t)}\,\mathrm{d}t\,. \tag{8}$$

The derivative value is not known at a moment after $\boldsymbol{t}$, and is then extrapolated from the value at moment $\boldsymbol{t}$ using the Jacobian, leading to the semi-implicit expression that requires the resolution of a linear system:

$$Q_{(t+\mathrm{d}t)} - Q_{(t)} = \left(I - \alpha \frac{\partial Q'}{\partial Q_{(t)}}\,\mathrm{d}t\right) Q'_{(t)}\,\mathrm{d}t\,. \tag{9}$$

We have introduced the coefficient $\boldsymbol{\alpha}$ so as to modulate the "implicity" of the formula [27]. Hence, $\boldsymbol{\alpha} = 1$ is the regular implicit backward Euler step (stable), whereas $\boldsymbol{\alpha} = 0$ is the explicit forward Euler step (unstable), and $\boldsymbol{\alpha} = 1/2$ is the second-order implicit midpoint step (the most accurate, at the threshold of stability).

The $\boldsymbol{\alpha}$ parameter is a good lever for adjusting the compromise between stability and accuracy. While maximum robustness is obviously observed for large values, reducing its value increases accuracy (this reduces numerical damping) at the expense of stability, and speeds up the computation as well (better conditioning of the linear system to be resolved). Hence, for our real-time application, we can modulate this value according to the simulation and interaction requirements to offer the best accuracy and robustness. The requirement of high robustness of haptic applications also makes higher-order methods [11, 14] less adequate.

3 Haptic rendering

Haptic rendering of deformable surfaces has raised a lot of interest in recent years due to the large range of applications that it might allow, such as simulation of medical tissues for medical training or interaction with textiles in our case.

We propose here a first implementation of a point based interaction to raise some limitations and then propose solutions. Limitations addressed concerns the discontinuities that arise in the haptic rendering. Screenshots of the results obtained can be seen in Fig. 6.

Fig. 6. Screen shot of the deformed surface

Among the methods for computing the force to be sent to the haptic device, we used the proxy paradigm described by Ruspini et al. [22] and Zilles et al. [28]. This method is best suited to the case of point based interaction. The force is computed by detecting and generating responses from the collision between the haptic cursor and the surface.

First we see the mechanisms to compute the force, then we describe the collision detection process and finally we put emphasis on the use of physically based haptic rendering.

3.1 Proxy-based method

With the paradigm of point based interaction, the proxy-based method was used. It basically consists of the process described below. At the moment when a collision occurs, the HIP (haptic interface point) penetrates the surface and the IHIP (ideal haptic interface point) is forced to stay on the surface. Then the force sent to the haptic device is computed based on the relative position of the HIP and the IHIP, as it can be seen in Fig. 7. It can be computed from the laws of Hooke and Coulomb [23].

However, since the computation of the force is based on the simulated surface, the discrete nature of the textile will be noticed. Then to solve this first limitation we propose to use the force shading introduced by Morgenbesser et al. [21].

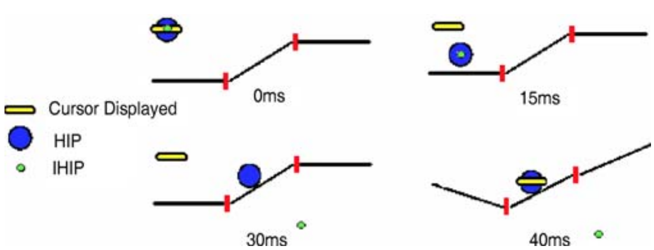

Fig. 7. Penetration of the haptic cursor with the update process of the IHIP position

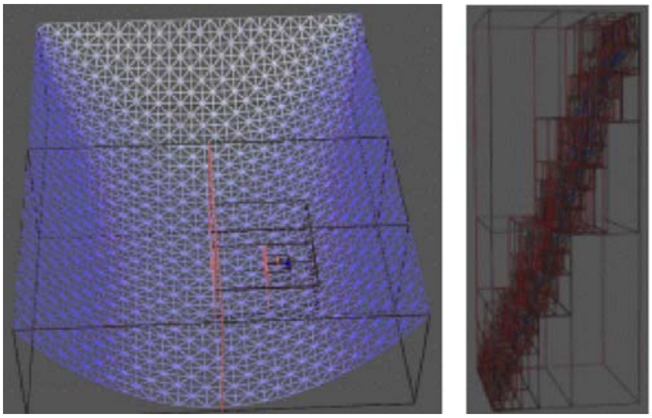

Fig. 8. List of touched boxes and the full hierarchy of bounding boxes.

3.2 Collision processing

To detect the collision between the surface and the haptic cursor, at first the region in a neighborhood of the point is computed. Then the exact collision can be determined for the set of triangles in this region of interest using the well-known algorithms of segment to triangle collision detection query.

The first task is performed through an adapted bounding-volume hierarchy algorithm, which uses a constant discrete-orientation-polytope hierarchy constructed on the mesh [20, 26]. The haptic cursor is itself embedded in a polytope, and collision detection is done through traversal of the colliding nodes of the hierarchy as can be seen in Fig. 8.

A second mandatory step to catch all collisions is to use dynamic collision detection. Indeed, two threads run in this model, one graphic thread running at 30 Hz and one haptic thread running at 1 kHz. Then synchronization between those two threads is required to properly catch the collisions. However, discontinuity of the force sent since the transition between two consecutive steps from the simulation model will be noticed. To solve this limitation, we propose to smooth the transition by interpolating the force sent during the synchronization.

3.3 Integration of physical measurements

In order to offer a compelling haptic rendering for the simulation of textiles, physical measures should be used to compute the force sent. We plan to use the measure of friction, roughness and stiffness acquired from the Kawabata tests to set the haptic rendering.

4 Conclusion

Achieving a convincing virtual textile simulation requires that a good compromise be reached between the need for accuracy in the material representation and the need for speed for obtaining visually realistic simulation frame rates compatible with real-time perception. Both factors were considered in the development of a mechanical model that combines accurate representation of nonlinear cloth material properties with state-of-the-art numerical integration techniques. Using this system, the nonlinear cloth strain–stress behaviour extracted from experimental data could be accurately considered. Meanwhile, efficient collision processing technologies were implemented to offer a quick computation of the cloth behaviour near the haptic interaction point, allowing synchronization between the simulation loop and the haptic rendering loop.

The ultimate goal of this framework is to complete this integration through tactile devices that should bring to the perception of the fabric a new level of accuracy.

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References

1. AATCC COMMITTEE RR89: Fabric Hand: Guidelines for the Subjective Evaluation. AATCC Evaluation Procedure **5** (2001)
2. Astley, O.R., Hayward, V.: Multirate haptic simulation achieved by coupling finite element meshes through Norton equivalents. In: Proceedings of IEEE International Conference on Robotics and Automation, vol. 2, pp. 989–994 (1998)
3. Baraff, D., Witkin, A.: Large steps in cloth simulation. Comput. Graph., Ann. Conf. Ser. **32**, 43–54 (1998)
4. Baraff, D., Witkin, A., Kass, M.: Untangling cloth. ACM Trans. Graph. (Proceedings of ACM SIGGRAPH 2003) **22**, 862–870 (2003)
5. Bishop, D.P.: Fabrics: sensory and mechanical properties. Textile Progress **26**(3) (1996)
6. Bridson, R., Marino, S., Fedkiw, R.: Simulation of clothing with folds and wrinkles. In: Proceedings ACM/Eurographics Symposium on Computer Animation, pp. 28–36 (2003)
7. Choi, K., Ko, H.: Stable but responsive cloth. In: Proceedings of ACM SIGGRAPH'2002, pp. 604–611 (2002)
8. Desbrun, M., Schröder, P., Barr, A.: Interactive animation of structured deformable objects. In: Proceedings of Graphics Interface, Morgan Kaufmann (1999)
9. Dillon, P., Moody, W., Bartlett, R., Scully, P., Morgan, R., James, C.: Sensing the fabric: To simulate sensation through sensory evaluation and in response to standard acceptable properties of specific materials when viewed as a digital image. In: Proceedings of Haptic Human-Computer Interaction, Springer (2001)
10. Eberhardt, P., Weber, A., Strasser, W.: A Fast, flexible, particle-system model for cloth draping. IEEE Comput. Graph. Appl. **16**(5), 52–59 (1996)

11. Eberhardt, B., Etzmuss, O., Hauth, M.: Implicit-explicit schemes for fast animation with particles systems. In: Proceedings of Eurographics Workshop on Computer Animation and Simulation, pp. 137–151 (2000)
12. Eischen, J.W, Deng, S., Clapp, T.G.: Finite-element modeling and control of flexible fabric parts. IEEE Comput. Graph. Appl. **16**(5), 71–80 (1996)
13. Govindaraj, M., Garg, A., Raheja, A., Huang, G., Metaxas, D.: Haptic simulation of fabric hand. In: I. Oakley, S. O'Modhrain, F. Newell (eds.) Eurohaptics Conference 2003, (2003)
14. Hauth, M., Etzmuss, O.: A high performance solver for the animation of deformable objects using advanced numerical methods. Comput. Graph. Forum (Eurographics 2001) **20**(3), 319–328 (2001)
15. Huang, G., Metaxas, D., Govindaraj, M.: Feel the "fabric": an audio-haptic interface. In: Proceedings of the 2003 ACM Siggraph/Eurographics Symposium on Computer Animation (2003)
16. Hui, C.L., Lau, T.W, Ng, S.F., Chan, K.C.C.: Neural network prediction of human psychological perceptions of fabric hand. Text. Res. J., May (2004)
17. Magnenat-Thalmann, N., Cordier, F., Keckeisen, M., Kimmerle, S., Klein, R., Meseth, J.: Simulation of clothes for real-time applications. In: Proceedings of Eurographics 2004, Tutorial 1, (2004)
18. Mäkinen, M., Meinander, H., Luible, C., Magnenat-Thalmann, N.: Influence of physical parameters on fabric hand. In: Proceedings of the HAPTEX Workshop, University of Hannover, Hannover (2005)
19. Meyer, M., Debunne, G., Desbrun, M., Barr, A.H.: Interactive animation of cloth-like objects in virtual reality. J. Vis. Comput. Anim. (2000)
20. Metzger, J., Kimmerle, S., Etzmuss, O.: Hierarchical techniques in collision detection for cloth animation. J. WSCG **11**(2), 322–329 (2003)
21. Morgenbesser, H.B., Srinivasan, M.A.: Force shading for haptic shape perception. In: Proceedings of the ASME Dynamic Systems and Control Division, vol. 58, pp. 407–412 (1996)
22. Ruspini, D., Kolarov, K., Khatib, O.: The haptic display of complex graphical environments. In: Proceedings of 24th Annual Conference on Computer Graphics and Interactive Techniques, pp. 345–352 (1997)
23. Salisbury, J.K., Brock, D., Massie, T., Swarup, N., Zilles, C.: Haptic rendering: Programming touch interaction with virtual objects. In: Proceedings of the ACM Symposium on Interactive 3D Graphics (1995)
24. Salsedo, F., Fontana, M., Tarri, F., Ruffaldi, E., Bergamasco, M., Magnenat-Thalmann, N., Volino, P., Bonnani, U., Brady, A., Summers, I., Qu, J., Allerkamp, D., Böttcher, G., Wolter, F.-E., Mäkinen, M., Meinander, H.: Architectural design of the HAPTEX system. In: Proceedings of the HAPTEX Workshop, University of Hannover, Hannover (2005)
25. Volino, P., Magnenat-Thalmann, N.: Comparing efficiency of integration methods for cloth animation. In: Proceedings of the Conference on Computer Graphics International (CGI-01), IEEE Computer Society (2001)
26. Volino, P., Magnenat-Thalmann, N.: Implementing fast cloth simulation with collision response. In: Computer Graphics International Proceedings, pp. 257–266, IEEE Computer Society (2000)
27. Volino, P., Magnenat-Thalmann, N.: Accurate garment prototyping and simulation. Comput. Aid. Des. Appl. **2**(1-4), CAD Solutions.
28. Zilles, C.B., Salisbury, J.K.: A constraint based God-Object method for haptic display. In: Proceedings of the IEEE Conference on Intelligent Robots and Systems, pp. 146–151 (1995)

     

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